Computer Science Curricula 2013

Curriculum Guidelines for Undergraduate Degree Programs in Computer Science

December 20, 2013

The Joint Task Force on Computing Curricula
Association for Computing Machinery (ACM)
IEEE Computer Society

A Cooperative Project of

Association for Computing Machinery
Advancing Computing as a Science & Profession

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Computer Science Curricula 2013

Final Report

December 2013

The Joint Task Force on Computing Curricula
Association for Computing Machinery
IEEE-Computer Society

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Chapter 1: Introduction

ACM and IEEE-Computer Society have a long history of sponsoring efforts to establish international curricular guidelines for undergraduate programs in computing on roughly a ten-year cycle, starting with the publication of Curriculum 68 [1] over 40 years ago. This volume is the latest in this series of curricular guidelines. As the field of computing has grown and diversified, so too have the curricular recommendations, and there are now curricular volumes for Computer Engineering, Information Systems, Information Technology, and Software Engineering in addition to Computer Science [3]. These volumes are updated regularly with the aim of keeping computing curricula modern and relevant. The last complete Computer Science curricular volume was released in 2001 (CC2001) [2], and an interim review effort concluded in 2008 (CS2008) [4].

This volume, Computer Science Curricula 2013 (CS2013), represents a comprehensive revision. The CS2013 guidelines include a redefined body of knowledge, a result of rethinking the essentials necessary for a Computer Science curriculum. It also seeks to identify exemplars of actual courses and programs to provide concrete guidance on curricular structure and development in a variety of institutional contexts.

The development of curricular guidelines for Computer Science has always been challenging given the rapid evolution and expansion of the field. The growing diversity of topics potentially relevant to an education in Computer Science and the increasing integration of computing with other disciplines create particular challenges for this effort. Balancing topical growth with the need to keep recommendations realistic and implementable in the context of undergraduate education is particularly difficult. As a result, the CS2013 Steering Committee made considerable effort to engage the broader computer science education community in a dialog to better understand new opportunities and local needs, and to identify successful models of computing curricula – whether established or novel.

Charter

The ACM and IEEE-Computer Society chartered the CS2013 effort with the following directive:

> *To review the Joint ACM and IEEE-CS Computer Science volume of Computing Curricula 2001 and the accompanying interim review CS 2008, and develop a revised and enhanced version for the year 2013 that will match the latest developments in the discipline and have lasting impact.*
>
> *The CS2013 task force will seek input from a diverse audience with the goal of broadening participation in computer science. The report will seek to be international in scope and offer curricular and pedagogical guidance applicable to a wide range of institutions. The process of producing the final report will include multiple opportunities for public consultation and scrutiny.*

The process by which the volume was produced followed directly from this charter.

Overview of the CS2013 Process

The ACM and IEEE-Computer Society respectively appointed the Steering Committee co-chairs, who, in turn, recruited the other members of the Steering Committee in the latter half of 2010. This group received its charter and began work in fall 2010, starting with a survey of Computer Science department chairs (described below). The Steering Committee met for the first time in February 2011, beginning work with a focus on revising the Body of Knowledge (BoK). This initial focus was chosen because both the CS2008 report and the results of the survey of department chairs pointed to a need for creation of new knowledge areas in the Body of Knowledge.

The Steering Committee met in person roughly every 6 months throughout the process of producing this volume and had conference call meetings at monthly intervals. Once the set of areas in the new Body of Knowledge was determined, a subcommittee was appointed to revise or create each Knowledge Area (KA). Each of these subcommittees was chaired by a member of the Steering Committee and included at least two additional Steering Committee members as well as other experts in the area chosen by the subcommittee chairs. As the subcommittees produced drafts of their Knowledge Areas, others in the community were asked to provide feedback, both through presentations at conferences and direct review requests. The Steering Committee also collected community input through an online review and comment process. The

KA subcommittee Chairs (as members of the CS2013 Steering Committee) worked to resolve conflicts, eliminate redundancies and appropriately categorize and cross-reference topics between the various KAs. Thus, the computer science community beyond the Steering Committee played a significant role in shaping the Body of Knowledge throughout the development of CS2013. This two-year process ultimately converged on the version of the Body of Knowledge presented here.

Beginning at its summer meeting in 2012, the Steering Committee turned much of its focus to course and curricular exemplars. In this effort, a broad community engagement was once again a key component of the process of collecting exemplars for inclusion in the volume. The results of these efforts are seen in Appendix C which presents these exemplars.

Survey Input

To lay the groundwork for CS2013, the Steering Committee conducted a survey of the use of the CC2001 and CS2008 volumes. The survey was sent to approximately 1500 Computer Science (and related discipline) department chairs and directors of undergraduate studies in the United States and an additional 2000 department chairs internationally. We received 201 responses, representing a wide range of institutions (self-identified):

- Research-oriented universities (55%)
- Teaching-oriented universities (17.5%)
- Undergraduate-only colleges (22.5%)
- Community colleges (5%)

The institutions also varied considerably in size, with the following distribution:

- Less than 1,000 students (6.5%)
- 1,000 to 5,000 students (30%)
- 5,000 to 10,000 students (19%)
- More than 10,000 students (44.5%)

In response to questions about how they used the CC2001/CS2008 reports, survey respondents reported that the Body of Knowledge (i.e., the outline of topics that should appear in undergraduate Computer Science curricula) was the most used component of the reports. When

questioned about new topical areas that should be added to the Body of Knowledge, survey respondents indicated a strong need to add the topics of *Security* as well as *Parallel and Distributed Computing*. Indeed, feedback during the CS2008 review had also indicated the importance of these two areas, but the CS2008 steering committee had felt that creating new KAs was beyond their purview and deferred the development of those areas to the next full curricular report. CS2013 includes these two new KAs (among others): *Information Assurance and Security*, and *Parallel and Distributed Computing*.

High-level Themes

In developing CS2013, several high-level themes provided an overarching guide for the development of this volume. The followings themes embody and reflect the CS2013 Principles (described in detail in the next chapter of this volume):

- *The "Big Tent" view of CS.* As CS expands to include more cross-disciplinary work and new programs of the form "Computational Biology," "Computational Engineering," and "Computational X" are developed, it is important to embrace an outward-looking view that sees CS as a discipline actively seeking to work with and integrate into other disciplines.
- *Managing the size of the curriculum.* Although the field of computer science continues to rapidly expand, it is not feasible to proportionately expand the size of the curriculum. As a result, CS2013 seeks to re-evaluate the essential topics in computing to make room for new topics without requiring more total instructional hours than the CS2008 guidelines. At the same time, the circumscription of curriculum size promotes more flexible models for curricula without losing the essence of a rigorous CS education.
- *Actual course exemplars.* CS2001 took on the significant challenge of providing descriptions of six *curriculum models* and forty-seven possible *course descriptions* variously incorporating the knowledge units as defined in that report. While this effort was valiant, in retrospect such course guidance did not seem to have much impact on actual course design. CS2013 takes a different approach: we identify and describe existing successful courses and curricula to show how relevant knowledge units are addressed and incorporated in actual programs.
- *Institutional needs.* CS2013 aims to be applicable in a broad range of geographic and cultural contexts, understanding that curricula exist within specific institutional needs, goals, and resource constraints. As a result, CS2013 allows for explicit flexibility in curricular structure through a tiered set of core topics, where a small set of Core-Tier1 topics are considered essential for all CS programs, but individual programs choose their coverage of Core-Tier2 topics. This tiered structure is described in more detail in Chapter 4 of this report.

Knowledge Areas

The CS2013 Body of Knowledge is organized into a set of 18 Knowledge Areas (KAs), corresponding to topical areas of study in computing. The Knowledge Areas are:

- AL - Algorithms and Complexity
- AR - Architecture and Organization
- CN - Computational Science
- DS - Discrete Structures
- GV - Graphics and Visualization
- HCI - Human-Computer Interaction
- IAS - Information Assurance and Security
- IM - Information Management
- IS - Intelligent Systems
- NC - Networking and Communications
- OS - Operating Systems
- PBD - Platform-based Development
- PD - Parallel and Distributed Computing
- PL - Programming Languages
- SDF - Software Development Fundamentals
- SE - Software Engineering
- SF - Systems Fundamentals
- SP - Social Issues and Professional Practice

Many of these Knowledge Areas are derived directly from CC2001/CS2008, but have been revised—in some cases quite significantly—in CS2013; other KAs are new to CS2013. Some represent new areas that have grown in significance since CC2001 and are now integral to studies in computing. For example, the increased importance of computer and network security in the past decade led to the development of Information Assurance and Security (IAS). Other new KAs represent a restructuring of knowledge units from CC2001/CS2008, reorganized in a way to make them more relevant to modern practices. For example, Software Development Fundamentals (SDF) pulls together basic knowledge and skills related to software development,

including knowledge units that were formerly spread across Programming Fundamentals, Software Engineering, Programming Languages, and Algorithms and Complexity. Similarly, Systems Fundamentals (SF) brings together fundamental, cross-cutting systems concepts that can serve as a foundation for more advanced work in a number of areas.

It is important to recognize that Knowledge Areas are interconnected and that concepts in one KA may build upon or complement material from other KAs. The reader should take care in reading the Body of Knowledge as a whole, rather than focusing on any given Knowledge Area in isolation. Chapter 4 contains a more comprehensive overview of the KAs, including motivations for the new additions.

Professional Practice

The education that undergraduates in computer science receive must adequately prepare them for the workforce in a more holistic way than simply conveying technical facts. Indeed, soft skills (such as teamwork, verbal and written communication, time management, problem solving, and flexibility) and personal attributes (such as risk tolerance, collegiality, patience, work ethic, identification of opportunity, sense of social responsibility, and appreciation for diversity) play a critical role in the workplace. Successfully applying technical knowledge in practice often requires an ability to tolerate ambiguity and to negotiate and work well with others from different backgrounds and disciplines. These overarching considerations are important for promoting successful professional practice in a variety of career paths.

Students will gain some soft skills and personal attributes through the general college experience (e.g., patience, time management, work ethic, and an appreciation for diversity), and others through specific curricula. CS2013 includes examples of ways in which an undergraduate Computer Science program encourages the development of soft skills and personal attributes. Core hours for teamwork and risk management are covered in the Software Engineering (SE) Knowledge Area under Project Management. The ability to tolerate ambiguity is also core in Software Engineering under Requirements Engineering. Written and verbal communications are also part of the core in the Social Issues and Professional Practice (SP) Knowledge Area under Professional Communication. The inclusion of core hours in the Social Issues and Professional Practice KA under the Social Context knowledge unit helps to promote a greater understanding

of the implications of social responsibility among students. The importance of lifelong learning as well as professional development is described in the preamble of the Social Issues and Professional Practice Knowledge Area as well as in both Chapter 2 (Principles) and Chapter 3 (Characteristics of Graduates).

Exemplars of Curricula and Courses

The CS2013 report includes examples of actual fielded courses—from a variety of universities and colleges—to illustrate how topics in the Knowledge Areas may be covered and combined in diverse ways. The report also offers examples of CS curricula from a handful of institutions to show different ways in which a larger collection of courses can be put together to form a complete curriculum. Importantly, we believe that the presentation of exemplar courses and curricula promotes greater sharing of educational ideas within the computing community. It also promotes on-going engagement by encouraging educators to share new courses and curricula from their own institutions (or other institutions with which they may be familiar) with the broader community.

Community Involvement and Website

The CS2013 report benefitted from a broad engagement of members of the computing community who reviewed and critiqued successive drafts of this document. Indeed, the development of this report benefited from the input of more than 100 contributors beyond the Steering Committee. More information about the CS2013 effort is available at the CS2013 website:

http://cs2013.org

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Additionally, review of various portions of draft CS2013 report took place in several venues, including: the 42nd ACM Technical Symposium of the Special Interest Group on Computer Science Education (SIGCSE-11); the 24th IEEE-CS Conference on Software Engineering Education and Training (CSEET-11); the 2011 IEEE Frontiers in Education Conference (FIE-

11); the 2011 Federated Computing Research Conference (FCRC-11); the 2nd Symposium on Educational Advances in Artificial Intelligence (EAAI-11); the Conference of ACM Special Interest Group on Data Communication 2011 (SIGCOMM-11); the 2011 IEEE International Joint Conference on Computer, Information, and Systems Sciences and Engineering (CISSE-11); the 2011 Systems, Programming, Languages and Applications: Software for Humanity Conference (SPLASH-11); the 15th Colloquium for Information Systems Security Education; the 2011 National Centers of Academic Excellence in IA Education (CAE/IAE) Principles meeting; the 7th IFIP TC 11.8 World Conference on Information Security Education (WISE); the 43rd ACM Technical Symposium of the Special Interest Group on Computer Science Education (SIGCSE-12); the Special Session of the Special Interest Group on Computers and Society at SIGCSE-12; the Computer Research Association Snowbird Conference 2012; and the 2012 IEEE Frontiers in Education Conference (FIE-12), among others.

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Chapter 2: Principles

Early in its work, the 2013 Steering Committee agreed on a set of principles to guide the development of this volume. The principles adopted for CS2013 overlap significantly with the principles adopted for previous curricular efforts, most notably CC2001 and CS2008. As with previous ACM/IEEE curricula volumes, there are a variety of constituencies for CS2013, including individual faculty members and instructors at a wide range of colleges, universities, and technical schools on any of six continents; CS programs and the departments, colleges, and institutions housing them; accreditation and certification boards; authors; and researchers. Other constituencies include pre-college preparatory schools and advanced placement curricula as well as graduate programs in computer science. These principles were developed in consideration of these constituencies, as well as consideration of issues related to student outcomes, development of curricula, and the review process. The order of presentation is not intended to imply relative importance.

1. *Computer science curricula should be designed to provide students with the flexibility to work across many disciplines.* Computing is a broad field that connects to and draws from many disciplines, including mathematics, electrical engineering, psychology, statistics, fine arts, linguistics, and physical and life sciences. Computer Science students should develop the flexibility to work across disciplines.

2. *Computer science curricula should be designed to prepare graduates for a variety of professions, attracting the full range of talent to the field.* Computer science impacts nearly every modern endeavor. CS2013 takes a broad view of the field that includes topics such as "computational-x" (e.g., computational finance or computational chemistry) and "x-informatics" (e.g., eco-informatics or bio-informatics). Well-rounded CS graduates will have a balance of theory and application, as described in Chapter 3: Characteristics of Graduates.

3. *CS2013 should provide guidance for the expected level of mastery of topics by graduates*. It should suggest outcomes indicating the intended level of mastery and provide exemplars of instantiated courses and curricula that cover topics in the Body of Knowledge.

4. *CS2013 must provide realistic, adoptable recommendations that provide guidance and flexibility, allowing curricular designs that are innovative and track recent developments in the field.* The guidelines are intended to provide clear, implementable goals, while also providing the flexibility that programs need in order to respond to a rapidly changing field. CS2013 is intended as guidance, not as a minimal standard against which to evaluate a program.

5. *The CS2013 guidelines must be relevant to a variety of institutions.* Given the wide range of institutions and programs (including 2-year, 3-year, and 4-year programs; liberal arts, technological, and research institutions; and institutions of every size), it is neither possible nor desirable for these guidelines to dictate curricula for computing. Individual programs will need to evaluate their constraints and environments to construct curricula.

6. *The size of the essential knowledge must be managed*. While the range of relevant topics has expanded, the size of undergraduate education has not. Thus, CS2013 must carefully choose among topics and recommend the essential elements.

7. *Computer science curricula should be designed to prepare graduates to succeed in a rapidly changing field.* Computer Science is rapidly changing and will continue to change for the foreseeable future. Curricula must prepare students for lifelong learning and must include professional practice (e.g., communication skills, teamwork, ethics) as components of the undergraduate experience. Computer science students must learn to integrate theory and practice, to recognize the importance of abstraction, and to appreciate the value of good engineering design.

8. *CS2013 should identify the fundamental skills and knowledge that all computer science graduates should possess while providing the greatest flexibility in selecting topics.* To this end, we have introduced three levels of knowledge description: Tier-1 Core, Tier-2 Core, and Elective. For a full discussion of Tier-1 Core, Tier-2 Core, and Elective, see Chapter 4: Introduction to the Body of Knowledge.

9. *CS2013 should provide the greatest flexibility in organizing topics into courses and curricula.* Knowledge areas are not intended to describe specific courses. There are many

novel, interesting, and effective ways to combine topics from the Body of Knowledge into courses.

10. *The development and review of CS2013 must be broadly based.* The CS2013 effort must include participation from many different constituencies including industry, government, and the full range of higher education institutions involved in computer science education. It must take into account relevant feedback from these constituencies.

Chapter 3: Characteristics of Graduates

Graduates of computer science programs should have fundamental competency in the areas described by the Body of Knowledge (see Chapter 4), particularly the core topics contained there. However, there are also competences that graduates of CS programs should have that are not explicitly listed in the Body of Knowledge. Professionals in the field typically embody a characteristic style of thinking and problem solving, a style that emerges from the experiences obtained through study of the field and professional practice. Below, we describe the characteristics that we believe should be attained at least at an elementary level by graduates of computer science programs. These characteristics will enable their success in the field and further professional development. Some of these characteristics and skills also apply to other fields. They are included here because the development of these skills and characteristics should be explicitly addressed and encouraged by computer science programs. This list is based on a similar list in CC2001 and CS2008. The substantive changes that led to this new version were influenced by responses to a survey conducted by the CS2013 Steering Committee.

At a broad level, the expected characteristics of computer science graduates include the following:

Technical understanding of computer science

Graduates should have a mastery of computer science as described by the core of the Body of Knowledge.

Familiarity with common themes and principles

Graduates need understanding of a number of recurring themes, such as abstraction, complexity, and evolutionary change, and a set of general principles, such as sharing a common resource, security, and concurrency. Graduates should recognize that these themes and principles have broad application to the field of computer science and should not consider them as relevant only to the domains in which they were introduced.

Appreciation of the interplay between theory and practice

A fundamental aspect of computer science is understanding the interplay between theory and practice and the essential links between them. Graduates of a computer science program need to understand how theory and practice influence each other.

System-level perspective

Graduates of a computer science program need to think at multiple levels of detail and abstraction. This understanding should transcend the implementation details of the various components to encompass an appreciation for the structure of computer systems and the processes involved in their construction and analysis. They need to recognize the context in which a computer system may function, including its interactions with people and the physical world.

Problem solving skills

Graduates need to understand how to apply the knowledge they have gained to solve real problems, not just write code and move bits. They should to be able to design and improve a system based on a quantitative and qualitative assessment of its functionality, usability and performance. They should realize that there are multiple solutions to a given problem and that selecting among them is not a purely technical activity, as these solutions will have a real impact on people's lives. Graduates also should be able to communicate their solution to others, including why and how a solution solves the problem and what assumptions were made.

Project experience

To ensure that graduates can successfully apply the knowledge they have gained, all graduates of computer science programs should have been involved in at least one substantial project. In most cases, this experience will be a software development project, but other experiences are also appropriate in particular circumstances. Such projects should challenge students by being integrative, requiring evaluation of potential solutions, and requiring work on a larger scale than typical course projects. Students should have opportunities to develop their interpersonal communication skills as part of their project experience.

Commitment to life-long learning

Graduates should realize that the computing field advances at a rapid pace, and graduates must possess a solid foundation that allows and encourages them to maintain relevant skills as the

field evolves. Specific languages and technology platforms change over time. Therefore, graduates need to realize that they must continue to learn and adapt their skills throughout their careers. To develop this ability, students should be exposed to multiple programming languages, tools, paradigms, and technologies as well as the fundamental underlying principles throughout their education. In addition, graduates are now expected to manage their own career development and advancement. Graduates seeking career advancement often engage in professional development activities, such as certifications, management training, or obtaining domain-specific knowledge.

Commitment to professional responsibility

Graduates should recognize the social, legal, ethical, and cultural issues inherent in the discipline of computing. They must further recognize that social, legal, and ethical standards vary internationally. They should be knowledgeable about the interplay of ethical issues, technical problems, and aesthetic values that play an important part in the development of computing systems. Practitioners must understand their individual and collective responsibility and the possible consequences of failure. They must understand their own limitations as well as the limitations of their tools.

Communication and organizational skills

Graduates should have the ability to make effective presentations to a range of audiences about technical problems and their solutions. This may involve face-to-face, written, or electronic communication. They should be prepared to work effectively as members of teams. Graduates should be able to manage their own learning and development, including managing time, priorities, and progress.

Awareness of the broad applicability of computing

Platforms range from embedded micro-sensors to high-performance clusters and distributed clouds. Computer applications impact nearly every aspect of modern life. Graduates should understand the full range of opportunities available in computing.

Appreciation of domain-specific knowledge

Graduates should understand that computing interacts with many different domains. Solutions to many problems require both computing skills and domain knowledge. Therefore, graduates need

to be able to communicate with, and learn from, experts from different domains throughout their careers.

Chapter 4: Introduction to the Body of Knowledge

This chapter provides an introduction to the structure and rationale for the Body of Knowledge. It further describes the most substantial innovations in the Body of Knowledge. It does not propose a particular set of courses or curriculum structure -- that is the role of the course and curriculum exemplars. Rather, this chapter emphasizes the flexibility that the Body of Knowledge allows in adapting curricula to institutional needs and the continual evolution of the field. In Computer Science terms, one can view the Body of Knowledge as a specification of the content to be covered and a curriculum as an implementation. A large variety of curricula can meet the specification.

The following points are elaborated:

- Knowledge Areas are not intended to be in one-to-one correspondence with particular courses in a curriculum: We expect curricula will have courses that incorporate topics from multiple Knowledge Areas.
- Topics are identified as either “Core” or “Elective” with the core further subdivided into “Tier-1” and “Tier-2.”
    - A curriculum should include all topics in the Tier-1 core and ensure that all students cover this material.
    - A curriculum should include all or almost all topics in the Tier-2 core and ensure that all students encounter the vast majority of this material.
    - A curriculum should include significant elective material: Covering only “Core” topics is insufficient for a complete curriculum.
- Because it is a hierarchical outline, the Body of Knowledge under-emphasizes some key issues that must be considered when constructing a curriculum, such as the ways in which a curriculum allows students to develop the characteristics outlined in Chapter 3: *Characteristics of Graduates*.

- The learning outcomes and hour counts in the Body of Knowledge provide guidance on the depth of coverage towards which curricula should aim.
- There are several new Knowledge Areas that reflect important changes in the field.

Knowledge Areas are Not Necessarily Courses (and Important Examples Thereof)

It is naturally tempting to associate each Knowledge Area with a course. We explicitly discourage this practice in general, even though many curricula will have some courses containing material from only one Knowledge Area or, conversely, all the material from one Knowledge Area in one course. We view the hierarchical structure of the Body of Knowledge as a useful way to group related information, not as a stricture for organizing material into courses. Beyond this general flexibility, in several places we expect many curricula to integrate material from multiple Knowledge Areas, in particular:

- *Introductory courses:* There are diverse successful approaches to introductory courses in computer science. Many focus on the topics in Software Development Fundamentals together with a subset of the topics in Programming Languages or Software Engineering, while leaving most of the topics in these other Knowledge Areas to advanced courses. But *which* topics from other Knowledge Areas are covered in introductory courses can vary. Some courses use object-oriented programming; others, functional programming; and others, platform-based development (thereby covering topics in the Platform-Based Development Knowledge Area). Conversely, there is no requirement that all Software Development Fundamentals be covered in a first or second course, though in practice most topics will usually be covered in these early courses. A separate chapter discusses introductory courses more generally.
- *Systems courses:* The topics in the Systems Fundamentals Knowledge Area can be presented in courses designed to cover general systems principles or in those devoted to particular systems areas such as computer architecture, operating systems, networking, or distributed systems. For example, an Operating Systems course might be designed to cover more general systems principles, such as low-level programming, concurrency and

synchronization, performance measurement, or computer security, in addition to topics more specifically related to operating systems. Consequently, such courses will likely draw on material in several Knowledge Areas. Certain fundamental systems topics like latency or parallelism will likely arise in many places in a curriculum. While it is important that such topics do arise, preferably in multiple settings, the Body of Knowledge does not specify the particular settings in which to teach such topics. The course exemplars in Appendix C show multiple ways that such material may be organized into courses.

- *Parallel computing:* Among the changes to the Body of Knowledge from previous reports is a new Knowledge Area in Parallel and Distributed Computing. An alternative structure for the Body of Knowledge would place relevant topics in other Knowledge Areas: parallel algorithms with algorithms, programming constructs in software-development focused areas, multi-core design with computer architecture, and so forth. We chose instead to provide guidance on the essential parallelism topics in one place. Some, but not all, curricula will likely have courses dedicated to parallelism, at least in the near term.

Core Tier-1, Core Tier-2, Elective: What These Terms Mean, What is Required

As described at the beginning of this chapter, computer-science curricula should cover all the Core Tier-1 topics, all or almost all of the Core Tier-2 topics, and significant depth in many of the Elective topics (i.e., the core is not sufficient for an undergraduate degree in computer science). Here we provide additional perspective on what "Core Tier-1," "Core Tier-2", and "Elective" mean, including motivation for these distinctions.

Motivation for subdividing the core: Earlier curricular guidelines had only "Core" and "Elective" with every topic in the former being required. We departed from this strict interpretation of "everything in the core must be taught to every student" for these reasons:

- Many strong computer-science curricula were missing at least one hour of core material. It is misleading to suggest that such curricula are outside the definition of an undergraduate degree in computer science.
- As the field has grown, there is ever-increasing pressure to grow the core and to allow students to specialize in areas of interest. Doing so simply becomes impossible within the short time-frame of an undergraduate degree. Providing some flexibility on coverage of core topics enables curricula and students to specialize if they choose to do so.

Conversely, we could have allowed for *any* core topic to be skipped provided that the vast majority was part of every student's education. By retaining a smaller Core Tier-1 of required material, we provide additional guidance and structure for curriculum designers. In the Core Tier-1 are the topics that are fundamental to the structure of any computer-science program.

On the meaning of Core Tier-1: A Core Tier-1 topic should be a required part of every Computer Science curriculum. While Core Tier-2 and Elective topics are important, the Core Tier-1 topics are those with widespread consensus for inclusion in every program. While most Core Tier-1 topics will typically be covered in introductory courses, others may be covered in later courses.

On the meaning of Core Tier-2: Core Tier-2 topics are generally essential in an undergraduate computer-science degree. Requiring the vast majority of them is a *minimum* expectation, and if a program prefers to cover all of the Core Tier-2 topics, we encourage them to do so. That said, Computer Science programs can allow students to focus in certain areas in which some Core Tier-2 topics are not required. We also acknowledge that resource constraints, such as a small number of faculty or institutional limits on degree requirements, may make it prohibitively difficult to cover every topic in the core while still providing advanced elective material. **A computer-science curriculum should aim to cover 90-100% of the Core Tier-2 topics, with 80% considered a minimum.**

There is no expectation that Core Tier-1 topics necessarily precede all Core Tier-2 topics in a curriculum. In particular, we expect introductory courses will draw on both Core Tier-1 and

Core Tier-2 (and possibly elective) material and that some core material will be delayed until later courses.

On the meaning of Elective: A program covering only core material would provide insufficient breadth and depth in computer science. Most programs will not cover all the elective material in the Body of Knowledge and certainly few, if any, students will cover all of it within an undergraduate program. Conversely, the Body of Knowledge is by no means exhaustive, and advanced courses may often go beyond the topics and learning outcomes contained in it. Nonetheless, the Body of Knowledge provides a useful guide on material appropriate for a computer-science undergraduate degree, and all students of computer science should deepen their understanding in multiple areas via the elective topics.

A curriculum may well require material designated elective in the Body of Knowledge. Many curricula, especially those with a particular focus, will require some elective topics, by virtue of them being covered in required courses.

The size of the core: The size of the core (Tier-1 plus Tier-2) is a few hours larger than in previous curricular guidelines, but this is counterbalanced by our more flexible treatment of the core. As a result, we are not increasing the number of required courses a curriculum should need. Indeed, a curriculum covering 90% of the Tier-2 hours would have the same number of core hours as a curriculum covering the core in the CS2008 volume, and a curriculum covering 80% of the Tier-2 hours would have fewer core hours than even a curriculum covering the core in the CC2001 volume (the core grew from 2001 to 2008). A more thorough quantitative comparison is presented at the end of this chapter.

A note on balance: Computer Science is an elegant interplay of theory, software, hardware, and applications. The core in general and Tier-1 in particular, when viewed in isolation, may seem to focus on programming, discrete structures, and algorithms. This focus results from the fact that these topics typically come early in a curriculum so that advanced courses can use them as prerequisites. Essential experience with systems and applications can be achieved in more disparate ways using elective material in the Body of Knowledge. Because all curricula will

include appropriate elective material, an overall curriculum can and should achieve an appropriate balance.

Further Considerations in Designing a Curriculum

As useful as the Body of Knowledge is, it is important to complement it with a thoughtful understanding of cross-cutting themes in a curriculum, the "big ideas" of computer science. In designing a curriculum, it is also valuable to identify curriculum-wide objectives, for which the Principles and the Characteristics of Graduates chapters of this volume should prove useful.

In the last few years, two on-going trends have had deep effects on many curricula. First, the continuing growth of computer science has led to many programs organizing their curricula to allow for *intradisciplinary* specialization (using terms such as threads, tracks, and vectors). Second, the importance of computing to almost every other field has increasingly led to the creation of *interdisciplinary* programs (e.g., joint majors and double majors) and incorporating interdisciplinary material into computer-science programs. We applaud both trends and believe a flexible Body of Knowledge, including a flexible core, supports them. Conversely, such specialization is not required: Many programs will continue to offer a broad yet thorough coverage of computer science as a distinct and coherent discipline.

Organization of the Body of Knowledge

The CS2013 Body of Knowledge is presented as a set of Knowledge Areas (KAs), organized on topical themes rather than by course boundaries. Each KA is further organized into a set of Knowledge Units (KUs), which are summarized in a table at the head of each KA section. We expect that the topics within the KAs will be organized into courses in different ways at different institutions.

Curricular Hours

Continuing in the tradition of CC2001/CS2008, we define the unit of coverage in the Body of Knowledge in terms of **lecture hours**, as being the sole unit that is understandable in (and transferable to) cross-cultural contexts. An "hour" corresponds to the time required to present the

material in a traditional lecture-oriented format; the hour count does not include any additional work that is associated with a lecture (e.g., in self-study, laboratory sessions, and assessments). Indeed, we expect students to spend a significant amount of additional time outside of class developing facility with the material presented in class. As with previous reports, we maintain the principle that the use of a lecture-hour as the unit of measurement does not require or endorse the use of traditional lectures for the presentation of material.

The specification of topic hours represents the minimum amount of time we expect such coverage to take. Any institution may opt to cover the same material in a longer period of time as warranted by the individual needs of that institution.

Courses

Throughout the Body of Knowledge, when we refer to a "course" we mean an institutionally-recognized unit of study. Depending on local circumstance, full-time students will take several "courses" at any one time, typically several per academic year. While "course" is a common term at some institutions, others will use other names, for example "module" or "paper."

Guidance on Learning Outcomes

Each KU within a KA lists both a set of topics and the learning outcomes students are expected to achieve with respect to the topics specified. Learning outcomes are not of equal size and do not have a uniform mapping to curriculum hours; topics with the same number of hours may have quite different numbers of associated learning outcomes. Each learning outcome has an associated level of mastery. In defining different levels we drew from other curriculum approaches, especially Bloom's Taxonomy, which has been well explored within computer science. We did not directly apply Bloom's levels in part because several of them are driven by pedagogic context, which would introduce too much plurality in a document of this kind; in part because we intend the mastery levels to be indicative and not to impose theoretical constraint on users of this document.

We use three levels of mastery, defined as:

- ***Familiarity***: The student understands what a concept is or what it means. This level of mastery concerns a basic awareness of a concept as opposed to expecting real facility with its application. It provides an answer to the question "What do you know about this?"
- ***Usage***: The student is able to use or apply a concept in a concrete way. Using a concept may include, for example, appropriately using a specific concept in a program, using a particular proof technique, or performing a particular analysis. It provides an answer to the question "What do you know how to do?"
- ***Assessment***: The student is able to consider a concept from multiple viewpoints and/or justify the selection of a particular approach to solve a problem. This level of mastery implies more than using a concept; it involves the ability to select an appropriate approach from understood alternatives. It provides an answer to the question "Why would you do that?"

As a concrete, although admittedly simplistic, example of these levels of mastery, we consider the notion of iteration in software development, for example for-loops, while-loops, and iterators. At the level of "Familiarity," a student would be expected to have a definition of the concept of iteration in software development and know why it is a useful technique. In order to show mastery at the "Usage" level, a student should be able to write a program properly using a form of iteration. Understanding iteration at the "Assessment" level would require a student to understand multiple methods for iteration and be able to appropriately select among them for different applications.

The descriptions we have included for learning outcomes may not exactly match those used by institutions, in either specifics or emphasis. Institutions may have different learning outcomes that capture the same level of mastery and intent for a given topic. Nevertheless, we believe that by giving descriptive learning outcomes, we both make our intention clear and facilitate interpretation of what outcomes mean in the context of a particular curriculum.

Overview of New Knowledge Areas

While computer science encompasses technologies that change rapidly over time, it is defined by essential concepts, perspectives, and methodologies that are constant. As a result, much of the

core Body of Knowledge remains unchanged from earlier curricular volumes. However, new developments in computing technology and pedagogy mean that some aspects of the core evolve over time, and some of the previous structures and organization may no longer be appropriate for describing the discipline. As a result, CS2013 has modified the organization of the Body of Knowledge in various ways, adding some new KAs and restructuring others. We highlight these changes in the remainder of this section.

Information Assurance and Security (IAS)

IAS is a new KA in recognition of the world's critical reliance on information technology and computing. IAS as a domain is the set of controls and processes, both technical and policy, intended to protect and defend information and information systems. IAS draws together topics that are pervasive throughout other KAs. Topics germane to *only* IAS are presented in depth in this KA, whereas other topics are noted and cross referenced to the KAs that contain them. As such, this KA is prefaced with a detailed table of cross-references to other KAs.

Networking and Communication (NC)

CC2001 introduced a KA entitled "Net-Centric Computing", which encompassed a combination of topics including traditional networking, web development, and network security. Given the growth and divergence in these topics since the last report, we renamed and re-factored this KA to focus specifically on topics in networking and communication. Discussions of web applications and mobile device development are now covered in the new Platform-Based Development KA. Security is covered in the new Information Assurance and Security KA.

Platform-Based Development (PBD)

PBD is a new KA that recognizes the increasing use of platform-specific programming environments, both at the introductory level and in upper-level electives. Platforms such as the Web or mobile devices enable students to learn within and about environments constrained by hardware, APIs, and special services (often in cross-disciplinary contexts). These environments are sufficiently different from "general purpose" programming to warrant this new (wholly elective) KA.

Parallel and Distributed Computing (PD)

Previous curricular volumes had parallelism topics distributed across disparate KAs as electives. Given the vastly increased importance of parallel and distributed computing, it seemed crucial to identify essential concepts in this area and to promote those topics to the core. To highlight and coordinate this material, CS2013 dedicates a KA to this area. This new KA includes material on programming models, programming pragmatics, algorithms, performance, computer architecture, and distributed systems.

Software Development Fundamentals (SDF)

This new KA generalizes introductory programming to focus on more of the software development process, identifying concepts and skills that should be mastered in the first year of a computer-science program. As a result of its broad purpose, the SDF KA includes fundamental concepts and skills that could appear in other software-oriented KAs (e.g., programming constructs from Programming Languages, simple algorithm analysis from Algorithms and Complexity, simple development methodologies from Software Engineering). Likewise, each of those KAs will contain more advanced material that builds upon the fundamental concepts and skills in SDF. Compared to previous volumes, key approaches to programming -- including object-oriented programming, functional programming, and event-driven programming -- are kept in one place, namely the Programming Languages KA, with an expectation that any curriculum will cover some of these topics in introductory courses.

Systems Fundamentals (SF)

In previous curricular volumes, the interacting layers of a typical computing system, from hardware building blocks, to architectural organization, to operating system services, to application execution environments (particularly for parallel execution in a modern view of applications), were presented in independent knowledge areas. The new Systems Fundamentals KA presents a unified systems perspective and common conceptual foundation for other KAs (notably Architecture and Organization, Network and Communications, Operating Systems, and Parallel and Distributed Algorithms). An organizational principle is “programming for performance”: what a programmer needs to understand about the underlying system to achieve high performance, particularly in terms of exploiting parallelism.

Core Hours in Knowledge Areas

An overview of the number of core hours (both Tier-1 and Tier-2) by KA in the CS2013 Body of Knowledge is provided below. For comparison, the number of core hours from both the previous CS2008 and CC2001 reports are provided as well.

Knowledge Area	CS2013 Tier1	CS2013 Tier2	CS2008 Core	CC2001 Core
AL-Algorithms and Complexity	19	9	31	31
AR-Architecture and Organization	0	16	36	36
CN-Computational Science	1	0	0	0
DS-Discrete Structures	37	4	43	43
GV-Graphics and Visualization	2	1	3	3
HCI-Human-Computer Interaction	4	4	8	8
IAS-Information Assurance and Security	3	6	--	--
IM-Information Management	1	9	11	10
IS-Intelligent Systems	0	10	10	10
NC-Networking and Communication	3	7	15	15
OS-Operating Systems	4	11	18	18
PBD-Platform-based Development	0	0	--	--
PD-Parallel and Distributed Computing	5	10	--	--
PL-Programming Languages	8	20	21	21
SDF-Software Development Fundamentals	43	0	47	38
SE-Software Engineering	6	22	31	31
SF-Systems Fundamentals	18	9	--	--
SP-Social Issues and Professional Practice	11	5	16	16
Total Core Hours	**165**	**143**	**290**	**280**

All Tier1 + All Tier2 Total	**308**
All Tier1 + 90% of Tier2 Total	**293.7**
All Tier1 + 80% of Tier2 Total	**279.4**

As seen above, in CS2013 the total Tier-1 hours together with the entirety of Tier-2 hours slightly exceeds the total core hours from previous reports. However, it is important to note that the tiered structure of the core in CS2013 explicitly provides the flexibility for institutions to

select topics from Tier-2 (to include at least 80%). As a result, it is possible to implement the CS2013 guidelines with comparable hours to previous curricular guidelines.

Chapter 5: Introductory Courses

Computer science, unlike many technical disciplines, does not have a well-described list of topics that appear in virtually all introductory courses. In considering the changing landscape of introductory courses, we look at the evolution of such courses from CC2001 to CS2013. CC2001 classified introductory course sequences into six general models: *Imperative-first, Objects-first, Functional-first, Breadth-first, Algorithms-first*, and *Hardware-first*. While introductory courses with these characteristic features certainly still exist today, we believe that advances in the field have led to an even more diverse set of approaches in introductory courses than the models set out in CC2001. Moreover, the approaches employed in introductory courses are in a greater state of flux.

An important challenge for introductory courses, and a key reason the content of such courses remains a vigorous discussion topic after decades of debate, is that not everything relevant to a computer scientist (programming, software processes, algorithms, abstraction, performance, security, professionalism, etc.) can be taught from day one. In other words, not everything can come first and as a result some topics must be pushed further back in the curriculum, in some cases significantly so. Many topics will not appear in a first course or even a second course, meaning that students who do not continue further (for example, non-majors) will lose exposure to these topics. Ultimately, choosing what to cover in introductory courses results in a set of tradeoffs that must be considered when trying to decide what should be covered early in a curriculum.

Design Dimensions

We structure this chapter as a set of design dimensions relevant to crafting introductory courses, concluding each dimension with a summary of the trade-offs that are in tension along the dimension. A given introductory course, or course sequence, in computer science will represent a set of decisions within this multidimensional design space and achieve distinctive outcomes as a result. We note that our discussion here focuses on introductory courses meant as part of an undergraduate program in computer science. Notably, we do not discuss the increasingly

common"CS0" courses: precursor courses often focusing on computer fluency or computational thinking. Such courses may include some introductory computer science concepts or material, but are not part of this Body of Knowledge and are outside the scope of our consideration.

Pathways Through Introductory Courses

We recognize that introductory courses are not constructed in the abstract, but rather are designed for specific target audiences and contexts. Departments know their institutional contexts best and must be sensitive to their own students and their needs. Introductory courses differ across institutions, especially with regard to the nature and length of an introductory sequence (that is, the number of courses that a student must take before any branching is allowed). A sequence of courses may also have different entry points to accommodate students with significant differences in previous computing experience and/or who come from a wide diversity of backgrounds. Having multiple pathways into and through the introductory course sequence can help to better align students' abilities with the appropriate level of coursework. It can also help create more flexibility with articulation between two-year and four-year institutions, and smooth the transition for students transferring from other colleges/programs. Increasingly, computing in general and programming in particular are essential to students in other fields. Courses for these non-majors may or may not be distinct from courses that lead to years of computer science study. Additionally, having multiple pathways through introductory courses may provide greater options to students who choose to start take courses in computing late in their college programs.

Building courses for diverse audiences – not just students who are already sure of a major in computer science – is essential for making computing accessible to a wide range of students. Given the importance of computation across many disciplines, the appeal of introductory programming courses has significantly broadened beyond the traditionally accommodated engineering fields. For target audiences with different backgrounds, and different expectations, the practice of having thematically-focused introductory courses (e.g., computational biology, robotics, digital media manipulation, etc.) has become popular. In this way, material is made relevant to the expectations and aspirations of students with a variety of disciplinary orientations.

Tradeoffs:

- Providing multiple pathways into and through introductory course sequences can make computer science more accessible to different audiences, but requires greater investment (in work and resources) by a department to construct such pathways and/or provide different themed options to students. Moreover, care must be taken to give students guidance with regard to choosing an appropriate introductory course pathway. (This is as true for those students with extensive prior computing experience as for those with none.)
- By having longer introductory course sequences (i.e., longer or more structured pre-requisite chains), educators can assume more prior knowledge in each course, but such lengthy sequences sacrifice flexibility and increase the time before students are able to take advanced courses more focused on their areas of interest.

Programming Focus

The vast majority of introductory courses are programming-focused, in which students learn about concepts in computer science (e.g., abstraction, decomposition, etc.) through the explicit tasks of learning a given programming language and building software artifacts. A programming focus can provide early training in this crucial skill for computer science majors and help elevate students with different backgrounds in computing to a more equal footing. Even given a programming focus, there is a further subdivision between having students write whole programs – to ensure understanding how the pieces fit together and give the full experience of program construction – versus having students complete or modify existing programs and skeletons, which can be more like real-world experience and allow creating larger and more complex programs. Moving away from emphasizing programming, some introductory courses are designed to provide a broader introduction to concepts in computing without the constraints of learning the syntax of a programming language. They are consciously programming de-focused. Such a perspective is roughly analogous to the "Breadth-first" model in CC2001. Whether or not programming is the primary focus of their first course, it is important that students do not perceive computer science as only learning the specifics of particular programming languages. Care must be taken to emphasize the more general concepts in computing within the context of learning how to program.

Tradeoffs: A programming-focused introductory course can help develop essential skills in students early on and provide a *lingua franca* in which other computer science concepts can be described. This programming focus may also be useful for students from other areas of study who wish to use programming as a tool in cross-disciplinary work. However, too narrow a programming focus in an introductory class, while giving immediate facility in a programming language, can also give students a too-narrow (and misleading) view of the place of programming in the field. Such a narrow perspective may limit the appeal of computer science for some students.

Programming Paradigm and Choice of Language

A defining factor for many introductory courses is the choice of programming paradigm, which then drives the choice of programming language. Indeed, half of the six introductory course models listed in CC2001 were described by programming paradigm (Imperative-first, Objects-first, Functional-first). Such paradigm-based introductory courses still exist and their relative merits continue to be debated. We note that rather than a particular paradigm or language coming to be favored over time, the past decade has only broadened the list of programming languages now successfully used in introductory courses. There does, however, appear to be a growing trend toward "safer" or more managed languages (for example, moving from C to Java) as well as the use of more dynamic languages, such as Python or JavaScript. Visual programming languages, such as Alice and Scratch, have also become popular choices to provide a "syntax-light" introduction to programming; these are often (although not exclusively) used with non-majors or at the start of an introductory course. Some introductory course sequences choose to provide a presentation of alternative programming paradigms, such as scripting vs. procedural programming or functional vs. object-oriented programming, to give students a greater appreciation of the diverse perspectives in programming, to avoid language-feature fixation, and to disabuse them of the notion that there is a single "correct" or "best" programming language.

Tradeoffs: This is an area where there are numerous tradeoffs, including:

- The use of "safer" or more managed languages and environments can help scaffold students' learning. But, such languages may provide a level of abstraction that obscures an understanding of actual machine execution and makes is difficult to evaluate performance trade-offs. The decision as to whether to use a "lower-level" language to promote a particular mental model of program execution that is closer to the actual execution by the machine is often a matter of local audience needs.
- The use of a language or environment designed for introductory pedagogy can facilitate student learning, but may be of limited use beyond CS1. Conversely, a language or environment commonly used professionally may expose students to too much complexity too soon.

Software Development Practices

While programming is the means by which software is constructed, an introductory course may choose to present additional practices in software development to different extents. For example, the use of software development best practices, such as unit testing, version control systems, industrial integrated development environments (IDEs), and programming patterns may be stressed to different extents in different introductory courses. The inclusion of such software development practices can help students gain an early appreciation of some of the challenges in developing real software projects. On the other hand, while all computer scientists should have solid software development skills, those skills need not always be the primary focus of the first introductory programming course, especially if the intended audience is not just computer science majors. Care should be taken in introductory courses to balance the use of software development best practices from the outset with making introductory courses accessible to a broad population.

Tradeoffs: The inclusion of software development practices in introductory courses can help students develop important aspects of real-world software development early on. The extent to which such practices are included in introductory courses may impact and be impacted by the target audience for the course, and the choice of programming language and development environment.

Parallel Processing

Traditionally, introductory courses have assumed the availability of a single processor, a single process, and a single thread, with the execution of the program being completely driven by the programmer's instructions and expectation of sequential execution. Recent hardware and software developments have prompted educators to rethink these assumptions, even at the introductory level — multicore processors are now ubiquitous, user interfaces lend themselves to asynchronous event-driven processing, and "big data" requires parallel processing and distributed storage. As a result, some introductory courses stress parallel processing from the outset (with traditional single threaded execution models being considered a special case of the more general parallel paradigm). While we believe this is an interesting model to consider in the long-term, we anticipate that introductory courses will still be dominated by the "single thread of execution" model (perhaps with the inclusion of GUI-based or robotic event-driven programming) for the foreseeable future. As more successful pedagogical approaches are developed to make parallel processing accessible to novice programmers, and paradigms for parallel programming become more commonplace, we expect to see more elements of parallel programming appearing in introductory courses.

Tradeoffs*:* Understanding parallel processing is becoming increasingly important for computer science majors and learning such models early on can give students more practice in this arena. On the other hand, parallel programming remains more difficult in most contemporary programming environments.

Platform

While many introductory programming courses make use of traditional computing platforms (e.g., desktop/laptop computers) and are, as a result, somewhat "hardware agnostic," the past few years have seen a growing diversity in the set of programmable devices that are employed in such courses. For example, some introductory courses may choose to engage in web development or mobile device (e.g., smartphone, tablet) programming. Others have examined the use of specialty platforms, such as robots or game consoles, which may help generate more

enthusiasm for the subject among novices as well as emphasizing interaction with the external world as an essential and natural focus. Recent developments have led to physically-small, feature-restricted computational devices constructed specifically for the purpose of facilitating learning programming (e.g., raspberry-pi). In any of these cases, the use of a particular platform brings with it attendant choices for programming paradigms, component libraries, APIs, and security. Working within the software/hardware constraints of a given platform is a useful software-engineering skill, but also comes at the cost that the topics covered in the course may likewise be limited by the choice of platform.

Tradeoffs*:* The use of specific platforms can bring compelling real-world contexts into the classroom and platforms designed for pedagogy can have beneficial focus. However, it requires considerable care to ensure that platform-specific details do not swamp pedagogic objectives. Moreover, the specificity of the platform may impact the transferability of course content to downstream courses.

Mapping to the Body of Knowledge

Practically speaking, an introductory course sequence should not be construed as simply containing only the topics from the Software Development Fundamentals (SDF) Knowledge Area. Rather we encourage implementers of the CS2013 guidelines to think about the design space dimensions outlined above to draw on materials from multiple KAs for inclusion in an introductory course sequence. For example, even a fairly straightforward introductory course sequence will likely augment material from SDF with topics from the Programming Languages Knowledge Area related to the choice of language used in the course and potentially some concepts from Software Engineering. More broadly, a course using non-traditional platforms will draw from topics in Platform-Based Development and those emphasizing multi-processing will naturally include material from Parallel and Distributed Computing. We encourage readers to think of the CS2013 Body of Knowledge as an invitation for the construction of creative new introductory course sequences that best fit the needs of students at one's local institution.

Chapter 6: Institutional Challenges

While the Body of Knowledge provides a detailed specification of what content should be included in an undergraduate computer science curriculum, it is not to be taken as the sum total of what an undergraduate curriculum in computing should impart. In a rapidly moving field such as Computer Science, the particulars of what is taught are complementary to promoting a sense of on-going inquiry, helping students construct a framework for the assimilation of new knowledge, and advancing students' development as responsible professionals. Critical thinking, problem solving, and a foundation for life-long learning are skills that students need to develop throughout their undergraduate career. Education is not just the transmission of information, but at its best inspires passion for a subject, gives students encouragement to experiment and allows them to experience excitement in achievement. These things, too, need to be reflected in computer science curriculum and pedagogy.

Localizing CS2013

Successfully deploying an updated computer science curriculum at any individual institution requires sensitivity to local needs. CS2013 should not be read as a set of topical "check-boxes" to tick off, in a one-to-one mapping of classes to Knowledge Areas. Rather, we encourage institutions to think about ways in which the Body of Knowledge may be best integrated into a unique set of courses that reflect an institution's mission, faculty strength, student needs, and employer demands. Indeed, we created the two-tier structure of the Core precisely to provide such flexibility, keeping the Core Tier-1 material to an essential minimum to allow institutions greater leeway in selecting Core Tier-2 material to best suit their needs.

Actively Promoting Computer Science

Beyond coursework, we also stress the importance of advising, mentoring, and fostering relationships among faculty and students. Many students, perhaps especially those coming from disadvantaged backgrounds, may not appreciate the full breadth of career options that a degree in computer science can provide. Advertising and promoting the possibilities opened by studying

computer science, especially when customized to local employer needs, provides two benefits. First, it serves students by giving them information regarding career options they may not have considered. Second, it serves the department by helping to attract more students (potentially from a broader variety of backgrounds) into computer science courses. Offering a healthy computer science program over time requires maintaining a commitment to attracting students to the field regardless of current enrollment trends (which have ebbed and flowed quite widely in recent decades).

It is important to note also that many students still feel that studying computer science is equated with working as a "programmer," which in turn raises negative and incorrect stereotypes of isolated and rote work. At the same time, some students believe that if they do not already have significant prior programming experience, they will not be competitive in pursuing a degree in computer science. We strongly encourage departments to challenge both these perceptions. Extra-curricular activities aimed at showcasing potential career paths opened by a degree in computer science (for example, by inviting alumni to talk to current students) can help to show both that there are many possibilities beyond "being a programmer" as well as that software development is a significantly creative and collaborative process. In these efforts, an accessible curriculum with multiple entry points, allowing students with or without prior experience to smoothly transfer into a computer science degree program, is an important desideratum.

Broadening Participation

There is no doubt that there is a tremendous demand for students with computing skills. Indeed, vast shortfalls in information technology workers in the coming decade have been predicted [3]. As a result, there is a pressing need to broaden participation in the study of computer science and attract the full range of talent to the field, regardless of ethnicity, gender, or economic status. Institutions should make efforts to bring a wide range of students into the computer science pipeline and provide support structures to help all students successfully complete their programs.

Computer Science Across Campus

An argument can be made that computer science is becoming one of the core disciplines of a 21st century university education, that is, something that any educated individual must possess some level of proficiency and understanding. This transcends its role as a tool and methodology for research broadly across disciplines; it is likely that in the near future, at many universities, every undergraduate student will take some instruction in computer science, in recognition of computational thinking as being one of the fundamental skills desired of all graduates. There are implications for institutional resources to support such a significant scaling up of the teaching mission of computer science departments, particularly in terms of instructors and laboratories.

While CS2013 provides guidelines for undergraduate programs in computer science, we believe it is important for departments to provide computing education across a broad range of subject areas. To this end, computing departments may consider providing courses, especially at the introductory level, which are accessible and attractive to students from many disciplines. This also serves the dual purpose of attracting more students to the computing field who may not have had an initial inclination otherwise.

More broadly, as computing becomes an essential tool in other disciplines, it benefits computer science departments to be "outward facing," building bridges to other departments and curriculum areas, encouraging students to engage in multidisciplinary work, and promoting programs that span computer science and other fields of study (for example, programs in "Computational X," where X represents other disciplines such as biology or economics).

Computer Science Minors

Further to positioning computer science as one of the core disciplines of the university, departments may also consider providing minors in computer science. A minor should provide flexible options for students to gain coherent knowledge of computer science beyond that captured in one or two courses, yet encompass less than a full program. Indeed, the use of such minors can provide yet another means to allow students majoring in other disciplines to gain a solid foundation in computing for future work at the intersections of their fields.

It is well-known that students often make undergraduate major choices with highly varied levels of actual knowledge about different programs. As a result some students choose to not pursue a major in computer science simply as a result of knowing neither what computer science actually entails nor whether they might like the discipline, due to lack of prior exposure. A minor in computer science allows such students to still gain some credential in computing, if they discover late in their academic career that they have an interest in computing and what it offers. To give students the ability to major in computer science, "taster" courses should seek to reach students as soon as possible in their undergraduate studies.

Mathematics Requirements in Computer Science

There is a deep and beautiful connection between mathematics and many areas of computer science. While nearly all undergraduate programs in computer science include mathematics courses in their curricula, the full set of such requirements varies broadly by institution due to a number of factors. For example, whether or not a CS program is housed in a School of Engineering can directly influence the requirements for courses on calculus and/or differential equations, even if such courses include far more material in these areas than is generally needed for most CS majors. Similarly, restrictions on the number of courses that may be included in a major at some institutions—for example, at many liberal arts colleges—may lead to mathematics requirements that are specially circumscribed for CS majors. As a result, CS2013 only specifies mathematical requirements that we believe are directly relevant for the large majority of all CS undergraduates (for example, elements of set theory, logic, and discrete probability, among others). These mathematics requirements are specified in the Body of Knowledge primarily in the Discrete Structures (DS) Knowledge Area.

We recognize that general facility with mathematics is an important requirement for all CS students. Still, CS2013 distinguishes between the foundational mathematics that are likely to impact many parts of computer science—and are included in the CS2013 Body of Knowledge—from those that, while still important, may be most directly relevant to specific areas within computing. For example, an understanding of linear algebra plays a critical role in some areas of computing such as graphics and the analysis of graph algorithms. However, linear algebra would not necessarily be a requirement for all areas of computing (indeed, many high quality CS

programs do not have an explicit linear algebra requirement). Similarly, while we do note a growing trend in the use of probability and statistics in computing (reflected by the increased number of core hours on these topics in the Body of Knowledge) and believe that this trend is likely to continue in the future, we still believe it is not necessary for all CS programs to require a full course in probability theory for all majors.

More generally, we believe that a CS program must provide students with a level of "mathematical maturity." For example, an understanding of arithmetic manipulations, including simple summations and series is needed for analyzing algorithmic efficiency, but giving the detailed specifications of the basic arithmetic necessary for college-level coursework in computing is beyond the scope of CS2013. To wit, some programs use calculus requirements not as a means for domain knowledge, but more as a method for helping develop such mathematical maturity and clarity of mathematical thinking early in a college-level education. Thus, while we do not specify such requirements, we note that undergraduate CS students need enough mathematical maturity to have the basis on which to then build CS-specific mathematics (for example, as specified in the Discrete Structures Knowledge Area), which, importantly, does not explicitly require any significant college-level coursework in calculus, differential equations, or linear algebra.

Students moving on to advanced coursework in specific areas of computing will likely need focused mathematical coursework relevant to those areas. We believe that CS programs should help facilitate options in mathematics beyond Discrete Structures, which allow CS students to get the background needed for the specific areas in CS they choose to pursue. Such coursework requirements are best left to the discretion of the individual programs and the areas of CS they choose to emphasize.

Finally, we note that any mathematics requirements in a CS program must be mindful of the length of pre-requisite course chains specified to complete such requirements. Indeed, the pre-requisite structure of mathematics courses may not be in the purview of CS departments themselves, but must still be considered when designing programs that allow students without significant prior mathematics background to pursue a major in CS. Lengthy series of mathematics classes needed as pre-requisites for coursework in CS will make it more difficult for students to find CS accessible, to switch into a CS major at a later point in their college careers,

and/or to take CS-specific coursework early in their studies, which may discourage students from the field.

Computing Resources

Programs in computer science have a need for adequate computing resources, both for students and faculty. The needs of computer science programs often extend beyond traditional infrastructure (general campus computing labs) and may include specialized hardware and software, and/or large-scale computing infrastructure. Having adequate access to such resources is especially important for project and capstone courses. Moreover, institutions need to consider the growing heterogeneity of computing devices (e.g., smartphones, tablets) that can be used as a platform for coursework.

Maintaining a Flexible and Healthy Faculty

A strong program in computer science is founded on a sufficient number of (and sufficiently experienced) faculty to keep the department healthy and vibrant. Departmental hiring should provide not only sufficient capacity to keep a program viable, but also allow for existing faculty to have time for professional development and exploration of new ideas. To respond to rapid changes in the field, computer science faculty must have the opportunities to build new skills, learn about new areas, and stay abreast of new technologies. While there can be tension between teaching new technologies versus fundamental principles, focusing too far on either extreme will be a disservice to students. Faculty need to be given the time to acquire new ideas and technologies and bring them into courses and curricula. In this way, departments can model the value of professional and lifelong learning, as faculty incorporate new materials and approaches.

In addition to professional development, it is especially important for computer science programs to maintain a healthy capacity to respond to enrollment fluctuations. Indeed, computer science as a discipline has gone through several boom-and-bust cycles in the past decades that have resulted in significant enrollment changes in programs all over the world and across virtually all types of institutions. A department should take care to create structures to help it maintain resilience in the face of enrollment downturns, for example by making courses more broadly

accessible, building interdisciplinary programs with other departments, and offering service courses.

In the face of large sustained enrollment increases (as has been witnessed in recent years), the need for sufficient faculty hiring can become acute. Without sufficient capacity, faculty can be strained by larger course enrollments (each course requiring more sections and more student assessment) and more teaching obligations (more courses must be taught by each faculty member), which can result in lower quality instruction and potential faculty burn-out. The former issue causes students to abandon computer science. These outcomes are highly detrimental given the need to produce more, and more skilled, computing graduates as discussed above. Excellent arguments for the need to maintain strong faculty capacity in the face of growing enrollment have been extended, both in relation to the most recent boom [5] and extending back more than three decades [2].

Teaching Faculty

Permanent faculty, whose primary criteria for evaluation is based on teaching and educational contributions (broadly defined), can be instrumental in helping to build accessible courses, engage in curricular experimentation and revision, and provide outreach efforts to bring more students into the discipline. As with all institutional challenges, such appointments represent a balance of political and pragmatic issues. The value of this type of position was originally observed in CC2001 and that value has not diminished in the intervening decades, more recently receiving additional endorsement [7].

Undergraduate Teaching Assistants

While research universities have traditionally drawn on postgraduate students to serve as teaching assistants in the undergraduate curriculum, over the past 20 years growing numbers of departments have found it valuable to engage advanced undergraduates as teaching assistants in introductory computing courses. The reported benefits to the undergraduate teaching assistants include learning the material themselves when they are put in the role of helping teach it to someone else, better time management, improved ability dealing with organizational responsibilities, and presentation skills [4, 6]. Students in the introductory courses also benefit by having a larger course staff available, more accessible staff, and getting assistance from a "near-peer," someone with a recent familiarity in the kind of questions and struggles the student is likely facing.

Online Education

It has been suggested that there is a tsunami coming to higher education, brought on by online learning, and lately, Massive Open Online Courses (MOOCs) [1]. Discussing the full scope of the potential and pitfalls of online education is well beyond the scope of this document. Rather, we simply point out some aspects of online learning that may impact the ways in which departments deploy these guidelines.

First, online educational materials need not be structured as just full term-long classes. As a result, it may be possible to teach online mini-courses or modules (less than a term long, somtimes significantly so), that nevertheless contain coherent portions of the CS2013 Body of Knowledge. In this way, some departments, especially those with limited faculty resources, may choose to seek out and leverage online materials offered elsewhere. Blended learning is another model that has and can be pursued to accrue the benefits of both face-to-face and online learning in the same course.

Part of the excitement that has been generated by MOOCs is that they allow for ready scaling to large numbers of students. There are technological challenges in assessing programming assignments at scale, and there are those who believe that this represents a significant new research opportunity for computer science. The quantitative ability that MOOC platforms

provide for assessing the effectiveness of how students learn has the potential to transform the teaching of computer science itself.

While we appreciate the value of scaling course availability, we also note that there are important aspects of education that are not concerned with course content or the transmission of information, e.g., pedagogy, scaffolding learning. Then again, while MOOCs are a powerful medium for content delivery, we note that it is important to make sure that characteristics of CS graduates are still developed.

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Appendix A: The Body of Knowledge

Algorithms and Complexity (AL)

Algorithms are fundamental to computer science and software engineering. The real-world performance of any software system depends on: (1) the algorithms chosen and (2) the suitability and efficiency of the various layers of implementation. Good algorithm design is therefore crucial for the performance of all software systems. Moreover, the study of algorithms provides insight into the intrinsic nature of the problem as well as possible solution techniques independent of programming language, programming paradigm, computer hardware, or any other implementation aspect.

An important part of computing is the ability to select algorithms appropriate to particular purposes and to apply them, recognizing the possibility that no suitable algorithm may exist. This facility relies on understanding the range of algorithms that address an important set of well-defined problems, recognizing their strengths and weaknesses, and their suitability in particular contexts. Efficiency is a pervasive theme throughout this area.

This knowledge area defines the central concepts and skills required to design, implement, and analyze algorithms for solving problems. Algorithms are essential in all advanced areas of computer science: artificial intelligence, databases, distributed computing, graphics, networking, operating systems, programming languages, security, and so on. Algorithms that have specific utility in each of these are listed in the relevant knowledge areas. Cryptography, for example, appears in the new Knowledge Area on Information Assurance and Security (IAS), while parallel and distributed algorithms appear the Knowledge Area in Parallel and Distributed Computing (PD).

As with all knowledge areas, the order of topics and their groupings do not necessarily correlate to a specific order of presentation. Different programs will teach the topics in different courses and should do so in the order they believe is most appropriate for their students.

AL. Algorithms and Complexity (19 Core-Tier1 hours, 9 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
AL/Basic Analysis	**2**	**2**	**N**
AL/Algorithmic Strategies	**5**	**1**	**N**
AL/Fundamental Data Structures and Algorithms	**9**	**3**	**N**
AL/Basic Automata, Computability and Complexity	**3**	**3**	**N**
AL/Advanced Computational Complexity			**Y**
AL/Advanced Automata Theory and Computability			**Y**
AL/Advanced Data Structures, Algorithms, and Analysis			**Y**

AL/Basic Analysis

[2 Core-Tier1 hours, 2 Core-Tier2 hours]

Topics:

[Core-Tier1]

- Differences among best, expected, and worst case behaviors of an algorithm
- Asymptotic analysis of upper and expected complexity bounds
- Big O notation: formal definition
- Complexity classes, such as constant, logarithmic, linear, quadratic, and exponential
- Empirical measurements of performance
- Time and space trade-offs in algorithms

[Core-Tier2]

- Big O notation: use
- Little o, big omega and big theta notation
- Recurrence relations
- Analysis of iterative and recursive algorithms
- Some version of a Master Theorem

Learning Outcomes:

[Core-Tier1]

1. Explain what is meant by “best”, “expected”, and “worst” case behavior of an algorithm. [Familiarity]
2. In the context of specific algorithms, identify the characteristics of data and/or other conditions or assumptions that lead to different behaviors. [Assessment]
3. Determine informally the time and space complexity of simple algorithms. [Usage]

4. State the formal definition of big O. [Familiarity]
5. List and contrast standard complexity classes. [Familiarity]
6. Perform empirical studies to validate hypotheses about runtime stemming from mathematical analysis. Run algorithms on input of various sizes and compare performance. [Assessment]
7. Give examples that illustrate time-space trade-offs of algorithms. [Familiarity]

[Core-Tier2]

8. Use big O notation formally to give asymptotic upper bounds on time and space complexity of algorithms. [Usage]
9. Use big O notation formally to give expected case bounds on time complexity of algorithms. [Usage]
10. Explain the use of big omega, big theta, and little o notation to describe the amount of work done by an algorithm. [Familiarity]
11. Use recurrence relations to determine the time complexity of recursively defined algorithms. [Usage]
12. Solve elementary recurrence relations, e.g., using some form of a Master Theorem. [Usage]

AL/Algorithmic Strategies

[5 Core-Tier1 hours, 1 Core-Tier2 hours]

An instructor might choose to cover these algorithmic strategies in the context of the algorithms presented in "Fundamental Data Structures and Algorithms" below. While the total number of hours for the two knowledge units (18) could be divided differently between them, our sense is that the 1:2 ratio is reasonable.

Topics:

[Core-Tier1]

- Brute-force algorithms
- Greedy algorithms
- Divide-and-conquer (cross-reference SDF/Algorithms and Design/Problem-solving strategies)
- Recursive backtracking
- Dynamic Programming

[Core-Tier2]

- Branch-and-bound
- Heuristics
- Reduction: transform-and-conquer

Learning Outcomes:

[Core-Tier1]

1. For each of the strategies (brute-force, greedy, divide-and-conquer, recursive backtracking, and dynamic programming), identify a practical example to which it would apply. [Familiarity]
2. Use a greedy approach to solve an appropriate problem and determine if the greedy rule chosen leads to an optimal solution. [Assessment]
3. Use a divide-and-conquer algorithm to solve an appropriate problem. [Usage]
4. Use recursive backtracking to solve a problem such as navigating a maze. [Usage]
5. Use dynamic programming to solve an appropriate problem. [Usage]
6. Determine an appropriate algorithmic approach to a problem. [Assessment]

[Core-Tier2]

7. Describe various heuristic problem-solving methods. [Familiarity]
8. Use a heuristic approach to solve an appropriate problem. [Usage]
9. Describe the trade-offs between brute force and heuristic strategies. [Assessment]
10. Describe how a branch-and-bound approach may be used to improve the performance of a heuristic method. [Familiarity]

AL/Fundamental Data Structures and Algorithms

[9 Core-Tier1 hours, 3 Core-Tier2 hours]

This knowledge unit builds directly on the foundation provided by Software Development Fundamentals (SDF), particularly the material in SDF/Fundamental Data Structures and SDF/Algorithms and Design.

Topics:

[Core-Tier1]

- Simple numerical algorithms, such as computing the average of a list of numbers, finding the min, max, and mode in a list, approximating the square root of a number, or finding the greatest common divisor
- Sequential and binary search algorithms
- Worst case quadratic sorting algorithms (selection, insertion)
- Worst or average case O(N log N) sorting algorithms (quicksort, heapsort, mergesort)
- Hash tables, including strategies for avoiding and resolving collisions
- Binary search trees
    - Common operations on binary search trees such as select min, max, insert, delete, iterate over tree
- Graphs and graph algorithms
    - Representations of graphs (e.g., adjacency list, adjacency matrix)
    - Depth- and breadth-first traversals

[Core-Tier2]

- Heaps
- Graphs and graph algorithms
    - Shortest-path algorithms (Dijkstra's and Floyd's algorithms)
    - Minimum spanning tree (Prim's and Kruskal's algorithms)
- Pattern matching and string/text algorithms (e.g., substring matching, regular expression matching, longest common subsequence algorithms)

Learning Outcomes:

[Core-Tier1]

1. Implement basic numerical algorithms. [Usage]
2. Implement simple search algorithms and explain the differences in their time complexities. [Assessment]
3. Be able to implement common quadratic and O(N log N) sorting algorithms. [Usage]
4. Describe the implementation of hash tables, including collision avoidance and resolution. [Familiarity]
5. Discuss the runtime and memory efficiency of principal algorithms for sorting, searching, and hashing. [Familiarity]
6. Discuss factors other than computational efficiency that influence the choice of algorithms, such as programming time, maintainability, and the use of application-specific patterns in the input data. [Familiarity]
7. Explain how tree balance affects the efficiency of various binary search tree operations. [Familiarity]
8. Solve problems using fundamental graph algorithms, including depth-first and breadth-first search. [Usage]

9. Demonstrate the ability to evaluate algorithms, to select from a range of possible options, to provide justification for that selection, and to implement the algorithm in a particular context. [Assessment]

[Core-Tier2]

10. Describe the heap property and the use of heaps as an implementation of priority queues. [Familiarity]
11. Solve problems using graph algorithms, including single-source and all-pairs shortest paths, and at least one minimum spanning tree algorithm. [Usage]
12. Trace and/or implement a string-matching algorithm. [Usage]

AL/Basic Automata Computability and Complexity

[3 Core-Tier1 hours, 3 Core-Tier2 hours]

Topics:

[Core-Tier1]

- Finite-state machines
- Regular expressions
- The halting problem

[Core-Tier2]

- Context-free grammars (cross-reference PL/Syntax Analysis)
- Introduction to the P and NP classes and the P vs. NP problem
- Introduction to the NP-complete class and exemplary NP-complete problems (e.g., SAT, Knapsack)

Learning Outcomes:

[Core-Tier1]

1. Discuss the concept of finite state machines. [Familiarity]
2. Design a deterministic finite state machine to accept a specified language. [Usage]
3. Generate a regular expression to represent a specified language. [Usage]
4. Explain why the halting problem has no algorithmic solution. [Familiarity]

[Core-Tier2]

5. Design a context-free grammar to represent a specified language. [Usage]
6. Define the classes P and NP. [Familiarity]
7. Explain the significance of NP-completeness. [Familiarity]

AL/Advanced Computational Complexity

[Elective]

Topics:

- Review of the classes P and NP; introduce P-space and EXP
- Polynomial hierarchy
- NP-completeness (Cook's theorem)
- Classic NP-complete problems
- Reduction Techniques

Learning Outcomes:

1. Define the classes P and NP. (Also appears in AL/Basic Automata, Computability, and Complexity). [Familiarity]
2. Define the P-space class and its relation to the EXP class. [Familiarity]
3. Explain the significance of NP-completeness. (Also appears in AL/Basic Automata, Computability, and Complexity). [Familiarity]
4. Provide examples of classic NP-complete problems. [Familiarity]
5. Prove that a problem is NP-complete by reducing a classic known NP-complete problem to it. [Usage]

AL/Advanced Automata Theory and Computability

[Elective]

Topics:

- Sets and languages
    - Regular languages
    - Review of deterministic finite automata (DFAs)
    - Nondeterministic finite automata (NFAs)
    - Equivalence of DFAs and NFAs
    - Review of regular expressions; their equivalence to finite automata
    - Closure properties
    - Proving languages non-regular, via the pumping lemma or alternative means
- Context-free languages
    - Push-down automata (PDAs)
    - Relationship of PDAs and context-free grammars
    - Properties of context-free languages
- Turing machines, or an equivalent formal model of universal computation
- Nondeterministic Turing machines
- Chomsky hierarchy
- The Church-Turing thesis
- Computability
- Rice's Theorem
- Examples of uncomputable functions
- Implications of uncomputability

Learning Outcomes:

1. Determine a language's place in the Chomsky hierarchy (regular, context-free, recursively enumerable). [Assessment]
2. Convert among equivalently powerful notations for a language, including among DFAs, NFAs, and regular expressions, and between PDAs and CFGs. [Usage]
3. Explain the Church-Turing thesis and its significance. [Familiarity]
4. Explain Rice's Theorem and its significance. [Familiarity]
5. Provide examples of uncomputable functions. [Familiarity]
6. Prove that a problem is uncomputable by reducing a classic known uncomputable problem to it. [Usage]

AL/Advanced Data Structures Algorithms and Analysis

[Elective]

Many programs will want their students to have exposure to more advanced algorithms or methods of analysis. Below is a selection of possible advanced topics that are current and timely but by no means exhaustive.

Topics:

- Balanced trees (e.g., AVL trees, red-black trees, splay trees, treaps)
- Graphs (e.g., topological sort, finding strongly connected components, matching)
- Advanced data structures (e.g., B-trees, Fibonacci heaps)
- String-based data structures and algorithms (e.g., suffix arrays, suffix trees, tries)
- Network flows (e.g., max flow [Ford-Fulkerson algorithm], max flow – min cut, maximum bipartite matching)
- Linear Programming (e.g., duality, simplex method, interior point algorithms)
- Number-theoretic algorithms (e.g., modular arithmetic, primality testing, integer factorization)
- Geometric algorithms (e.g., points, line segments, polygons. [properties, intersections], finding convex hull, spatial decomposition, collision detection, geometric search/proximity)
- Randomized algorithms
- Stochastic algorithms
- Approximation algorithms
- Amortized analysis
- Probabilistic analysis
- Online algorithms and competitive analysis

Learning Outcomes:

1. Understand the mapping of real-world problems to algorithmic solutions (e.g., as graph problems, linear programs, etc.). [Assessment]
2. Select and apply advanced algorithmic techniques (e.g., randomization, approximation) to solve real problems. [Assessment]
3. Select and apply advanced analysis techniques (e.g., amortized, probabilistic, etc.) to algorithms. [Assessment]

Architecture and Organization (AR)

Computing professionals should not regard the computer as just a black box that executes programs by magic. The knowledge area Architecture and Organization builds on Systems Fundamentals (SF) to develop a deeper understanding of the hardware environment upon which all computing is based, and the interface it provides to higher software layers. Students should acquire an understanding and appreciation of a computer system's functional components, their characteristics, performance, and interactions, and, in particular, the challenge of harnessing parallelism to sustain performance improvements now and into the future. Students need to understand computer architecture to develop programs that can achieve high performance through a programmer's awareness of parallelism and latency. In selecting a system to use, students should be able to understand the tradeoff among various components, such as CPU clock speed, cycles per instruction, memory size, and average memory access time.

The learning outcomes specified for these topics correspond primarily to the core and are intended to support programs that elect to require only the minimum 16 hours of computer architecture of their students. For programs that want to teach more than the minimum, the same AR topics can be treated at a more advanced level by implementing a two-course sequence. For programs that want to cover the elective topics, those topics can be introduced within a two-course sequence and/or be treated in a more comprehensive way in a third course.

AR. Architecture and Organization (0 Core-Tier1 hours, 16 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 Hours	Includes Elective
AR/Digital Logic and Digital Systems		**3**	**N**
AR/Machine Level Representation of Data		**3**	**N**
AR/Assembly Level Machine Organization		**6**	**N**
AR/Memory System Organization and Architecture		**3**	**N**
AR/Interfacing and Communication		**1**	**N**
AR/Functional Organization			**Y**
AR/Multiprocessing and Alternative Architectures			**Y**
AR/Performance Enhancements			**Y**

AR/Digital Logic and Digital Systems

[3 Core-Tier2 hours]

***Topics**:*

- Overview and history of computer architecture
- Combinational vs. sequential logic/Field programmable gate arrays as a fundamental combinational + sequential logic building block
- Multiple representations/layers of interpretation (hardware is just another layer)
- Computer-aided design tools that process hardware and architectural representations
- Register transfer notation/Hardware Description Language (Verilog/VHDL)
- Physical constraints (gate delays, fan-in, fan-out, energy/power)

***Learning outcomes**:*

1. Describe the progression of computer technology components from vacuum tubes to VLSI, from mainframe computer architectures to the organization of warehouse-scale computers. [Familiarity]
2. Comprehend the trend of modern computer architectures towards multi-core and that parallelism is inherent in all hardware systems. [Familiarity]
3. Explain the implications of the "power wall" in terms of further processor performance improvements and the drive towards harnessing parallelism. [Familiarity]
4. Articulate that there are many equivalent representations of computer functionality, including logical expressions and gates, and be able to use mathematical expressions to describe the functions of simple combinational and sequential circuits. [Familiarity]
5. Design the basic building blocks of a computer: arithmetic-logic unit (gate-level), registers (gate-level), central processing unit (register transfer-level), memory (register transfer-level). [Usage]
6. Use CAD tools for capture, synthesis, and simulation to evaluate simple building blocks (e.g., arithmetic-logic unit, registers, movement between registers) of a simple computer design. [Usage]

7. Evaluate the functional and timing diagram behavior of a simple processor implemented at the logic circuit level. [Assessment]

AR/Machine Level Representation of Data

[3 Core-Tier2 hours]

Topics:

- Bits, bytes, and words
- Numeric data representation and number bases
- Fixed- and floating-point systems
- Signed and twos-complement representations
- Representation of non-numeric data (character codes, graphical data)
- Representation of records and arrays

Learning outcomes:

1. Explain why everything is data, including instructions, in computers. [Familiarity]
2. Explain the reasons for using alternative formats to represent numerical data. [Familiarity]
3. Describe how negative integers are stored in sign-magnitude and twos-complement representations. [Familiarity]
4. Explain how fixed-length number representations affect accuracy and precision. [Familiarity]
5. Describe the internal representation of non-numeric data, such as characters, strings, records, and arrays. [Familiarity]
6. Convert numerical data from one format to another. [Usage]
7. Write simple programs at the assembly/machine level for string processing and manipulation. [Usage]

AR/Assembly Level Machine Organization

[6 Core-Tier2 hours]

Topics:

- Basic organization of the von Neumann machine
- Control unit; instruction fetch, decode, and execution
- Instruction sets and types (data manipulation, control, I/O)
- Assembly/machine language programming
- Instruction formats
- Addressing modes
- Subroutine call and return mechanisms (cross-reference PL/Language Translation and Execution)
- I/O and interrupts
- Heap vs. Static vs. Stack vs. Code segments
- Shared memory multiprocessors/multicore organization
- Introduction to SIMD vs. MIMD and the Flynn Taxonomy

***Learning outcomes*:**

1. Explain the organization of the classical von Neumann machine and its major functional units. [Familiarity]
2. Describe how an instruction is executed in a classical von Neumann machine, with extensions for threads, multiprocessor synchronization, and SIMD execution. [Familiarity]

3. Describe instruction level parallelism and hazards, and how they are managed in typical processor pipelines. [Familiarity]
4. Summarize how instructions are represented at both the machine level and in the context of a symbolic assembler. [Familiarity]
5. Demonstrate how to map between high-level language patterns into assembly/machine language notations. [Familiarity]
6. Explain different instruction formats, such as addresses per instruction and variable length vs. fixed length formats. [Familiarity]
7. Explain how subroutine calls are handled at the assembly level. [Familiarity]
8. Explain the basic concepts of interrupts and I/O operations. [Familiarity]
9. Write simple assembly language program segments. [Usage]
10. Show how fundamental high-level programming constructs are implemented at the machine-language level. [Usage]

AR/Memory System Organization and Architecture

[3 Core-Tier2 hours]

Cross-reference OS/Memory Management/Virtual Machines

Topics:

- Storage systems and their technology
- Memory hierarchy: importance of temporal and spatial locality
- Main memory organization and operations
- Latency, cycle time, bandwidth, and interleaving
- Cache memories (address mapping, block size, replacement and store policy)
- Multiprocessor cache consistency/Using the memory system for inter-core synchronization/atomic memory operations
- Virtual memory (page table, TLB)
- Fault handling and reliability
- Error coding, data compression, and data integrity (cross-reference SF/Reliability through Redundancy)

Learning outcomes:

1. Identify the main types of memory technology (e.g., SRAM, DRAM, Flash, magnetic disk) and their relative cost and performance. [Familiarity]
2. Explain the effect of memory latency on running time. [Familiarity]
3. Describe how the use of memory hierarchy (cache, virtual memory) is used to reduce the effective memory latency. [Familiarity]
4. Describe the principles of memory management. [Familiarity]
5. Explain the workings of a system with virtual memory management. [Familiarity]
6. Compute Average Memory Access Time under a variety of cache and memory configurations and mixes of instruction and data references. [Usage]

AR/Interfacing and Communication

[1 Core-Tier2 hour]

Cross-reference Operating Systems (OS) Knowledge Area for a discussion of the operating system view of input/output processing and management. The focus here is on the hardware mechanisms for supporting device interfacing and processor-to-processor communications.

Topics:

- I/O fundamentals: handshaking, buffering, programmed I/O, interrupt-driven I/O
- Interrupt structures: vectored and prioritized, interrupt acknowledgment
- External storage, physical organization, and drives
- Buses: bus protocols, arbitration, direct-memory access (DMA)
- Introduction to networks: communications networks as another layer of remote access
- Multimedia support
- RAID architectures

***Learning outcomes*:**

1. Explain how interrupts are used to implement I/O control and data transfers. [Familiarity]
2. Identify various types of buses in a computer system. [Familiarity]
3. Describe data access from a magnetic disk drive. [Familiarity]
4. Compare common network organizations, such as ethernet/bus, ring, switched vs. routed. [Familiarity]
5. Identify the cross-layer interfaces needed for multimedia access and presentation, from image fetch from remote storage, through transport over a communications network, to staging into local memory, and final presentation to a graphical display. [Familiarity]
6. Describe the advantages and limitations of RAID architectures. [Familiarity]

AR/Functional Organization

[Elective]

Note: elective for computer scientist; would be core for computer engineering curriculum.

Topics:

- Implementation of simple datapaths, including instruction pipelining, hazard detection and resolution
- Control unit: hardwired realization vs. microprogrammed realization
- Instruction pipelining
- Introduction to instruction-level parallelism (ILP)

Learning outcomes:

1. Compare alternative implementation of datapaths. [Familiarity]
2. Discuss the concept of control points and the generation of control signals using hardwired or microprogrammed implementations. [Familiarity]
3. Explain basic instruction level parallelism using pipelining and the major hazards that may occur. [Familiarity]
4. Design and implement a complete processor, including datapath and control. [Usage]
5. Determine, for a given processor and memory system implementation, the average cycles per instruction. [Assessment]

AR/Multiprocessing and Alternative Architectures

[Elective]

The view here is on the hardware implementation of SIMD and MIMD architectures.

Cross-reference PD/Parallel Architecture.

Topics:

- Power Law
- Example SIMD and MIMD instruction sets and architectures
- Interconnection networks (hypercube, shuffle-exchange, mesh, crossbar)
- Shared multiprocessor memory systems and memory consistency
- Multiprocessor cache coherence

***Learning outcomes*:**

1. Discuss the concept of parallel processing beyond the classical von Neumann model. [Familiarity]
2. Describe alternative parallel architectures such as SIMD and MIMD. [Familiarity]
3. Explain the concept of interconnection networks and characterize different approaches. [Familiarity]
4. Discuss the special concerns that multiprocessing systems present with respect to memory management and describe how these are addressed. [Familiarity]
5. Describe the differences between memory backplane, processor memory interconnect, and remote memory via networks, their implications for access latency and impact on program performance. [Familiarity]

AR/Performance Enhancements

[Elective]

Topics:

- Superscalar architecture
- Branch prediction, Speculative execution, Out-of-order execution
- Prefetching
- Vector processors and GPUs
- Hardware support for multithreading
- Scalability
- Alternative architectures, such as VLIW/EPIC, and Accelerators and other kinds of Special-Purpose Processors

Learning outcomes:

1. Describe superscalar architectures and their advantages. [Familiarity]
2. Explain the concept of branch prediction and its utility. [Familiarity]
3. Characterize the costs and benefits of prefetching. [Familiarity]
4. Explain speculative execution and identify the conditions that justify it. [Familiarity]
5. Discuss the performance advantages that multithreading offered in an architecture along with the factors that make it difficult to derive maximum benefits from this approach. [Familiarity]
6. Describe the relevance of scalability to performance. [Familiarity]

Computational Science (CN)

Computational Science is a field of applied computer science, that is, the application of computer science to solve problems across a range of disciplines. In the book *Introduction to Computational Science* [3], the authors offer the following definition: "the field of computational science combines computer simulation, scientific visualization, mathematical modeling, computer programming and data structures, networking, database design, symbolic computation, and high performance computing with various disciplines." Computer science, which largely focuses on the theory, design, and implementation of algorithms for manipulating data and information, can trace its roots to the earliest devices used to assist people in computation over four thousand years ago. Various systems were created and used to calculate astronomical positions. Ada Lovelace's programming achievement was intended to calculate Bernoulli numbers. In the late nineteenth century, mechanical calculators became available, and were immediately put to use by scientists. The needs of scientists and engineers for computation have long driven research and innovation in computing. As computers increase in their problem-solving power, computational science has grown in both breadth and importance. It is a discipline in its own right [2] and is considered to be "one of the five college majors on the rise [1]." An amazing assortment of sub-fields have arisen under the umbrella of Computational Science, including computational biology, computational chemistry, computational mechanics, computational archeology, computational finance, computational sociology and computational forensics.

Some fundamental concepts of computational science are germane to every computer scientist (e.g., modeling and simulation), and computational science topics are extremely valuable components of an undergraduate program in computer science. This area offers exposure to many valuable ideas and techniques, including precision of numerical representation, error analysis, numerical techniques, parallel architectures and algorithms, modeling and simulation, information visualization, software engineering, and optimization. Topics relevant to computational science include fundamental concepts in program construction (SDF/Fundamental Programming Concepts), algorithm design (SDF/Algorithms and Design), program testing (SDF/Development Methods), data representations (AR/Machine Representation of Data), and basic computer architecture (AR/Memory System Organization and Architecture). At the same

time, students who take courses in this area have an opportunity to apply these techniques in a wide range of application areas, such as molecular and fluid dynamics, celestial mechanics, economics, biology, geology, medicine, and social network analysis. Many of the techniques used in these areas require advanced mathematics such as calculus, differential equations, and linear algebra. The descriptions here assume that students have acquired the needed mathematical background elsewhere.

In the computational science community, the terms *run*, *modify*, and *create* are often used to describe levels of understanding. This chapter follows the conventions of other chapters in this volume and uses the terms *familiarity*, *usage*, and *assessment*.

References

[1] Fischer, K. and Glenn, D., "5 College Majors on the Rise," *The Chronicle of Higher Education*, August 31, 2009.

[2] President's Information Technology Advisory Committee, 2005: p. 13. http://www.nitrd.gov/pitac/reports/20050609_computational/computational.pdf

[3] Shiflet, A. B. and Shiflet, G. W. *Introduction to Computational Science: Modeling and Simulation for the Sciences*, Princeton University Press, 2006: p. 3.

CN. Computational Science (1 Core-Tier1 hours, 0 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
CN/Introduction to Modeling and Simulation	**1**		**N**
CN/Modeling and Simulation			**Y**
CN/Processing			**Y**
CN/Interactive Visualization			**Y**
CN/Data, Information, and Knowledge			**Y**
CN/Numerical Analysis			**Y**

CN/Introduction to Modeling and Simulation

[1 Core-Tier1 hours]

Abstraction is a fundamental concept in computer science. A principal approach to computing is to abstract the real world, create a model that can be simulated on a machine. The roots of computer science can be traced to this approach, modeling things such as trajectories of artillery shells and the modeling cryptographic protocols, both of which pushed the development of early computing systems in the early and mid-1940's.

Modeling and simulation of real world systems represent essential knowledge for computer scientists and provide a foundation for computational sciences. Any introduction to modeling and simulation would either include or presume an introduction to computing. In addition, a general set of modeling and simulation techniques, data visualization methods, and software testing and evaluation mechanisms are also important.

Topics:

- Models as abstractions of situations
- Simulations as dynamic modeling
- Simulation techniques and tools, such as physical simulations, human-in-the-loop guided simulations, and virtual reality
- Foundational approaches to validating models (e.g., comparing a simulation's output to real data or the output of another model)
- Presentation of results in a form relevant to the system being modeled

Learning Outcomes:

1. Explain the concept of modeling and the use of abstraction that allows the use of a machine to solve a problem. [Familiarity]
2. Describe the relationship between modeling and simulation, i.e., thinking of simulation as dynamic modeling. [Familiarity]
3. Create a simple, formal mathematical model of a real-world situation and use that model in a simulation. [Usage]
4. Differentiate among the different types of simulations, including physical simulations, human-guided simulations, and virtual reality. [Familiarity]
5. Describe several approaches to validating models. [Familiarity]
6. Create a simple display of the results of a simulation. [Usage]

CN/Modeling and Simulation

[Elective]

Topics:

- Purpose of modeling and simulation including optimization; supporting decision making, forecasting, safety considerations; for training and education
- Tradeoffs including performance, accuracy, validity, and complexity
- The simulation process; identification of key characteristics or behaviors, simplifying assumptions; validation of outcomes
- Model building: use of mathematical formulas or equations, graphs, constraints; methodologies and techniques; use of time stepping for dynamic systems

- Formal models and modeling techniques: mathematical descriptions involving simplifying assumptions and avoiding detail. Examples of techniques include:
    - Monte Carlo methods
    - Stochastic processes
    - Queuing theory
    - Petri nets and colored Petri nets
    - Graph structures such as directed graphs, trees, networks
    - Games, game theory, the modeling of things using game theory
    - Linear programming and its extensions
    - Dynamic programming
    - Differential equations: ODE, PDE
    - Non-linear techniques
    - State spaces and transitions
- Assessing and evaluating models and simulations in a variety of contexts; verification and validation of models and simulations
- Important application areas including health care and diagnostics, economics and finance, city and urban planning, science, and engineering
- Software in support of simulation and modeling; packages, languages

Learning Outcomes:

1. Explain and give examples of the benefits of simulation and modeling in a range of important application areas. [Familiarity]
2. Demonstrate the ability to apply the techniques of modeling and simulation to a range of problem areas. [Usage]
3. Explain the constructs and concepts of a particular modeling approach. [Familiarity]
4. Explain the difference between validation and verification of a model; demonstrate the difference with specific examples[1]. [Assessment]
5. Verify and validate the results of a simulation. [Assessment]
6. Evaluate a simulation, highlighting the benefits and the drawbacks. [Assessment]
7. Choose an appropriate modeling approach for a given problem or situation. [Assessment]
8. Compare results from different simulations of the same situation and explain any differences. [Assessment]
9. Infer the behavior of a system from the results of a simulation of the system. [Assessment]
10. Extend or adapt an existing model to a new situation. [Assessment]

[1] *Verification* means that the computations of the model are correct. If we claim to compute total time, for example, the computation actually does that. *Validation* asks whether the model matches the real situation.

CN/Processing

[Elective]

The processing topic area includes numerous topics from other knowledge areas. Specifically, coverage of processing should include a discussion of hardware architectures, including parallel systems, memory hierarchies, and interconnections among processors. These are covered in AR/Interfacing and Communication, AR/Multiprocessing and Alternative Architectures, AR/Performance Enhancements.

Topics:

- Fundamental programming concepts:
    - The concept of an algorithm consisting of a finite number of well-defined steps, each of which completes in a finite amount of time, as does the entire process.
    - Examples of well-known algorithms such as sorting and searching.
    - The concept of analysis as understanding what the problem is really asking, how a problem can be approached using an algorithm, and how information is represented so that a machine can process it.
    - The development or identification of a workflow.
    - The process of converting an algorithm to machine-executable code.
    - Software processes including lifecycle models, requirements, design, implementation, verification and maintenance.
    - Machine representation of data computer arithmetic.
- Numerical methods
    - Algorithms for numerically fitting data (e.g., Newton's method)
    - Architectures for numerical computation, including parallel architectures
- Fundamental properties of parallel and distributed computation:
    - Bandwidth.
    - Latency.
    - Scalability.
    - Granularity.
    - Parallelism including task, data, and event parallelism.
    - Parallel architectures including processor architectures, memory and caching.
    - Parallel programming paradigms including threading, message passing, event driven techniques, parallel software architectures, and MapReduce.
    - Grid computing.
    - The impact of architecture on computational time.
    - Total time to science curve for parallelism: continuum of things.
- Computing costs, e.g., the cost of re-computing a value vs. the cost of storing and lookup.

Learning Outcomes:

1. Explain the characteristics and defining properties of algorithms and how they relate to machine processing. [Familiarity]
2. Analyze simple problem statements to identify relevant information and select appropriate processing to solve the problem. [Assessment]
3. Identify or sketch a workflow for an existing computational process such as the creation of a graph based on experimental data. [Familiarity]
4. Describe the process of converting an algorithm to machine-executable code. [Familiarity]
5. Summarize the phases of software development and compare several common lifecycle models. [Familiarity]
6. Explain how data is represented in a machine. Compare representations of integers to floating point numbers. Describe underflow, overflow, round off, and truncation errors in data representations. [Familiarity]

7. Apply standard numerical algorithms to solve ODEs and PDEs. Use computing systems to solve systems of equations. [Usage]
8. Describe the basic properties of bandwidth, latency, scalability and granularity. [Familiarity]
9. Describe the levels of parallelism including task, data, and event parallelism. [Familiarity]
10. Compare and contrast parallel programming paradigms recognizing the strengths and weaknesses of each. [Assessment]
11. Identify the issues impacting correctness and efficiency of a computation. [Familiarity]
12. Design, code, test and debug programs for a parallel computation. [Usage]

CN/Interactive Visualization

[Elective]

This sub-area is related to modeling and simulation. Most topics are discussed in detail in other knowledge areas in this document. There are many ways to present data and information, including immersion, realism, variable perspectives; haptics and heads-up displays, sonification, and gesture mapping.

Interactive visualization in general requires understanding of human perception (GV/Basics); graphics pipelines, geometric representations and data structures (GV/Fundamental Concepts); 2D and 3D rendering, surface and volume rendering (GV/Rendering, GV/Modeling, and GV/Advanced Rendering); and the use of APIs for developing user interfaces using standard input components such as menus, sliders, and buttons; and standard output components for data display, including charts, graphs, tables, and histograms (HCI/GUI Construction, HCI/GUI Programming).

Topics:

- Principles of data visualization
- Graphing and visualization algorithms
- Image processing techniques
- Scalability concerns

Learning Outcomes:

1. Compare common computer interface mechanisms with respect to ease-of-use, learnability, and cost. [Assessment]
2. Use standard APIs and tools to create visual displays of data, including graphs, charts, tables, and histograms. [Usage]
3. Describe several approaches to using a computer as a means for interacting with and processing data. [Familiarity]
4. Extract useful information from a dataset. [Assessment]
5. Analyze and select visualization techniques for specific problems. [Assessment]
6. Describe issues related to scaling data analysis from small to large data sets. [Familiarity]

CN/Data, Information, and Knowledge

[Elective]

Many topics are discussed in detail in other knowledge areas in this document, specifically Information Management (IM/Information Management Concepts, IM/Database Systems, and IM/Data Modeling), Algorithms and Complexity (AL/Basic Analysis, AL/Fundamental Data Structures and Algorithms), and Software Development Fundamentals (SDF/Fundamental Programming Concepts, SDF/Development Methods).

Topics:

- Content management models, frameworks, systems, design methods (as in IM. Information Management)
- Digital representations of content including numbers, text, images (e.g., raster and vector), video (e.g., QuickTime, MPEG2, MPEG4), audio (e.g., written score, MIDI, sampled digitized sound track) and animations; complex/composite/aggregate objects; FRBR
- Digital content creation/capture and preservation, including digitization, sampling, compression, conversion, transformation/translation, migration/emulation, crawling, harvesting
- Content structure / management, including digital libraries and static/dynamic/stream aspects for:
    - Data: data structures, databases
    - Information: document collections, multimedia pools, hyperbases (hypertext, hypermedia), catalogs, repositories
    - Knowledge: ontologies, triple stores, semantic networks, rules
- Processing and pattern recognition, including indexing, searching (including: queries and query languages; central / federated / P2P), retrieving, clustering, classifying/categorizing, analyzing/mining/extracting, rendering, reporting, handling transactions
- User / society support for presentation and interaction, including browse, search, filter, route, visualize, share, collaborate, rate, annotate, personalize, recommend
- Modeling, design, logical and physical implementation, using relevant systems/software

Learning Outcomes:

1. Identify all of the data, information, and knowledge elements and related organizations, for a computational science application. [Assessment]
2. Describe how to represent data and information for processing. [Familiarity]
3. Describe typical user requirements regarding that data, information, and knowledge. [Familiarity]
4. Select a suitable system or software implementation to manage data, information, and knowledge. [Assessment]
5. List and describe the reports, transactions, and other processing needed for a computational science application. [Familiarity]
6. Compare and contrast database management, information retrieval, and digital library systems with regard to handling typical computational science applications. [Assessment]
7. Design a digital library for some computational science users/societies, with appropriate content and services. [Usage]

CN/Numerical Analysis

[Elective]

Cross-reference AR/Machine Level Representation of Data

Topics:

- Error, stability, convergence, including truncation and round-off
- Function approximation including Taylor's series, interpolation, extrapolation, and regression

- Numerical differentiation and integration (Simpson's Rule, explicit and implicit methods)
- Differential equations (Euler's Method, finite differences)

Learning Outcomes:

1. Define error, stability, machine precision concepts and the inexactness of computational approximations. [Familiarity]
2. Implement Taylor series, interpolation, extrapolation, and regression algorithms for approximating functions. [Usage]
3. Implement algorithms for differentiation and integration. [Usage]
4. Implement algorithms for solving differential equations. [Usage]

Discrete Structures (DS)

Discrete structures are foundational material for computer science. By foundational we mean that relatively few computer scientists will be working primarily on discrete structures, but that many other areas of computer science require the ability to work with concepts from discrete structures. Discrete structures include important material from such areas as set theory, logic, graph theory, and probability theory.

The material in discrete structures is pervasive in the areas of data structures and algorithms but appears elsewhere in computer science as well. For example, an ability to create and understand a proof—either a formal symbolic proof or a less formal but still mathematically rigorous argument—is important in virtually every area of computer science, including (to name just a few) formal specification, verification, databases, and cryptography. Graph theory concepts are used in networks, operating systems, and compilers. Set theory concepts are used in software engineering and in databases. Probability theory is used in intelligent systems, networking, and a number of computing applications.

Given that discrete structures serves as a foundation for many other areas in computing, it is worth noting that the boundary between discrete structures and other areas, particularly Algorithms and Complexity, Software Development Fundamentals, Programming Languages, and Intelligent Systems, may not always be crisp. Indeed, different institutions may choose to organize the courses in which they cover this material in very different ways. Some institutions may cover these topics in one or two focused courses with titles like "discrete structures" or "discrete mathematics," whereas others may integrate these topics in courses on programming, algorithms, and/or artificial intelligence. Combinations of these approaches are also prevalent (e.g., covering many of these topics in a single focused introductory course and covering the remaining topics in more advanced topical courses).

DS. Discrete Structures (37 Core-Tier1 hours, 4 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
DS/Sets, Relations, and Functions	**4**		**N**
DS/Basic Logic	**9**		**N**
DS/Proof Techniques	**10**	**1**	**N**
DS/Basics of Counting	**5**		**N**
DS/Graphs and Trees	**3**	**1**	**N**
DS/Discrete Probability	**6**	**2**	**N**

DS/Sets, Relations, and Functions

[4 Core-Tier1 hours]

Topics:

- Sets
  - Venn diagrams
  - Union, intersection, complement
  - Cartesian product
  - Power sets
  - Cardinality of finite sets
- Relations
  - Reflexivity, symmetry, transitivity
  - Equivalence relations, partial orders
- Functions
  - Surjections, injections, bijections
  - Inverses
  - Composition

Learning Outcomes:

1. Explain with examples the basic terminology of functions, relations, and sets. [Familiarity]
2. Perform the operations associated with sets, functions, and relations. [Usage]
3. Relate practical examples to the appropriate set, function, or relation model, and interpret the associated operations and terminology in context. [Assessment]

DS/Basic Logic

[9 Core-Tier1 hours]

Topics:

- Propositional logic (cross-reference: Propositional logic is also reviewed in IS/Knowledge Based Reasoning)
- Logical connectives
- Truth tables
- Normal forms (conjunctive and disjunctive)
- Validity of well-formed formula
- Propositional inference rules (concepts of modus ponens and modus tollens)
- Predicate logic
    - Universal and existential quantification
- Limitations of propositional and predicate logic (e.g., expressiveness issues)

Learning Outcomes:

1. Convert logical statements from informal language to propositional and predicate logic expressions. [Usage]
2. Apply formal methods of symbolic propositional and predicate logic, such as calculating validity of formulae and computing normal forms. [Usage]
3. Use the rules of inference to construct proofs in propositional and predicate logic. [Usage]
4. Describe how symbolic logic can be used to model real-life situations or applications, including those arising in computing contexts such as software analysis (e.g., program correctness), database queries, and algorithms. [Usage]
5. Apply formal logic proofs and/or informal, but rigorous, logical reasoning to real problems, such as predicting the behavior of software or solving problems such as puzzles. [Usage]
6. Describe the strengths and limitations of propositional and predicate logic. [Familiarity]

DS/Proof Techniques

[10 Core-Tier1 hours, 1 Core-Tier2 hour]

Topics:

[Core-Tier1]

- Notions of implication, equivalence, converse, inverse, contrapositive, negation, and contradiction
- The structure of mathematical proofs
- Direct proofs
- Disproving by counterexample
- Proof by contradiction
- Induction over natural numbers
- Structural induction
- Weak and strong induction (i.e., First and Second Principle of Induction)
- Recursive mathematical definitions

[Core-Tier2]

- Well orderings

Learning Outcomes:

[Core-Tier1]

1. Identify the proof technique used in a given proof. [Familiarity]
2. Outline the basic structure of each proof technique (direct proof, proof by contradiction, and induction) described in this unit. [Usage]
3. Apply each of the proof techniques (direct proof, proof by contradiction, and induction) correctly in the construction of a sound argument. [Usage]
4. Determine which type of proof is best for a given problem. [Assessment]
5. Explain the parallels between ideas of mathematical and/or structural induction to recursion and recursively defined structures. [Assessment]
6. Explain the relationship between weak and strong induction and give examples of the appropriate use of each. [Assessment]

[Core-Tier2]

7. State the well-ordering principle and its relationship to mathematical induction. [Familiarity]

DS/Basics of Counting

[5 Core-Tier1 hours]

Topics:

- Counting arguments
  - Set cardinality and counting
  - Sum and product rule
  - Inclusion-exclusion principle
  - Arithmetic and geometric progressions
- The pigeonhole principle
- Permutations and combinations
  - Basic definitions
  - Pascal's identity
  - The binomial theorem
- Solving recurrence relations (cross-reference: AL/Basic Analysis)
  - An example of a simple recurrence relation, such as Fibonacci numbers
  - Other examples, showing a variety of solutions
- Basic modular arithmetic

Learning Outcomes:

1. Apply counting arguments, including sum and product rules, inclusion-exclusion principle and arithmetic/geometric progressions. [Usage]
2. Apply the pigeonhole principle in the context of a formal proof. [Usage]
3. Compute permutations and combinations of a set, and interpret the meaning in the context of the particular application. [Usage]
4. Map real-world applications to appropriate counting formalisms, such as determining the number of ways to arrange people around a table, subject to constraints on the seating arrangement, or the number of ways to determine certain hands in cards (e.g., a full house). [Usage]
5. Solve a variety of basic recurrence relations. [Usage]
6. Analyze a problem to determine underlying recurrence relations. [Usage]
7. Perform computations involving modular arithmetic. [Usage]

DS/Graphs and Trees

[3 Core-Tier1 hours, 1 Core-Tier2 hour]

Cross-reference: AL/Fundamental Data Structures and Algorithms, especially with relation to graph traversal strategies.

Topics:

[Core-Tier1]

- Trees
  - Properties
  - Traversal strategies
- Undirected graphs
- Directed graphs
- Weighted graphs

[Core-Tier2]

- Spanning trees/forests
- Graph isomorphism

Learning Outcomes:

[Core-Tier1]

1. Illustrate by example the basic terminology of graph theory, as well as some of the properties and special cases of each type of graph/tree. [Familiarity]
2. Demonstrate different traversal methods for trees and graphs, including pre-, post-, and in-order traversal of trees. [Usage]
3. Model *a variety of* real-world problems in computer science using appropriate forms of graphs and trees, such as representing a network topology or the organization of a hierarchical file system. [Usage]
4. Show how concepts from graphs and trees appear in data structures, algorithms, proof techniques (structural induction), and counting. [Usage]

[Core-Tier2]

5. Explain how to construct a spanning tree of a graph. [Usage]
6. Determine if two graphs are isomorphic. [Usage]

DS/Discrete Probability

[6 Core-Tier1 hours, 2 Core-Tier2 hour]

Topics:

[Core-Tier1]

- Finite probability space, events
- Axioms of probability and probability measures
- Conditional probability, Bayes' theorem
- Independence
- Integer random variables (Bernoulli, binomial)
- Expectation, including Linearity of Expectation

[Core-Tier2]

- Variance
- Conditional Independence

Learning Outcomes:

[Core-Tier1]

1. Calculate probabilities of events and expectations of random variables for elementary problems such as games of chance. [Usage]
2. Differentiate between dependent and independent events. [Usage]
3. Identify a case of the binomial distribution and compute a probability using that distribution. [Usage]
4. Apply Bayes theorem to determine conditional probabilities in a problem. [Usage]
5. Apply the tools of probability to solve problems such as the average case analysis of algorithms or analyzing hashing. [Usage]

[Core-Tier2]

6. Compute the variance for a given probability distribution. [Usage]
7. Explain how events that are independent can be conditionally dependent (and vice-versa). Identify real-world examples of such cases. [Usage]

Graphics and Visualization (GV)

Computer graphics is the term commonly used to describe the computer generation and manipulation of images. It is the science of enabling visual communication through computation. Its uses include cartoons, film special effects, video games, medical imaging, engineering, as well as scientific, information, and knowledge visualization. Traditionally, graphics at the undergraduate level has focused on rendering, linear algebra, and phenomenological approaches. More recently, the focus has begun to include physics, numerical integration, scalability, and special-purpose hardware. In order for students to become adept at the use and generation of computer graphics, many implementation-specific issues must be addressed, such as file formats, hardware interfaces, and application program interfaces. These issues change rapidly, and the description that follows attempts to avoid being overly prescriptive about them. The area encompassed by Graphics and Visualization is divided into several interrelated fields:

- Fundamentals: Computer graphics depends on an understanding of how humans use vision to perceive information and how information can be rendered on a display device. Every computer scientist should have some understanding of where and how graphics can be appropriately applied as well as the fundamental processes involved in display rendering.
- Modeling: Information to be displayed must be encoded in computer memory in some form, often in the form of a mathematical specification of shape and form.
- Rendering: Rendering is the process of displaying the information contained in a model.
- Animation: Animation is the rendering in a manner that makes images appear to move and the synthesis or acquisition of the time variations of models.
- Visualization: The field of visualization seeks to determine and present underlying correlated structures and relationships in data sets from a wide variety of application areas. The prime objective of the presentation should be to communicate the information in a dataset so as to enhance understanding
- Computational Geometry: Computational Geometry is the study of algorithms that are stated in terms of geometry.

Graphics and Visualization is related to machine vision and image processing, which are found in the Intelligent Systems (IS) KA, and algorithms such as computational geometry, which are found in the Algorithms and Complexity (AL) KA. Topics in virtual reality are found in the Human-Computer Interaction (HCI) KA.

This description assumes students are familiar with fundamental concepts of data representation, abstraction, and program implementation.

GV. Graphics and Visualization (2 Core-Tier1 hours, 1 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
GV/Fundamental Concepts	**2**	**1**	**Y**
GV/Basic Rendering			**Y**
GV/Geometric Modeling			**Y**
GV/Advanced Rendering			**Y**
GV/Computer Animation			**Y**
GV/Visualization			**Y**

GV/Fundamental Concepts

[2 Core-Tier1 and 1 Core-Tier2 hours]

For nearly every computer scientist and software developer, an understanding of how humans interact with machines is essential. While these topics may be covered in a standard undergraduate graphics course, they may also be covered in introductory computer science and programming courses. Part of our motivation for including immediate and retained modes is that these modes are analogous to polling vs. event driven programming. This is a fundamental question in computer science: Is there a button object, or is there just the display of a button on the screen? Note that most of the outcomes in this section are at the knowledge level, and many of these topics are revisited in greater depth in later sections.

Topics:

[Core-Tier1]

- Media applications including user interfaces, audio and video editing, game engines, cad, visualization, virtual reality
- Digitization of analog data, resolution, and the limits of human perception, e.g., pixels for visual display, dots for laser printers, and samples for audio (HCI/Foundations)
- Use of standard APIs for the construction of UIs and display of standard media formats (see HCI/GUI construction)
- Standard media formats, including lossless and lossy formats

[Core-Tier2]

- Additive and subtractive color models (CMYK and RGB) and why these provide a range of colors
- Tradeoffs between storing data and re-computing data as embodied by vector and raster representations of images
- Animation as a sequence of still images

[Elective]

- Double buffering

Learning Outcomes:

[Core-Tier1]

1. Identify common uses of digital presentation to humans (e.g., computer graphics, sound). [Familiarity]
2. Explain in general terms how analog signals can be reasonably represented by discrete samples, for example, how images can be represented by pixels. [Familiarity]
3. Explain how the limits of human perception affect choices about the digital representation of analog signals. [Familiarity]
4. Construct a simple user interface using a standard API. [Usage]
5. Describe the differences between lossy and lossless image compression techniques, for example as reflected in common graphics image file formats such as JPG, PNG, MP3, MP4, and GIF. [Familiarity]

[Core-Tier2]

6. Describe color models and their use in graphics display devices. [Familiarity]
7. Describe the tradeoffs between storing information vs. storing enough information to reproduce the information, as in the difference between vector and raster rendering. [Familiarity]

[Elective]

8. Describe the basic process of producing continuous motion from a sequence of discrete frames (sometimes called "flicker fusion"). [Familiarity]
9. Describe how double-buffering can remove flicker from animation. [Familiarity]

GV/Basic Rendering

[Elective]

This section describes basic rendering and fundamental graphics techniques that nearly every undergraduate course in graphics will cover and that are essential for further study in graphics. Sampling and anti-aliasing are related to the effect of digitization and appear in other areas of computing, for example, in audio sampling.

Topics:

- Rendering in nature, e.g., the emission and scattering of light and its relation to numerical integration
- Forward and backward rendering (i.e., ray-casting and rasterization)
- Polygonal representation
- Basic radiometry, similar triangles, and projection model
- Affine and coordinate system transformations
- Ray tracing
- Visibility and occlusion, including solutions to this problem such as depth buffering, Painter's algorithm, and ray tracing
- The forward and backward rendering equation
- Simple triangle rasterization
- Rendering with a shader-based API
- Texture mapping, including minification and magnification (e.g., trilinear MIP-mapping)
- Application of spatial data structures to rendering
- Sampling and anti-aliasing
- Scene graphs and the graphics pipeline

Learning Outcomes:

1. Discuss the light transport problem and its relation to numerical integration i.e., light is emitted, scatters around the scene, and is measured by the eye. [Familiarity]
2. Describe the basic graphics pipeline and how forward and backward rendering factor in this. [Familiarity]
3. Create a program to display 3D models of simple graphics images. [Usage]
4. Derive linear perspective from similar triangles by converting points (x, y, z) to points (x/z, y/z, 1). [Usage]
5. Obtain 2-dimensional and 3-dimensional points by applying affine transformations. [Usage]
6. Apply 3-dimensional coordinate system and the changes required to extend 2D transformation operations to handle transformations in 3D. [Usage]
7. Contrast forward and backward rendering. [Assessment]
8. Explain the concept and applications of texture mapping, sampling, and anti-aliasing. [Familiarity]
9. Explain the ray tracing/rasterization duality for the visibility problem. [Familiarity]
10. Implement simple procedures that perform transformation and clipping operations on simple 2-dimensional images. [Usage]
11. Implement a simple real-time renderer using a rasterization API (e.g., OpenGL) using vertex buffers and shaders. [Usage]
12. Compare and contrast the different rendering techniques. [Assessment]
13. Compute space requirements based on resolution and color coding. [Assessment]
14. Compute time requirements based on refresh rates, rasterization techniques. [Assessment]

GV/Geometric Modeling

[Elective]

Topics:

- Basic geometric operations such as intersection calculation and proximity tests
- Volumes, voxels, and point-based representations
- Parametric polynomial curves and surfaces
- Implicit representation of curves and surfaces
- Approximation techniques such as polynomial curves, Bezier curves, spline curves and surfaces, and non-uniform rational basis (NURB) spines, and level set method
- Surface representation techniques including tessellation, mesh representation, mesh fairing, and mesh generation techniques such as Delaunay triangulation, marching cubes
- Spatial subdivision techniques
- Procedural models such as fractals, generative modeling, and L-systems
- Graftals, cross referenced with programming languages (grammars to generated pictures)
- Elastically deformable and freeform deformable models
- Subdivision surfaces
- Multiresolution modeling
- Reconstruction
- Constructive Solid Geometry (CSG) representation

Learning Outcomes:

1. Represent curves and surfaces using both implicit and parametric forms. [Usage]
2. Create simple polyhedral models by surface tessellation. [Usage]
3. Generate a mesh representation from an implicit surface. [Usage]
4. Generate a fractal model or terrain using a procedural method. [Usage]
5. Generate a mesh from data points acquired with a laser scanner. [Usage]
6. Construct CSG models from simple primitives, such as cubes and quadric surfaces. [Usage]
7. Contrast modeling approaches with respect to space and time complexity and quality of image. [Assessment]

GV/Advanced Rendering

[Elective]

Topics:

- Solutions and approximations to the rendering equation, for example:
    - Distribution ray tracing and path tracing
    - Photon mapping
    - Bidirectional path tracing
    - Reyes (micropolygon) rendering
    - Metropolis light transport
- Time (motion blur), lens position (focus), and continuous frequency (color) and their impact on rendering
- Shadow mapping
- Occlusion culling
- Bidirectional Scattering Distribution function (BSDF) theory and microfacets
- Subsurface scattering
- Area light sources
- Hierarchical depth buffering
- The Light Field, image-based rendering

- Non-photorealistic rendering
- GPU architecture
- Human visual systems including adaptation to light, sensitivity to noise, and flicker fusion

Learning Outcomes:

1. Demonstrate how an algorithm estimates a solution to the rendering equation. [Assessment]
2. Prove the properties of a rendering algorithm, e.g., complete, consistent, and unbiased. [Assessment]
3. Analyze the bandwidth and computation demands of a simple algorithm. [Assessment]
4. Implement a non-trivial shading algorithm (e.g., toon shading, cascaded shadow maps) under a rasterization API. [Usage]
5. Discuss how a particular artistic technique might be implemented in a renderer. [Familiarity]
6. Explain how to recognize the graphics techniques used to create a particular image. [Familiarity]
7. Implement any of the specified graphics techniques using a primitive graphics system at the individual pixel level. [Usage]
8. Implement a ray tracer for scenes using a simple (e.g., Phong model) BRDF plus reflection and refraction. [Usage]

GV/Computer Animation

[Elective]

Topics:

- Forward and inverse kinematics
- Collision detection and response
- Procedural animation using noise, rules (boids/crowds), and particle systems
- Skinning algorithms
- Physics based motions including rigid body dynamics, physical particle systems, mass-spring networks for cloth and flesh and hair
- Key-frame animation
- Splines
- Data structures for rotations, such as quaternions
- Camera animation
- Motion capture

Learning Outcomes:

1. Compute the location and orientation of model parts using a forward kinematic approach. [Usage]
2. Compute the orientation of articulated parts of a model from a location and orientation using an inverse kinematic approach. [Usage]
3. Describe the tradeoffs in different representations of rotations. [Assessment]
4. Implement the spline interpolation method for producing in-between positions and orientations. [Usage]
5. Implement algorithms for physical modeling of particle dynamics using simple Newtonian mechanics, for example Witkin & Kass, snakes and worms, symplectic Euler, Stormer/Verlet, or midpoint Euler methods. [Usage]
6. Discuss the basic ideas behind some methods for fluid dynamics for modeling ballistic trajectories, for example for splashes, dust, fire, or smoke. [Familiarity]
7. Use common animation software to construct simple organic forms using metaball and skeleton. [Usage]

GV/Visualization

[Elective]

Visualization has strong ties to the Human-Computer Interaction (HCI) knowledge area as well as Computational Science (CN). Readers should refer to the HCI and CN KAs for additional topics related to user population and interface evaluations.

Topics:

- Visualization of 2D/3D scalar fields: color mapping, isosurfaces
- Direct volume data rendering: ray-casting, transfer functions, segmentation
- Visualization of:
    - Vector fields and flow data
    - Time-varying data
    - High-dimensional data: dimension reduction, parallel coordinates,
    - Non-spatial data: multi-variate, tree/graph structured, text
- Perceptual and cognitive foundations that drive visual abstractions
- Visualization design
- Evaluation of visualization methods
- Applications of visualization

Learning Outcomes:

1. Describe the basic algorithms for scalar and vector visualization. [Familiarity]
2. Describe the tradeoffs of visualization algorithms in terms of accuracy and performance. [Assessment]
3. Propose a suitable visualization design for a particular combination of data characteristics and application tasks. [Assessment]
4. Analyze the effectiveness of a given visualization for a particular task. [Assessment]
5. Design a process to evaluate the utility of a visualization algorithm or system. [Assessment]
6. Recognize a variety of applications of visualization including representations of scientific, medical, and mathematical data; flow visualization; and spatial analysis. [Familiarity]

Human-Computer Interaction (HCI)

Human-computer interaction (HCI) is concerned with designing interactions between human activities and the computational systems that support them, and with constructing interfaces to afford those interactions.

Interaction between users and computational artefacts occurs at an interface that includes both software and hardware. Thus interface design impacts the software life-cycle in that it should occur early; the design and implementation of core functionality can influence the user interface – for better or worse.

Because it deals with people as well as computational systems, as a knowledge area HCI demands the consideration of cultural, social, organizational, cognitive and perceptual issues. Consequently it draws on a variety of disciplinary traditions, including psychology, ergonomics, computer science, graphic and product design, anthropology and engineering.

HCI: Human Computer Interaction (4 Core-Tier1 hours, 4 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
HCI/Foundations	**4**		**N**
HCI/Designing Interaction		**4**	**N**
HCI/Programming Interactive Systems			**Y**
HCI/User-Centered Design & Testing			**Y**
HCI/New Interactive Technologies			**Y**
HCI/Collaboration & Communication			**Y**
HCI/Statistical Methods for HCI			**Y**
HCI/Human Factors & Security			**Y**
HCI/Design-Oriented HCI			**Y**
HCI/Mixed, Augmented and Virtual Reality			**Y**

HCI/Foundations

[4 Core-Tier1 hours]

Motivation: For end-users, the interface *is* the system. So design in this domain must be interaction-focused and human-centered. Students need a different repertoire of techniques to address this than is provided elsewhere in the curriculum.

Topics:

- Contexts for HCI (anything with a user interface, e.g., webpage, business applications, mobile applications, and games)
- Processes for user-centered development, e.g., early focus on users, empirical testing, iterative design
- Different measures for evaluation, e.g., utility, efficiency, learnability, user satisfaction
- Usability heuristics and the principles of usability testing
- Physical capabilities that inform interaction design, e.g., color perception, ergonomics
- Cognitive models that inform interaction design, e.g., attention, perception and recognition, movement, and memory; gulfs of expectation and execution
- Social models that inform interaction design, e.g., culture, communication, networks and organizations
- Principles of good design and good designers; engineering tradeoffs
- Accessibility, e.g., interfaces for differently-abled populations (e.g., blind, motion-impaired)
- Interfaces for differently-aged population groups (e.g., children, 80+)

Learning Outcomes:

1. Discuss why human-centered software development is important. [Familiarity]
2. Summarize the basic precepts of psychological and social interaction. [Familiarity]
3. Develop and use a conceptual vocabulary for analyzing human interaction with software: affordance, conceptual model, feedback, and so forth. [Usage]
4. Define a user-centered design process that explicitly takes account of the fact that the user is not like the developer or their acquaintances. [Usage]
5. Create and conduct a simple usability test for an existing software application. [Assessment]

HCI/Designing Interaction

[4 Core-Tier2 hours]

Motivation: CS students need a minimal set of well-established methods and tools to bring to interface construction.

Topics:

- Principles of graphical user interfaces (GUIs)
- Elements of visual design (layout, color, fonts, labeling)
- Task analysis, including qualitative aspects of generating task analytic models
- Low-fidelity (paper) prototyping
- Quantitative evaluation techniques, e.g., keystroke-level evaluation
- Help and documentation
- Handling human/system failure
- User interface standards

Learning Outcomes:

1. For an identified user group, undertake and document an analysis of their needs. [Assessment]
2. Create a simple application, together with help and documentation, that supports a graphical user interface. [Usage]
3. Conduct a quantitative evaluation and discuss/report the results. [Usage]
4. Discuss at least one national or international user interface design standard. [Familiarity]

HCI/Programming Interactive Systems

[Elective]

Motivation: To take a user-experience-centered view of software development and then cover approaches and technologies to make that happen.

Topics:

- Software Architecture Patterns, e.g., Model-View controller; command objects, online, offline (cross reference PL/Event Driven and Reactive Programming, where MVC is used in the context of event-driven programming)
- Interaction Design Patterns: visual hierarchy, navigational distance
- Event management and user interaction
- Geometry management (cross-reference GV/Geometric Modelling)
- Choosing interaction styles and interaction techniques
- Presenting information: navigation, representation, manipulation
- Interface animation techniques (e.g., scene graphs)
- Widget classes and libraries
- Modern GUI libraries (e.g. iOS, Android, JavaFX) GUI builders and UI programming environments (cross-reference PBD/Mobile Platforms)
- Declarative Interface Specification: Stylesheets and DOMs
- Data-driven applications (database-backed web pages)
- Cross-platform design
- Design for resource-constrained devices (e.g. small, mobile devices)

Learning Outcomes:

1. Explain the importance of Model-View controller to interface programming. [Familiarity]
2. Create an application with a modern graphical user interface. [Usage]
3. Identify commonalities and differences in UIs across different platforms. [Familiarity]
4. Explain and use GUI programming concepts: event handling, constraint-based layout management, etc. [Familiarity]

HCI/User-Centered Design and Testing

[Elective]

Motivation: An exploration of techniques to ensure that end-users are fully considered at all stages of the design process, from inception to implementation.

Topics:

- Approaches to, and characteristics of, the design process
- Functionality and usability requirements (cross-reference to SE/Requirements Engineering)
- Techniques for gathering requirements, e.g., interviews, surveys, ethnographic and contextual enquiry
- Techniques and tools for the analysis and presentation of requirements, e.g., reports, personas
- Prototyping techniques and tools, e.g., sketching, storyboards, low-fidelity prototyping, wireframes
- Evaluation without users, using both qualitative and quantitative techniques, e.g., walkthroughs, GOMS, expert-based analysis, heuristics, guidelines, and standards
- Evaluation with users, e.g., observation, think-aloud, interview, survey, experiment
- Challenges to effective evaluation, e.g., sampling, generalization
- Reporting the results of evaluations
- Internationalization, designing for users from other cultures, cross-cultural

Learning Outcomes:

1. Explain how user-centered design complements other software process models. [Familiarity]
2. Use lo-fi (low fidelity) prototyping techniques to gather, and report, user responses. [Usage]
3. Choose appropriate methods to support the development of a specific UI. [Assessment]
4. Use a variety of techniques to evaluate a given UI. [Assessment]
5. Compare the constraints and benefits of different evaluative methods. [Assessment]

HCI/New Interactive Technologies

[Elective]

Motivation: As technologies evolve, new interaction styles are made possible. This knowledge unit should be considered extensible, to track emergent technology.

Topics:

- Choosing interaction styles and interaction techniques
- Representing information to users: navigation, representation, manipulation
- Approaches to design, implementation and evaluation of non-mouse interaction
    - Touch and multi-touch interfaces
    - Shared, embodied, and large interfaces
    - New input modalities (such as sensor and location data)
    - New Windows, e.g., iPhone, Android
    - Speech recognition and natural language processing (cross reference IS/Natural Language Processing)
    - Wearable and tangible interfaces
    - Persuasive interaction and emotion
    - Ubiquitous and context-aware interaction technologies (Ubicomp)
    - Bayesian inference (e.g. predictive text, guided pointing)
    - Ambient/peripheral display and interaction

Learning Outcomes:

1. Describe when non-mouse interfaces are appropriate. [Familiarity]
2. Understand the interaction possibilities beyond mouse-and-pointer interfaces. [Familiarity]
3. Discuss the advantages (and disadvantages) of non-mouse interfaces. [Assessment]

HCI/Collaboration and Communication

[Elective]

Motivation: Computer interfaces not only support users in achieving their individual goals but also in their interaction with others, whether that is task-focused (work or gaming) or task-unfocused (social networking).

Topics:

- Asynchronous group communication, e.g., e-mail, forums, social networks
- Synchronous group communication, e.g., chat rooms, conferencing, online games
- Social media, social computing, and social network analysis
- Online collaboration, 'smart' spaces, and social coordination aspects of workflow technologies
- Online communities
- Software characters and intelligent agents, virtual worlds and avatars (cross-reference IS/Agents)
- Social psychology

Learning Outcomes:

1. Describe the difference between synchronous and asynchronous communication. [Familiarity]
2. Compare the HCI issues in individual interaction with group interaction. [Assessment]
3. Discuss several issues of social concern raised by collaborative software. [Familiarity]
4. Discuss the HCI issues in software that embodies human intention. [Familiarity]

HCI/Statistical Methods for HCI

[Elective]

Motivation: Much HCI work depends on the proper use, understanding and application of statistics. This knowledge is often held by students who join the field from psychology, but less common in students with a CS background.

Topics:

- t-tests
- ANOVA
- Randomization (non-parametric) testing, within vs. between-subjects design
- Calculating effect size
- Exploratory data analysis
- Presenting statistical data
- Combining qualitative and quantitative results

Learning Outcomes:

1. Explain basic statistical concepts and their areas of application. [Familiarity]
2. Extract and articulate the statistical arguments used in papers that quantitatively report user studies. [Usage]
3. Design a user study that will yield quantitative results. [Usage]
4. Conduct and report on a study that utilizes both qualitative and quantitative evaluation. [Usage]

HCI/Human Factors and Security

[Elective]

Motivation: Effective interface design requires basic knowledge of security psychology. Many attacks do not have a technological basis, but exploit human propensities and vulnerabilities. "Only amateurs attack machines; professionals target people" (Bruce Schneier, https://www.schneier.com/blog/archives/2013/03/phishing_has_go.h.)

Topics:

- Applied psychology and security policies
- Security economics
- Regulatory environments – responsibility, liability and self-determination
- Organizational vulnerabilities and threats
- Usability design and security
- Pretext, impersonation and fraud, e.g., phishing and spear phishing (cross-reference IAS/Threats and Attacks)
- Trust, privacy and deception
- Biometric authentication (camera, voice)
- Identity management

Learning Outcomes:

1. Explain the concepts of phishing and spear phishing, and how to recognize them. [Familiarity]
2. Describe the issues of trust in interface design with an example of a high and low trust system. [Assessment]
3. Design a user interface for a security mechanism. [Assessment]
4. Explain the concept of identity management and its importance. [Familiarity]
5. Analyze a security policy and/or procedures to show where they consider, or fail to consider, human factors. [Usage]

HCI/Design-Oriented HCI

[Elective]

Motivation: Some curricula will want to emphasize an understanding of the norms and values of HCI work itself as emerging from, and deployed within specific historical, disciplinary and cultural contexts.

Topics:

- Intellectual styles and perspectives to technology and its interfaces
- Consideration of HCI as a design discipline
  - Sketching
  - Participatory design
- Critically reflective HCI
  - Critical technical practice
  - Technologies for political activism
  - Philosophy of user experience
  - Ethnography and ethnomethodology
- Indicative domains of application
  - Sustainability
  - Arts-informed computing

Learning Outcomes:

1. Explain what is meant by "HCI is a design-oriented discipline". [Familiarity]
2. Detail the processes of design appropriate to specific design orientations. [Familiarity]
3. Apply a variety of design methods to a given problem. [Usage]

HCI/Mixed, Augmented and Virtual Reality

[Elective]

Motivation: A detailed consideration of the interface components required for the creation and development of immersive environments, especially games.

Topics:

- Output
  - Sound
  - Stereoscopic display
  - Force feedback simulation, haptic devices
- User input
  - Viewer and object tracking
  - Pose and gesture recognition
  - Accelerometers
  - Fiducial markers
  - User interface issues
- Physical modelling and rendering
  - Physical simulation: collision detection & response, animation
  - Visibility computation
  - Time-critical rendering, multiple levels of details (LOD)
- System architectures

    - Game engines
    - Mobile augmented reality
    - Flight simulators
    - CAVEs
    - Medical imaging
- Networking
    - p2p, client-server, dead reckoning, encryption, synchronization
    - Distributed collaboration

Learning Outcomes:

1. Describe the optical model realized by a computer graphics system to synthesize stereoscopic view. [Familiarity]
2. Describe the principles of different viewer tracking technologies. [Familiarity]
3. Describe the differences between geometry- and image-based virtual reality. [Familiarity]
4. Describe the issues of user action synchronization and data consistency in a networked environment. [Familiarity]
5. Determine the basic requirements on interface, hardware, and software configurations of a VR system for a specified application. [Usage]
6. Describe several possible uses for games engines, including their potential and their limitations. [Familiarity]

Information Assurance and Security (IAS)

In CS2013, the Information Assurance and Security KA is added to the Body of Knowledge in recognition of the world's reliance on information technology and its critical role in computer science education. Information assurance and security as a domain is the set of controls and processes both technical and policy intended to protect and defend information and information systems by ensuring their confidentiality, integrity, and availability, and by providing for authentication and non-repudiation. The concept of assurance also carries an attestation that current and past processes and data are valid. Both assurance and security concepts are needed to ensure a complete perspective. Information assurance and security education, then, includes all efforts to prepare a workforce with the needed knowledge, skills, and abilities to protect our information systems and attest to the assurance of the past and current state of processes and data. The importance of security concepts and topics has emerged as a core requirement in the Computer Science discipline, much like the importance of performance concepts has been for many years.

The Information Assurance and Security KA is unique among the set of KAs presented here given the manner in which the topics are pervasive throughout other Knowledge Areas. The topics germane to only IAS are presented in the IAS section; other topics are noted and cross-referenced in the IAS KA. In the IAS KA the many topics are represented with only 9 hours of Core-Tier1 and Tier2 coverage. This is balanced with the level of mastery primarily at the familiarity level and the more indepth coverage distributed in the referenced KAs where they are applied. The broad application of the IAS KA concepts (63.5 hours) across all other KAs provides the depth of coverage and mastery for an undergraduate computer science student.

The IAS KA is shown in two groups: (1) concepts where the depth is unique to Information Assurance and Security and (2) IAS topics that are integrated into other KAs that reflect naturally implied or specified topics with a strong role in security concepts and topics. For completeness, the total distribution of hours is summarized in the table below.

IAS. Information Assurance and Security "Core" and Distributed

	Core-Tier1 hours	Core-Tier2 hours	Elective Topics
IAS	**3**	**6**	**Y**
IAS distributed in other KA's	**32**	**31.5**	**Y**

IAS. Information Assurance and Security (3 Core-Tier1 hours, 6 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
IAS/Foundational Concepts in Security	**1**		**N**
IAS/Principles of Secure Design	**1**	**1**	**N**
IAS/Defensive Programming	**1**	**1**	**Y**
IAS/Threats and Attacks		**1**	**N**
IAS/Network Security		**2**	**Y**
IAS/Cryptography		**1**	**N**
IAS/Web Security			**Y**
IAS/Platform Security			**Y**
IAS/Security Policy and Governance			**Y**
IAS/Digital Forensics			**Y**
IAS/Secure Software Engineering			**Y**

The following table shows the distribution of hours throughout all other KA's in CS2013 where security is appropriately addressed either as fundamental to the KU topics (for example, OS/Security or Protection or SE/Software Construction) or as a supportive use case for the topic (for example, HCI/Foundations or NC/Routing and Forwarding or SP/Intellectual Property). The hours represent the set of hours in that KA/KU where the topics are particularly relevant to Information Assurance and Security.

IAS. Information Assurance and Security (distributed) (32 Core-Tier1 hours, 31.5 Core-Tier2 hours)

Knowledge Area and Topic	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
AR/Assembly Level Machine Organization		1	
AR/Memory System Organization and Architecture		0.5	
AR/Multiprocessing and Alternative Architectures			Y
HCI/Foundations	1		
HCI/Human Factors and Security			Y
IM/Information Management Concepts	0.5	0.5	
IM/Transaction Processing			Y
IM/Distributed Databases			Y
IS/Reasoning Under Uncertainty			Y
NC/Introduction	1		
NC/Networked Applications	0.5		
NC/Reliable Data Delivery		1.5	
NC/Routing and Forwarding		1	
NC/Local Area Networks		1	
NC/Resource Allocation		0.5	
NC/Mobility		1	
OS/Overview of OS	2		
OS/OS Principles	1		

OS/Concurrency		**1.5**	
OS/Scheduling and Dispatch		**2**	
OS/Memory Management		**2**	
OS/Security and Protection		**2**	
OS/Virtual Machines			**Y**
OS/Device Management			**Y**
OS/File Systems			**Y**
OS/Real Time and Embedded Systems			**Y**
OS/Fault Tolerance			**Y**
OS/System Performance Evaluation			**Y**
PBD/Web Platforms			**Y**
PBD/Mobile Platforms			**Y**
PBD/Industrial Platforms			**Y**
PD/Parallelism Fundamentals	**1**		
PD/Parallel Decomposition	**0.5**		
PD/Communication and Coordination	**1**	**1**	**Y**
PD/Parallel Architecture	**0.5**		**Y**
PD/Distributed Systems			**Y**
PD/Cloud Computing			**Y**
PL/Object-Oriented Programming	**1**	**3**	
PL/Functional Programming	**1**		

PL/Basic Type Systems	**0.5**	**2**	
PL/Language Translation and Execution		**1**	
PL/Runtime Systems			**Y**
PL/Static Analysis			**Y**
PL/Concurrency and Parallelism			**Y**
PL/Type Systems			**Y**
SDF/Fundamental Programming Concepts	**1**		
SDF/Development Methods	**8**		
SE/Software Processes	**1**		
SE/Software Project Management		**1**	**Y**
SE/Tools and Environments		**1**	
SE/Software Construction		**2**	**Y**
SE/Software Verification and Validation		**1**	**Y**
SE/Software Evolution		**1.5**	
SE/Software Reliability	**1**		
SF/Cross-Layer Communications	**3**		
SF/Parallelism	**1**		
SF/Resource Allocation and Scheduling	**0.5**		
SF/Virtualization and Isolation		**1**	
SF/Reliability through Redundancy		**2**	

SP/Social Context	**0.5**		
SP/Analytical Tools	**1**		
SP/Professional Ethics	**1**	**0.5**	
SP/Intellectual Property	**2**		**Y**
SP/Privacy and Civil Liberties	**0.5**		
SP/Security Policies, Laws and Computer Crimes			**Y**

IAS/Foundational Concepts in Security

[1 Core-Tier1 hour]

Topics:

- CIA (Confidentiality, Integrity, Availability)
- Concepts of risk, threats, vulnerabilities, and attack vectors (cros- reference SE/Software Project Management/Risk)
- Authentication and authorization, access control (mandatory vs. discretionary)
- Concept of trust and trustworthiness
- Ethics (responsible disclosure). (cross-reference SP/Professional Ethics/Accountability, responsibility and liability)

Learning outcomes:

1. Analyze the tradeoffs of balancing key security properties (Confidentiality, Integrity, and Availability). [Usage]
2. Describe the concepts of risk, threats, vulnerabilities and attack vectors (including the fact that there is no such thing as perfect security). [Familiarity]
3. Explain the concepts of authentication, authorization, access control. [Familiarity]
4. Explain the concept of trust and trustworthiness. [Familiarity]
5. Describe important ethical issues to consider in computer security, including ethical issues associated with fixing or not fixing vulnerabilities and disclosing or not disclosing vulnerabilities. [Familiarity]

IAS/Principles of Secure Design

[1 Core-Tier1 hour, 1 Core-Tier2 hour]

Topics:

. [Core-Tier1]

- Least privilege and isolation (cross-reference OS/Security and Protection/Policy/mechanism separation and SF/Virtualization and Isolation/Rationale for protection and predictable performance and PL/Language Translation and Execution/Memory management)
- Fail-safe defaults (cross-reference SE/Software Construction/ Coding practices: techniques, idioms/patterns, mechanisms for building quality programs and SDF/Development Methods/Programming correctness)
- Open design (cross-reference SE/Software Evolution/ Software development in the context of large, pre-existing code bases)
- End-to-end security (cross-reference SF/Reliability through Redundancy/ How errors increase the longer the distance between the communicating entities; the end-to-end principle)
- Defense in depth (e.g., defensive programming, layered defense)
- Security by design (cross-reference SE/Software Design/System design principles)
- Tensions between security and other design goals

[Core-Tier2]

- Complete mediation
- Use of vetted security components
- Economy of mechanism (reducing trusted computing base, minimize attack surface) (cross-reference SE/Software Design/System design principles and SE/Software Construction/Development context: "green field" vs. existing code base)
- Usable security (cross-reference HCI/Foundations/Cognitive models that inform interaction design)
- Security composability
- Prevention, detection, and deterrence (cross-reference SF/Reliability through Redundancy/Distinction between bugs and faults and NC/Reliable Data Delivery/Error control and NC/Reliable Data Delivery/Flow control)

Learning outcomes:

[Core-Tier1]

1. Describe the principle of least privilege and isolation as applied to system design. [Familiarity]
2. Summarize the principle of fail-safe and deny-by-default. [Familiarity]
3. Discuss the implications of relying on open design or the secrecy of design for security. [Familiarity]
4. Explain the goals of end-to-end data security. [Familiarity]
5. Discuss the benefits of having multiple layers of defenses. [Familiarity]
6. For each stage in the lifecycle of a product, describe what security considerations should be evaluated. [Familiarity]
7. Describe the cost and tradeoffs associated with designing security into a product. [Familiarity]

[Core-Tier2]

8. Describe the concept of mediation and the principle of complete mediation. [Familiarity]
9. Describe standard components for security operations, and explain the benefits of their use instead of re-inventing fundamentals operations. [Familiarity]
10. Explain the concept of trusted computing including trusted computing base and attack surface and the principle of minimizing trusted computing base. [Familiarity]

11. Discuss the importance of usability in security mechanism design. [Familiarity]
12. Describe security issues that arise at boundaries between multiple components. [Familiarity]
13. Identify the different roles of prevention mechanisms and detection/deterrence mechanisms. [Familiarity]

IAS/Defensive Programming

[1 Core-Tier1 hour, 1 Core-Tier2 hour]

Topics in defensive programming are generally not thought about in isolation, but applied to other topics particularly in SDF, SE and PD Knowledge Areas.

Topics:

[Core-Tier1]

- Input validation and data sanitization (cross-reference SDF/Development Methods/Program Correctness)
- Choice of programming language and type-safe languages
- Examples of input validation and data sanitization errors (cross-reference SDF/Development Methods/Program Correctness and SE/Software Construction/Coding Practices)
    - Buffer overflows
    - Integer errors
    - SQL injection
    - XSS vulnerability
- Race conditions (cross-reference SF/Parallelism/Parallel programming and PD/Parallel Architecture/Shared vs. distributed memory and PD/Communication and Coordination/Shared Memory and PD/Parallelism Fundamentals/Programming errors not found in sequential programming)
- Correct handling of exceptions and unexpected behaviors (cross-reference SDF/Development Methods/program correctness)

[Core-Tier2]

- Correct usage of third-party components (cross-reference SDF/Development Methods/program correctness and Operating System Principles/Concepts of application program interfaces (APIs)
- Effectively deploying security updates (cross-reference OS/Security and Protection/Security methods and devices)

[Electives]

- Information flow control
- Correctly generating randomness for security purposes
- Mechanisms for detecting and mitigating input and data sanitization errors
- Fuzzing
- Static analysis and dynamic analysis
- Program verification
- Operating system support (e.g., address space randomization, canaries)
- Hardware support (e.g., DEP, TPM)

Learning outcomes:

[Core-Tier1]

1. Explain why input validation and data sanitization is necessary in the face of adversarial control of the input channel. [Familiarity]
2. Explain why you might choose to develop a program in a type-safe language like Java, in contrast to an unsafe programming language like C/C++. [Familiarity]
3. Classify common input validation errors, and write correct input validation code. [Usage]
4. Demonstrate using a high-level programming language how to prevent a race condition from occurring and how to handle an exception. [Usage]
5. Demonstrate the identification and graceful handling of error conditions. [Usage]

[Core-Tier2]

6. Explain the risks with misusing interfaces with third-party code and how to correctly use third-party code. [Familiarity]
7. Discuss the need to update software to fix security vulnerabilities and the lifecycle management of the fix. [Familiarity]

[Elective]

8. List examples of direct and indirect information flows. [Familiarity]
9. Explain the role of random numbers in security, beyond just cryptography (e.g. password generation, randomized algorithms to avoid algorithmic denial of service attacks). [Familiarity]
10. Explain the different types of mechanisms for detecting and mitigating data sanitization errors. [Familiarity]
11. Demonstrate how programs are tested for input handling errors. [Usage]
12. Use static and dynamic tools to identify programming faults. [Usage]
13. Describe how memory architecture is used to protect runtime attacks. [Familiarity]

IAS/Threats and Attacks

[1 Core-Tier2 hour]

Topics:

[Core-Tier2]

- Attacker goals, capabilities, and motivations (such as underground economy, digital espionage, cyberwarfare, insider threats, hacktivism, advanced persistent threats)
- Examples of malware (e.g., viruses, worms, spyware, botnets, Trojan horses or rootkits)
- Denial of Service (DoS) and Distributed Denial of Service (DDoS)
- Social engineering (e.g., phishing) (cross-reference SP/Social Context/Social implications of computing in a networked world and HCI/Designing Interaction/Handling human/system failure)

[Elective]

- Attacks on privacy and anonymity (cross-reference HCI/Foundations/Social models that inform interaction design: culture, communication, networks and organizations (cross-reference SP/Privacy and Civil Liberties/technology-based solutions for privacy protection)
- Malware/unwanted communication such as covert channels and steganography

Learning outcomes:

[Core-Tier2]

1. Describe likely attacker types against a particular system. [Familiarity]
2. Discuss the limitations of malware countermeasures (e.g., signature-based detection, behavioral detection). [Familiarity]
3. Identify instances of social engineering attacks and Denial of Service attacks. [Familiarity]
4. Discuss how Denial of Service attacks can be identified and mitigated. [Familiarity]

[Elective]

5. Describe risks to privacy and anonymity in commonly used applications. [Familiarity]
6. Discuss the concepts of covert channels and other data leakage procedures. [Familiarity]

IAS/Network Security

[2 Core-Tier2 hours]

Discussion of network security relies on previous understanding on fundamental concepts of networking, including protocols, such as TCP/IP, and network architecture/organization (cross-reference NC/Network Communication).

Topics:

[Core-Tier2]

- Network specific threats and attack types (e.g., denial of service, spoofing, sniffing and traffic redirection, man-in-the-middle, message integrity attacks, routing attacks, and traffic analysis)
- Use of cryptography for data and network security
- Architectures for secure networks (e.g., secure channels, secure routing protocols, secure DNS, VPNs, anonymous communication protocols, isolation)
- Defense mechanisms and countermeasures (e.g., network monitoring, intrusion detection, firewalls, spoofing and DoS protection, honeypots, tracebacks)

. [Elective]

- Security for wireless, cellular networks (cross-reference NC/Mobility/Principles of cellular networks; cross-reference NC/Mobility/802.11)
- Other non-wired networks (e.g., ad hoc, sensor, and vehicular networks)
- Censorship resistance
- Operational network security management (e.g., configure network access control)

Learning outcomes:

[Core-Tier2]

1. Describe the different categories of network threats and attacks. [Familiarity]
2. Describe the architecture for public and private key cryptography and how public key infrastructure (PKI) supports network security. [Familiarity]
3. Describe virtues and limitations of security technologies at each layer of the network stack. [Familiarity]
4. Identify the appropriate defense mechanism(s) and its limitations given a network threat. [Familiarity]

[Elective]

5. Discuss security properties and limitations of other non-wired networks. [Familiarity]
6. Identify the additional threats faced by non-wired networks. [Familiarity]

7. Describe threats that can and cannot be protected against using secure communication channels. [Familiarity]
8. Summarize defenses against network censorship. [Familiarity]
9. Diagram a network for security. [Familiarity]

IAS/Cryptography

[1 Core-Tier2 hour]

Topics:

[Core-Tier2]

- Basic Cryptography Terminology covering notions pertaining to the different (communication) partners, secure/unsecure channel, attackers and their capabilities, encryption, decryption, keys and their characteristics, signatures
- Cipher types (e.g., Caesar cipher, affine cipher) together with typical attack methods such as frequency analysis
- Public Key Infrastructure support for digital signature and encryption and its challenges

[Elective]

- Mathematical Preliminaries essential for cryptography, including topics in linear algebra, number theory, probability theory, and statistics
- Cryptographic primitives:
    - pseudo-random generators and stream ciphers
    - block ciphers (pseudo-random permutations), e.g., AES
    - pseudo-random functions
    - hash functions, e.g., SHA2, collision resistance
    - message authentication codes
    - key derivations functions
- Symmetric key cryptography
    - Perfect secrecy and the one time pad
    - Modes of operation for semantic security and authenticated encryption (e.g., encrypt-then-MAC, OCB, GCM)
    - Message integrity (e.g., CMAC, HMAC)
- Public key cryptography:
    - Trapdoor permutation, e.g., RSA
    - Public key encryption, e.g., RSA encryption, EI Gamal encryption
    - Digital signatures
    - Public-key infrastructure (PKI) and certificates
    - Hardness assumptions, e.g., Diffie-Hellman, integer factoring
- Authenticated key exchange protocols, e.g., TLS
- Cryptographic protocols: challenge-response authentication, zero-knowledge protocols, commitment, oblivious transfer, secure 2-party or multi-party computation, secret sharing, and applications
- Motivate concepts using real-world applications, e.g., electronic cash, secure channels between clients and servers, secure electronic mail, entity authentication, device pairing, voting systems.
- Security definitions and attacks on cryptographic primitives:
    - Goals: indistinguishability, unforgeability, collision-resistance
    - Attacker capabilities: chosen-message attack (for signatures), birthday attacks, side channel attacks, fault injection attacks.
- Cryptographic standards and references implementations
- Quantum cryptography

Learning outcomes:

[Core-Tier2]

1. Describe the purpose of cryptography and list ways it is used in data communications. [Familiarity]
2. Define the following terms: cipher, cryptanalysis, cryptographic algorithm, and cryptology, and describe the two basic methods (ciphers) for transforming plain text in cipher text. [Familiarity]
3. Discuss the importance of prime numbers in cryptography and explain their use in cryptographic algorithms. [Familiarity]
4. Explain how public key infrastructure supports digital signing and encryption and discuss the limitations/vulnerabilities. [Familiarity]

[Elective]

5. Use cryptographic primitives and describe their basic properties. [Usage]
6. Illustrate how to measure entropy and how to generate cryptographic randomness. [Usage]
7. Use public-key primitives and their applications. [Usage]
8. Explain how key exchange protocols work and how they fail. [Familiarity]
9. Discuss cryptographic protocols and their properties. [Familiarity]
10. Describe real-world applications of cryptographic primitives and protocols. [Familiarity]
11. Summarize security definitions related to attacks on cryptographic primitives, including attacker capabilities and goals.[Familiarity]
12. Apply appropriate known cryptographic techniques for a given scenario. [Usage]
13. Appreciate the dangers of inventing one's own cryptographic methods. [Familiarity]
14. Describe quantum cryptography and the impact of quantum computing on cryptographic algorithms. [Familiarity]

IAS/Web Security

[Elective]

Topics:

- Web security model
    - Browser security model including same-origin policy
    - Client-server trust boundaries, e.g., cannot rely on secure execution in the client
- Session management, authentication
    - Single sign-on
    - HTTPS and certificates
- Application vulnerabilities and defenses
    - SQL injection
    - XSS
    - CSRF
- Client-side security
    - Cookies security policy
    - HTTP security extensions, e.g. HSTS
    - Plugins, extensions, and web apps
    - Web user tracking
- Server-side security tools, e.g. Web Application Firewalls (WAFs) and fuzzers

Learning outcomes:

1. Describe the browser security model including same-origin policy and threat models in web security. [Familiarity]

2. Discuss the concept of web sessions, secure communication channels such as TLS and importance of secure certificates, authentication including single sign-on such as OAuth and SAML. [Familiarity]
3. Describe common types of vulnerabilities and attacks in web applications, and defenses against them. [Familiarity]
4. Use client-side security capabilities in an application. [Usage]

IAS/Platform Security

[Elective]

Topics:

- Code integrity and code signing
- Secure boot, measured boot, and root of trust
- Attestation
- TPM and secure co-processors
- Security threats from peripherals, e.g., DMA, IOMMU
- Physical attacks: hardware Trojans, memory probes, cold boot attacks
- Security of embedded devices, e.g., medical devices, cars
- Trusted path

Learning outcomes:

1. Explain the concept of code integrity and code signing and the scope it applies to. [Familiarity]
2. Discuss the concept of root of trust and the process of secure boot and secure loading. [Familiarity]
3. Describe the mechanism of remote attestation of system integrity. [Familiarity]
4. Summarize the goals and key primitives of TPM. [Familiarity]
5. Identify the threats of plugging peripherals into a device. [Familiarity]
6. Identify physical attacks and countermeasures. [Familiarity]
7. Identify attacks on non-PC hardware platforms. [Familiarity]
8. Discuss the concept and importance of trusted path. [Familiarity]

IAS/Security Policy and Governance

[Elective]

See general cross-referencing with the SP/Security Policies, Laws and Computer Crimes.

Topics:

- Privacy policy (cross-reference SP/Social Context/Social implications of computing in a networked world; cross-reference SP/Professional Ethics/Accountability, responsibility and liability; cross-reference SP/Privacy and Civil Liberties/Legal foundations of privacy protection)
- Inference controls/statistical disclosure limitation
- Backup policy, password refresh policy
- Breach disclosure policy
- Data collection and retention policies
- Supply chain policy
- Cloud security tradeoffs

Learning outcomes:

1. Describe the concept of privacy including personally private information, potential violations of privacy due to security mechanisms, and describe how privacy protection mechanisms run in conflict with security mechanisms. [Familiarity]
2. Describe how an attacker can infer a secret by interacting with a database. [Familiarity]
3. Explain how to set a data backup policy or password refresh policy. [Familiarity]
4. Discuss how to set a breach disclosure policy. [Familiarity]
5. Describe the consequences of data retention policies. [Familiarity]
6. Identify the risks of relying on outsourced manufacturing. [Familiarity]
7. Identify the risks and benefits of outsourcing to the cloud. [Familiarity]

IAS/Digital Forensics

[Elective]

Topics:

- Basic Principles and methodologies for digital forensics
- Design systems with forensic needs in mind
- Rules of Evidence – general concepts and differences between jurisdictions and Chain of Custody
- Search and Seizure of evidence: legal and procedural requirements
- Digital Evidence methods and standards
- Techniques and standards for Preservation of Data
- Legal and Reporting Issues including working as an expert witness
- OS/File System Forensics
- Application Forensics
- Web Forensics
- Network Forensics
- Mobile Device Forensics
- Computer/network/system attacks
- Attack detection and investigation
- Anti-forensics

Learning outcomes:

1. Describe what a digital investigation is, the sources of digital evidence, and the limitations of forensics. [Familiarity]
2. Explain how to design software to support forensics. [Familiarity]
3. Describe the legal requirements for use of seized data. [Familiarity]
4. Describe the process of evidence seizure from the time when the requirement was identified to the disposition of the data. [Familiarity]
5. Describe how data collection is accomplished and the proper storage of the original and forensics copy. [Familiarity]
6. Conduct data collection on a hard drive. [Usage]
7. Describe a person's responsibility and liability while testifying as a forensics examiner. [Familiarity]
8. Recover data based on a given search term from an imaged system. [Usage]
9. Reconstruct application history from application artifacts. [Usage]
10. Reconstruct web browsing history from web artifacts. [Usage]
11. Capture and interpret network traffic. [Usage]
12. Discuss the challenges associated with mobile device forensics. [Familiarity]
13. Inspect a system (network, computer, or application) for the presence of malware or malicious activity. [Usage]
14. Apply forensics tools to investigate security breaches. [Usage]
15. Identify anti-forensic methods. [Familiarity]

IAS/Secure Software Engineering

[Elective]

Fundamentals of secure coding practices covered in other knowledge areas, including SDF and SE. For example, see SE/Software Construction; Software Verification and Validation.

Topics:

- Building security into the software development lifecycle (cross-reference SE/Software Processes)
- Secure design principles and patterns
- Secure software specifications and requirements
- Secure software development practices (cross-reference SE/Software Construction)
- Secure testing - the process of testing that security requirements are met (including static and dynamic analysis).
- Software quality assurance and benchmarking measurements

Learning outcomes:

1. Describe the requirements for integrating security into the software development lifecycle. [Familiarity]
2. Apply the concepts of the Design Principles for Protection Mechanisms, the Principles for Software Security [2], and the Principles for Secure Design [1] on a software development project. [Usage]
3. Develop specifications for a software development effort that fully specify functional requirements and identifies the expected execution paths. [Usage]
4. Describe software development best practices for minimizing vulnerabilities in programming code. [Familiarity]
5. Conduct a security verification and assessment (static and dynamic) of a software application. [Usage]

References

[1] Gasser, M. *Building a Secure Computer System*, Van Nostrand Reinhold, 1988.

[2] Viega, J. and McGraw, G. *Building Secure Software: How to Avoid Security Problems the Right Way*, Addison-Wesley, 2002.

Information Management (IM)

Information Management is primarily concerned with the capture, digitization, representation, organization, transformation, and presentation of information; algorithms for efficient and effective access and updating of stored information; data modeling and abstraction; and physical file storage techniques. The student needs to be able to develop conceptual and physical data models, determine which IM methods and techniques are appropriate for a given problem, and be able to select and implement an appropriate IM solution that addresses relevant design concerns including scalability, accessibility and usability.

We also note that IM is related to fundamental information security concepts that are described in the Information Assurance and Security (IAS) topic area, IAS/Fundamental Concepts.

IM. Information Management (1 Core-Tier1 hour; 9 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
IM/Information Management Concepts	**1**	**2**	**N**
IM/Database Systems		**3**	**Y**
IM/Data Modeling		**4**	**N**
IM/Indexing			**Y**
IM/Relational Databases			**Y**
IM/Query Languages			**Y**
IM/Transaction Processing			**Y**
IM/Distributed Databases			**Y**
IM/Physical Database Design			**Y**
IM/Data Mining			**Y**
IM/Information Storage And Retrieval			**Y**
IM/MultiMedia Systems			**Y**

IM. Information Management-related topics (distributed) (1 Core-Tier1 hour, 2 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
IAS/Fundamental Concepts*	**1**	**2**	**N**

* See Information Assurance and Security Knowledge Area for a description of this topic area.

IM/Information Management Concepts

[1 Core-Tier1 hour; 2 Core-Tier2 hours]

Topics:

[Core-Tier1]

- Information systems as socio-technical systems
- Basic information storage and retrieval (IS&R) concepts
- Information capture and representation
- Supporting human needs: searching, retrieving, linking, browsing, navigating

[Core-Tier2]

- Information management applications
- Declarative and navigational queries, use of links
- Analysis and indexing
- Quality issues: reliability, scalability, efficiency, and effectiveness

Learning Outcomes:

[Core-Tier1]

1. Describe how humans gain access to information and data to support their needs. [Familiarity]
2. Describe the advantages and disadvantages of central organizational control over data. [Assessment]
3. Identify the careers/roles associated with information management (e.g., database administrator, data modeler, application developer, end-user). [Familiarity]
4. Compare and contrast information with data and knowledge. [Assessment]
5. Demonstrate uses of explicitly stored metadata/schema associated with data. [Usage]
6. Identify issues of data persistence for an organization. [Familiarity]

[Core-Tier2]

7. Critique an information application with regard to satisfying user information needs. [Assessment]
8. Explain uses of declarative queries. [Familiarity]
9. Give a declarative version for a navigational query. [Familiarity]
10. Describe several technical solutions to the problems related to information privacy, integrity, security, and preservation. [Familiarity]
11. Explain measures of efficiency (throughput, response time) and effectiveness (recall, precision). [Familiarity]
12. Describe approaches to scale up information systems. [Familiarity]
13. Identify vulnerabilities and failure scenarios in common forms of information systems. [Usage]

IM/Database Systems

[3 Core-Tier2 hours]

Topics:

[Core-Tier2]

- Approaches to and evolution of database systems
- Components of database systems

- Design of core DBMS functions (e.g., query mechanisms, transaction management, buffer management, access methods)
- Database architecture and data independence
- Use of a declarative query language
- Systems supporting structured and/or stream content

[Elective]

- Approaches for managing large volumes of data (e.g., noSQL database systems, use of MapReduce).

Learning Outcomes:

[Core-Tier2]

1. Explain the characteristics that distinguish the database approach from the approach of programming with data files. [Familiarity]
2. Describe the most common designs for core database system components including the query optimizer, query executor, storage manager, access methods, and transaction processor. [Familiarity]
3. Cite the basic goals, functions, and models of database systems. [Familiarity]
4. Describe the components of a database system and give examples of their use. [Familiarity]
5. Identify major DBMS functions and describe their role in a database system. [Familiarity]
6. Explain the concept of data independence and its importance in a database system. [Familiarity]
7. Use a declarative query language to elicit information from a database. [Usage]
8. Describe facilities that datatbases provide supporting structures and/or stream (sequence) data, e.g., text. [Familiarity]

[Elective]

9. Describe major approaches to storing and processing large volumes of data. [Familiarity]

IM/Data Modeling

[4 Core-Tier2 hours]

Topics:

- Data modeling
- Conceptual models (e.g., entity-relationship, UML diagrams)
- Spreadsheet models
- Relational data models
- Object-oriented models (cross-reference PL/Object-Oriented Programming)
- Semi-structured data model (expressed using DTD or XML Schema, for example)

Learning Outcomes:

1. Compare and contrast appropriate data models, including internal structures, for different types of data. [Assessment]
2. Describe concepts in modeling notation (e.g., Entity-Relation Diagrams or UML) and how they would be used. [Familiarity]
3. Define the fundamental terminology used in the relational data model. [Familiarity]
4. Describe the basic principles of the relational data model. [Familiarity]
5. Apply the modeling concepts and notation of the relational data model. [Usage]
6. Describe the main concepts of the OO model such as object identity, type constructors, encapsulation, inheritance, polymorphism, and versioning. [Familiarity]

7. Describe the differences between relational and semi-structured data models. [Assessment]
8. Give a semi-structured equivalent (e.g., in DTD or XML Schema) for a given relational schema. [Usage]

IM/Indexing

[Elective]

Topics:

- The impact of indices on query performance
- The basic structure of an index
- Keeping a buffer of data in memory
- Creating indexes with SQL
- Indexing text
- Indexing the web (e.g., web crawling)

Learning Outcomes:

1. Generate an index file for a collection of resources. [Usage]
2. Explain the role of an inverted index in locating a document in a collection. [Familiarity]
3. Explain how stemming and stop words affect indexing. [Familiarity]
4. Identify appropriate indices for given relational schema and query set. [Usage]
5. Estimate time to retrieve information, when indices are used compared to when they are not used. [Usage]
6. Describe key challenges in web crawling, e.g., detecting duplicate documents, determining the crawling frontier. [Familiarity]

IM/Relational Databases

[Elective]

Topics:

- Mapping conceptual schema to a relational schema
- Entity and referential integrity
- Relational algebra and relational calculus
- Relational Database design
- Functional dependency
- Decomposition of a schema; lossless-join and dependency-preservation properties of a decomposition
- Candidate keys, superkeys, and closure of a set of attributes
- Normal forms (BCNF)
- Multi-valued dependency (4NF)
- Join dependency (PJNF, 5NF)
- Representation theory

Learning Outcomes:

1. Prepare a relational schema from a conceptual model developed using the entity- relationship model. [Usage]
2. Explain and demonstrate the concepts of entity integrity constraint and referential integrity constraint (including definition of the concept of a foreign key). [Usage]

3. Demonstrate use of the relational algebra operations from mathematical set theory (union, intersection, difference, and Cartesian product) and the relational algebra operations developed specifically for relational databases (select (restrict), project, join, and division). [Usage]
4. Write queries in the relational algebra. [Usage]
5. Write queries in the tuple relational calculus. [Usage]
6. Determine the functional dependency between two or more attributes that are a subset of a relation. [Assessment]
7. Connect constraints expressed as primary key and foreign key, with functional dependencies. [Usage]
8. Compute the closure of a set of attributes under given functional dependencies. [Usage]
9. Determine whether a set of attributes form a superkey and/or candidate key for a relation with given functional dependencies. [Assessment]
10. Evaluate a proposed decomposition, to say whether it has lossless-join and dependency-preservation. [Assessment]
11. Describe the properties of BCNF, PJNF, 5NF. [Familiarity]
12. Explain the impact of normalization on the efficiency of database operations especially query optimization. [Familiarity]
13. Describe what is a multi-valued dependency and what type of constraints it specifies. [Familiarity]

IM/Query Languages

[Elective]

Topics:

- Overview of database languages
- SQL (data definition, query formulation, update sublanguage, constraints, integrity)
- Selections
- Projections
- Select-project-join
- Aggregates and group-by
- Subqueries
- QBE and 4th-generation environments
- Different ways to invoke non-procedural queries in conventional languages
- Introduction to other major query languages (e.g., XPATH, SPARQL)
- Stored procedures

Learning Outcomes:

1. Create a relational database schema in SQL that incorporates key, entity integrity, and referential integrity constraints. [Usage]
2. Use SQL to create tables and retrieve (SELECT) information from a database. [Usage]
3. Evaluate a set of query processing strategies and select the optimal strategy. [Assessment]
4. Create a non-procedural query by filling in templates of relations to construct an example of the desired query result. [Usage]
5. Embed object-oriented queries into a stand-alone language such as C++ or Java (e.g., SELECT Col.Method() FROM Object). [Usage]
6. Write a stored procedure that deals with parameters and has some control flow, to provide a given functionality. [Usage]

IM/Transaction Processing

[Elective]

Topics:

- Transactions
- Failure and recovery
- Concurrency control
- Interaction of transaction management with storage, especially buffering

Learning Outcomes:

1. Create a transaction by embedding SQL into an application program. [Usage]
2. Explain the concept of implicit commits. [Familiarity]
3. Describe the issues specific to efficient transaction execution. [Familiarity]
4. Explain when and why rollback is needed and how logging assures proper rollback. [Assessment]
5. Explain the effect of different isolation levels on the concurrency control mechanisms. [Assessment]
6. Choose the proper isolation level for implementing a specified transaction protocol. [Assessment]
7. Identify appropriate transaction boundaries in application programs. [Assessment]

IM/Distributed Databases

[Elective]

Topics:

- Distributed DBMS
    - Distributed data storage
    - Distributed query processing
    - Distributed transaction model
    - Homogeneous and heterogeneous solutions
    - Client-server distributed databases (cross-reference SF/Computational Paradigms)
- Parallel DBMS
    - Parallel DBMS architectures: shared memory, shared disk, shared nothing;
    - Speedup and scale-up, e.g., use of the MapReduce processing model (cross-reference CN/Processing, PD/Parallel Decomposition)
    - Data replication and weak consistency models

Learning Outcomes:

1. Explain the techniques used for data fragmentation, replication, and allocation during the distributed database design process. [Familiarity]
2. Evaluate simple strategies for executing a distributed query to select the strategy that minimizes the amount of data transfer. [Assessment]
3. Explain how the two-phase commit protocol is used to deal with committing a transaction that accesses databases stored on multiple nodes. [Familiarity]
4. Describe distributed concurrency control based on the distinguished copy techniques and the voting method. [Familiarity]
5. Describe the three levels of software in the client-server model. [Familiarity]

IM/Physical Database Design

[Elective]

Topics:

- Storage and file structure
- Indexed files
- Hashed files
- Signature files
- B-trees
- Files with dense index
- Files with variable length records
- Database efficiency and tuning

Learning Outcomes:

1. Explain the concepts of records, record types, and files, as well as the different techniques for placing file records on disk. [Familiarity]
2. Give examples of the application of primary, secondary, and clustering indexes. [Familiarity]
3. Distinguish between a non-dense index and a dense index. [Assessment]
4. Implement dynamic multilevel indexes using B-trees. [Usage]
5. Explain the theory and application of internal and external hashing techniques. [Familiarity]
6. Use hashing to facilitate dynamic file expansion. [Usage]
7. Describe the relationships among hashing, compression, and efficient database searches. [Familiarity]
8. Evaluate costs and benefits of various hashing schemes. [Assessment]
9. Explain how physical database design affects database transaction efficiency. [Familiarity]

IM/Data Mining

[Elective]

Topics:

- Uses of data mining
- Data mining algorithms
- Associative and sequential patterns
- Data clustering
- Market basket analysis
- Data cleaning
- Data visualization (cross-reference GV/Visualization and CN/Interactive Visualization)

Learning Outcomes:

1. Compare and contrast different uses of data mining as evidenced in both research and application. [Assessment]
2. Explain the value of finding associations in market basket data. [Familiarity]
3. Characterize the kinds of patterns that can be discovered by association rule mining. [Assessment]
4. Describe how to extend a relational system to find patterns using association rules. [Familiarity]
5. Evaluate different methodologies for effective application of data mining. [Assessment]
6. Identify and characterize sources of noise, redundancy, and outliers in presented data. [Assessment]
7. Identify mechanisms (on-line aggregation, anytime behavior, interactive visualization) to close the loop in the data mining process. [Familiarity]
8. Describe why the various close-the-loop processes improve the effectiveness of data mining. [Familiarity]

IM/Information Storage and Retrieval

[Elective]

Topics:

- Documents, electronic publishing, markup, and markup languages
- Tries, inverted files, PAT trees, signature files, indexing
- Morphological analysis, stemming, phrases, stop lists
- Term frequency distributions, uncertainty, fuzziness, weighting
- Vector space, probabilistic, logical, and advanced models
- Information needs, relevance, evaluation, effectiveness
- Thesauri, ontologies, classification and categorization, metadata
- Bibliographic information, bibliometrics, citations
- Routing and (community) filtering
- Multimedia search, information seeking behavior, user modeling, feedback
- Information summarization and visualization
- Faceted search (e.g., using citations, keywords, classification schemes)
- Digital libraries
- Digitization, storage, interchange, digital objects, composites, and packages
- Metadata and cataloging
- Naming, repositories, archives
- Archiving and preservation, integrity
- Spaces (conceptual, geographical, 2/3D, VR)
- Architectures (agents, buses, wrappers/mediators), interoperability
- Services (searching, linking, browsing, and so forth)
- Intellectual property rights management, privacy, and protection (watermarking)

Learning Outcomes:

1. Explain basic information storage and retrieval concepts. [Familiarity]
2. Describe what issues are specific to efficient information retrieval. [Familiarity]
3. Give applications of alternative search strategies and explain why the particular search strategy is appropriate for the application. [Assessment]
4. Design and implement a small to medium size information storage and retrieval system, or digital library. [Usage]
5. Describe some of the technical solutions to the problems related to archiving and preserving information in a digital library. [Familiarity]

IM/Multimedia Systems

[Elective]

Topics:

- Input and output devices, device drivers, control signals and protocols, DSPs
- Standards (e.g., audio, graphics, video)
- Applications, media editors, authoring systems, and authoring
- Streams/structures, capture/represent/transform, spaces/domains, compression/coding
- Content-based analysis, indexing, and retrieval of audio, images, animation, and video

- Presentation, rendering, synchronization, multi-modal integration/interfaces
- Real-time delivery, quality of service (including performance), capacity planning, audio/video conferencing, video-on-demand

Learning Outcomes:

1. Describe the media and supporting devices commonly associated with multimedia information and systems. [Familiarity]
2. Demonstrate the use of content-based information analysis in a multimedia information system. [Usage]
3. Critique multimedia presentations in terms of their appropriate use of audio, video, graphics, color, and other information presentation concepts. [Assessment]
4. Implement a multimedia application using an authoring system. [Usage]
5. For each of several media or multimedia standards, describe in non-technical language what the standard calls for, and explain how aspects of human perception might be sensitive to the limitations of that standard. [Familiarity]
6. Describe the characteristics of a computer system (including identification of support tools and appropriate standards) that has to host the implementation of one of a range of possible multimedia applications. [Familiarity]

Intelligent Systems (IS)

Artificial intelligence (AI) is the study of solutions for problems that are difficult or impractical to solve with traditional methods. It is used pervasively in support of everyday applications such as email, word-processing and search, as well as in the design and analysis of autonomous agents that perceive their environment and interact rationally with the environment.

The solutions rely on a broad set of general and specialized knowledge representation schemes, problem solving mechanisms and learning techniques. They deal with sensing (e.g., speech recognition, natural language understanding, computer vision), problem-solving (e.g., search, planning), and acting (e.g., robotics) and the architectures needed to support them (e.g., agents, multi-agents). The study of Artificial Intelligence prepares the student to determine when an AI approach is appropriate for a given problem, identify the appropriate representation and reasoning mechanism, and implement and evaluate it.

IS. Intelligent Systems (10 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
IS/Fundamental Issues		**1**	**Y**
IS/Basic Search Strategies		**4**	**N**
IS/Basic Knowledge Representation and Reasoning		**3**	**N**
IS/Basic Machine Learning		**2**	**N**
IS/Advanced Search			**Y**
IS/Advanced Representation and Reasoning			**Y**
IS/Reasoning Under Uncertainty			**Y**
IS/Agents			**Y**
IS/Natural Language Processing			**Y**
IS/Advanced Machine Learning			**Y**
IS/Robotics			**Y**
IS/Perception and Computer Vision			**Y**

IS/Fundamental Issues

[1 Core-Tier2 hours]

Topics:

- Overview of AI problems, examples of successful recent AI applications
- What is intelligent behavior?
    - The Turing test
    - Rational versus non-rational reasoning
- Problem characteristics
    - Fully versus partially observable
    - Single versus multi-agent
    - Deterministic versus stochastic
    - Static versus dynamic
    - Discrete versus continuous
- Nature of agents
    - Autonomous versus semi-autonomous
    - Reflexive, goal-based, and utility-based
    - The importance of perception and environmental interactions
- Philosophical and ethical issues. [elective]

Learning Outcomes:

1. Describe Turing test and the "Chinese Room" thought experiment. [Familiarity]
2. Differentiate between the concepts of optimal reasoning/behavior and human-like reasoning/behavior. [Familiarity]
3. Determine the characteristics of a given problem that an intelligent system must solve. [Assessment]

IS/Basic Search Strategies

[4 Core-Tier2 hours]

Cross-reference AL/Basic Analysis, AL/Algorithmic Strategies, AL/Fundamental Data Structures and Algorithms

Topics:

- Problem spaces (states, goals and operators), problem solving by search
- Factored representation (factoring state into variables)
- Uninformed search (breadth-first, depth-first, depth-first with iterative deepening)
- Heuristics and informed search (hill-climbing, generic best-first, A*)
- Space and time efficiency of search
- Two-player games (introduction to minimax search)
- Constraint satisfaction (backtracking and local search methods)

Learning Outcomes:

1. Formulate an efficient problem space for a problem expressed in natural language (e.g., English) in terms of initial and goal states, and operators. [Usage]
2. Describe the role of heuristics and describe the trade-offs among completeness, optimality, time complexity, and space complexity. [Familiarity]
3. Describe the problem of combinatorial explosion of search space and its consequences. [Familiarity]
4. Select and implement an appropriate uninformed search algorithm for a problem, and characterize its time and space complexities. [Usage]
5. Select and implement an appropriate informed search algorithm for a problem by designing the necessary heuristic evaluation function. [Usage]
6. Evaluate whether a heuristic for a given problem is admissible/can guarantee optimal solution. [Assessment]
7. Formulate a problem specified in natural language (e.g., English) as a constraint satisfaction problem and implement it using a chronological backtracking algorithm or stochastic local search. [Usage]
8. Compare and contrast basic search issues with game playing issues. [Familiarity]

IS/Basic Knowledge Representation and Reasoning

[3 Core-Tier2 hours]

Topics:

- Review of propositional and predicate logic (cross-reference DS/Basic Logic)
- Resolution and theorem proving (propositional logic only)
- Forward chaining, backward chaining
- Review of probabilistic reasoning, Bayes theorem (cross-reference with DS/Discrete Probability)

Learning Outcomes:

1. Translate a natural language (e.g., English) sentence into predicate logic statement. [Usage]
2. Convert a logic statement into clause form. [Usage]
3. Apply resolution to a set of logic statements to answer a query. [Usage]
4. Make a probabilistic inference in a real-world problem using Bayes' theorem to determine the probability of a hypothesis given evidence. [Usage]

IS/Basic Machine Learning

[2 Core-Tier2 hours]

Topics:

- Definition and examples of broad variety of machine learning tasks, including classification
- Inductive learning
- Simple statistical-based learning, such as Naive Bayesian Classifier, decision trees
- The over-fitting problem
- Measuring classifier accuracy

Learning Outcomes:

1. List the differences among the three main styles of learning: supervised, reinforcement, and unsupervised. [Familiarity]
2. Identify examples of classification tasks, including the available input features and output to be predicted. [Familiarity]
3. Explain the difference between inductive and deductive learning. [Familiarity]

4. Describe over-fitting in the context of a problem. [Familiarity]
5. Apply the simple statistical learning algorithm such as Naive Bayesian Classifier to a classification task and measure the classifier's accuracy. [Usage]

IS/Advanced Search

[Elective]

Note that the general topics of Branch-and-bound and Dynamic Programing are listed in AL/Algorithmic Strategies.

Topics:

- Constructing search trees, dynamic search space, combinatorial explosion of search space
- Stochastic search
    - Simulated annealing
    - Genetic algorithms
    - Monte-Carlo tree search
- Implementation of A* search, beam search
- Minimax search, alpha-beta pruning
- Expectimax search (MDP-solving) and chance nodes

Learning Outcomes:

1. Design and implement a genetic algorithm solution to a problem. [Usage]
2. Design and implement a simulated annealing schedule to avoid local minima in a problem. [Usage]
3. Design and implement A*/beam search to solve a problem. [Usage]
4. Apply minimax search with alpha-beta pruning to prune search space in a two-player game. [Usage]
5. Compare and contrast genetic algorithms with classic search techniques. [Assessment]
6. Compare and contrast various heuristic searches vis-a-vis applicability to a given problem. [Assessment]

IS/Advanced Representation and Reasoning

[Elective]

Topics:

- Knowledge representation issues
    - Description logics
    - Ontology engineering
- Non-monotonic reasoning (e.g., non-classical logics, default reasoning)
- Argumentation
- Reasoning about action and change (e.g., situation and event calculus)
- Temporal and spatial reasoning
- Rule-based Expert Systems
- Semantic networks
- Model-based and Case-based reasoning
- Planning:
    - Partial and totally ordered planning
    - Plan graphs
    - Hierarchical planning
    - Planning and execution including conditional planning and continuous planning
    - Mobile agent/Multi-agent planning

Learning Outcomes:

1. Compare and contrast the most common models used for structured knowledge representation, highlighting their strengths and weaknesses. [Assessment]
2. Identify the components of non-monotonic reasoning and its usefulness as a representational mechanism for belief systems. [Familiarity]
3. Compare and contrast the basic techniques for representing uncertainty. [Assessment]
4. Compare and contrast the basic techniques for qualitative representation. [Assessment]
5. Apply situation and event calculus to problems of action and change. [Usage]
6. Explain the distinction between temporal and spatial reasoning, and how they interrelate. [Familiarity]
7. Explain the difference between rule-based, case-based and model-based reasoning techniques. [Familiarity]
8. Define the concept of a planning system and how it differs from classical search techniques. [Familiarity]
9. Describe the differences between planning as search, operator-based planning, and propositional planning, providing examples of domains where each is most applicable. [Familiarity]
10. Explain the distinction between monotonic and non-monotonic inference. [Familiarity]

IS/Reasoning Under Uncertainty

[Elective]

Topics:

- Review of basic probability (cross-reference DS/Discrete Probability)
- Random variables and probability distributions
    - Axioms of probability
    - Probabilistic inference
    - Bayes' Rule
- Conditional Independence
- Knowledge representations
    - Bayesian Networks
        - Exact inference and its complexity
        - Randomized sampling (Monte Carlo) methods (e.g. Gibbs sampling)
    - Markov Networks
    - Relational probability models
    - Hidden Markov Models
- Decision Theory
    - Preferences and utility functions
    - Maximizing expected utility

Learning Outcomes:

1. Apply Bayes' rule to determine the probability of a hypothesis given evidence. [Usage]
2. Explain how conditional independence assertions allow for greater efficiency of probabilistic systems. [Assessment]
3. Identify examples of knowledge representations for reasoning under uncertainty. [Familiarity]
4. State the complexity of exact inference. Identify methods for approximate inference. [Familiarity]
5. Design and implement at least one knowledge representation for reasoning under uncertainty. [Usage]
6. Describe the complexities of temporal probabilistic reasoning. [Familiarity]
7. Design and implement an HMM as one example of a temporal probabilistic system. [Usage]
8. Describe the relationship between preferences and utility functions. [Familiarity]
9. Explain how utility functions and probabilistic reasoning can be combined to make rational decisions. [Assessment]

IS/Agents

[Elective]

Cross-reference HCI/Collaboration and Communication

Topics:

- Definitions of agents
- Agent architectures (e.g., reactive, layered, cognitive)
- Agent theory
- Rationality, game theory
    - Decision-theoretic agents
    - Markov decision processes (MDP)
- Software agents, personal assistants, and information access
    - Collaborative agents
    - Information-gathering agents
    - Believable agents (synthetic characters, modeling emotions in agents)
- Learning agents
- Multi-agent systems
    - Collaborating agents
    - Agent teams
    - Competitive agents (e.g., auctions, voting)
    - Swarm systems and biologically inspired models

Learning Outcomes:

1. List the defining characteristics of an intelligent agent. [Familiarity]
2. Characterize and contrast the standard agent architectures. [Assessment]
3. Describe the applications of agent theory to domains such as software agents, personal assistants, and believable agents. [Familiarity]
4. Describe the primary paradigms used by learning agents. [Familiarity]
5. Demonstrate using appropriate examples how multi-agent systems support agent interaction. [Usage]

IS/Natural Language Processing

[Elective]

Cross-reference HCI/New Interactive Technologies

Topics:

- Deterministic and stochastic grammars
- Parsing algorithms
    - CFGs and chart parsers (e.g. CYK)
    - Probabilistic CFGs and weighted CYK
- Representing meaning / Semantics
    - Logic-based knowledge representations
    - Semantic roles
    - Temporal representations
    - Beliefs, desires, and intentions
- Corpus-based methods
- N-grams and HMMs
- Smoothing and backoff

- Examples of use: POS tagging and morphology
- Information retrieval (Cross-reference IM/Information Storage and Retrieval)
    - Vector space model
        - TF & IDF
    - Precision and recall
- Information extraction
- Language translation
- Text classification, categorization
    - Bag of words model

Learning Outcomes:

1. Define and contrast deterministic and stochastic grammars, providing examples to show the adequacy of each. [Assessment]
2. Simulate, apply, or implement classic and stochastic algorithms for parsing natural language. [Usage]
3. Identify the challenges of representing meaning. [Familiarity]
4. List the advantages of using standard corpora. Identify examples of current corpora for a variety of NLP tasks. [Familiarity]
5. Identify techniques for information retrieval, language translation, and text classification. [Familiarity]

IS/Advanced Machine Learning

[Elective]

Topics:

- Definition and examples of broad variety of machine learning tasks
- General statistical-based learning, parameter estimation (maximum likelihood)
- Inductive logic programming (ILP)
- Supervised learning
    - Learning decision trees
    - Learning neural networks
    - Support vector machines (SVMs)
- Ensembles
- Nearest-neighbor algorithms
- Unsupervised Learning and clustering
    - EM
    - K-means
    - Self-organizing maps
- Semi-supervised learning
- Learning graphical models (Cross-reference IS/Reasoning under Uncertainty)
- Performance evaluation (such as cross-validation, area under ROC curve)
- Learning theory
- The problem of overfitting, the curse of dimensionality
- Reinforcement learning
    - Exploration vs. exploitation trade-off
    - Markov decision processes
    - Value and policy iteration
- Application of Machine Learning algorithms to Data Mining (cross-reference IM/Data Mining)

Learning Outcomes:

1. Explain the differences among the three main styles of learning: supervised, reinforcement, and unsupervised. [Familiarity]
2. Implement simple algorithms for supervised learning, reinforcement learning, and unsupervised learning. [Usage]
3. Determine which of the three learning styles is appropriate to a particular problem domain. [Usage]
4. Compare and contrast each of the following techniques, providing examples of when each strategy is superior: decision trees, neural networks, and belief networks. [Assessment]
5. Evaluate the performance of a simple learning system on a real-world dataset. [Assessment]
6. Characterize the state of the art in learning theory, including its achievements and its shortcomings. [Familiarity]
7. Explain the problem of overfitting, along with techniques for detecting and managing the problem. [Usage]

IS/Robotics

[Elective]

Topics:

- Overview: problems and progress
    - State-of-the-art robot systems, including their sensors and an overview of their sensor processing
    - Robot control architectures, e.g., deliberative vs. reactive control and Braitenberg vehicles
    - World modeling and world models
    - Inherent uncertainty in sensing and in control
- Configuration space and environmental maps
- Interpreting uncertain sensor data
- Localizing and mapping
- Navigation and control
- Motion planning
- Multiple-robot coordination

Learning Outcomes:

1. List capabilities and limitations of today's state-of-the-art robot systems, including their sensors and the crucial sensor processing that informs those systems. [Familiarity]
2. Integrate sensors, actuators, and software into a robot designed to undertake some task. [Usage]
3. Program a robot to accomplish simple tasks using deliberative, reactive, and/or hybrid control architectures. [Usage]
4. Implement fundamental motion planning algorithms within a robot configuration space. [Usage]
5. Characterize the uncertainties associated with common robot sensors and actuators; articulate strategies for mitigating these uncertainties. [Familiarity]
6. List the differences among robots' representations of their external environment, including their strengths and shortcomings. [Familiarity]
7. Compare and contrast at least three strategies for robot navigation within known and/or unknown environments, including their strengths and shortcomings. [Assessment]
8. Describe at least one approach for coordinating the actions and sensing of several robots to accomplish a single task. [Familiarity]

IS/Perception and Computer Vision

[Elective]

Topics:

- Computer vision
    - Image acquisition, representation, processing and properties
    - Shape representation, object recognition and segmentation
    - Motion analysis
- Audio and speech recognition
- Modularity in recognition
- Approaches to pattern recognition (cross-reference IS/Advanced Machine Learning)
    - Classification algorithms and measures of classification quality
    - Statistical techniques

Learning Outcomes:

1. Summarize the importance of image and object recognition in AI and indicate several significant applications of this technology. [Familiarity]
2. List at least three image-segmentation approaches, such as thresholding, edge-based and region-based algorithms, along with their defining characteristics, strengths, and weaknesses. [Familiarity]
3. Implement 2d object recognition based on contour- and/or region-based shape representations. [Usage]
4. Distinguish the goals of sound-recognition, speech-recognition, and speaker-recognition and identify how the raw audio signal will be handled differently in each of these cases. [Familiarity]
5. Provide at least two examples of a transformation of a data source from one sensory domain to another, e.g., tactile data interpreted as single-band 2d images. [Familiarity]
6. Implement a feature-extraction algorithm on real data, e.g., an edge or corner detector for images or vectors of Fourier coefficients describing a short slice of audio signal. [Usage]
7. Implement an algorithm combining features into higher-level percepts, e.g., a contour or polygon from visual primitives or phoneme hypotheses from an audio signal. [Usage]
8. Implement a classification algorithm that segments input percepts into output categories and quantitatively evaluates the resulting classification. [Usage]
9. Evaluate the performance of the underlying feature-extraction, relative to at least one alternative possible approach (whether implemented or not) in its contribution to the classification task (8), above. [Assessment]
10. Describe at least three classification approaches, their prerequisites for applicability, their strengths, and their shortcomings. [Familiarity]

Networking and Communication (NC)

The Internet and computer networks are now ubiquitous and a growing number of computing activities strongly depend on the correct operation of the underlying network. Networks, both fixed and mobile, are a key part of the computing environment of today and tomorrow. Many computing applications that are used today would not be possible without networks. This dependency on the underlying network is likely to increase in the future.

The high-level learning objective of this module can be summarized as follows:

- Thinking in a networked world. The world is more and more interconnected and the use of networks will continue to increase. Students must understand how the networks behave and the key principles behind the organization and operation of the networks.
- Continued study. The networking domain is rapidly evolving and a first networking course should be a starting point to other more advanced courses on network design, network management, sensor networks, etc.
- Principles and practice interact. Networking is real and many of the design choices that involve networks also depend on practical constraints. Students should be exposed to these practical constraints by experimenting with networking, using tools, and writing networked software.

There are different ways of organizing a networking course. Some educators prefer a top-down approach, i.e., the course starts from the applications and then explains reliable delivery, routing and forwarding. Other educators prefer a bottom-up approach where the students start with the lower layers and build their understanding of the network, transport and application layers later.

NC. Networking and Communication (3 Core-Tier1 hours, 7 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
NC/Introduction	**1.5**		**N**
NC/Networked Applications	**1.5**		**N**
NC/Reliable Data Delivery		**2**	**N**
NC/Routing And Forwarding		**1.5**	**N**
NC/Local Area Networks		**1.5**	**N**
NC/Resource Allocation		**1**	**N**
NC/Mobility		**1**	**N**
NC/Social Networking			**Y**

NC/Introduction

[1.5 Core-Tier1 hours]

Cross-reference IAS/Network Security, which discusses network security and its applications.

Topics:

- Organization of the Internet (Internet Service Providers, Content Providers, etc.)
- Switching techniques (e.g., circuit, packet)
- Physical pieces of a network, including hosts, routers, switches, ISPs, wireless, LAN, access point, and firewalls
- Layering principles (encapsulation, multiplexing)
- Roles of the different layers (application, transport, network, datalink, physical)

Learning Outcomes:

1. Articulate the organization of the Internet. [Familiarity]
2. List and define the appropriate network terminology. [Familiarity]
3. Describe the layered structure of a typical networked architecture. [Familiarity]
4. Identify the different types of complexity in a network (edges, core, etc.). [Familiarity]

NC/Networked Applications

[1.5 Core-Tier1 hours]

Topics:

- Naming and address schemes (DNS, IP addresses, Uniform Resource Identifiers, etc.)
- Distributed applications (client/server, peer-to-peer, cloud, etc.)
- HTTP as an application layer protocol
- Multiplexing with TCP and UDP
- Socket APIs

Learning Outcomes:

1. List the differences and the relations between names and addresses in a network. [Familiarity]
2. Define the principles behind naming schemes and resource location. [Familiarity]
3. Implement a simple client-server socket-based application. [Usage]

NC/Reliable Data Delivery

[2 Core-Tier2 hours]

This knowledge unit is related to Systems Fundamentals (SF). Cross-reference SF/State and State Machines and SF/Reliability through Redundancy.

Topics:

- Error control (retransmission techniques, timers)
- Flow control (acknowledgements, sliding window)
- Performance issues (pipelining)
- TCP

Learning Outcomes:

1. Describe the operation of reliable delivery protocols. [Familiarity]
2. List the factors that affect the performance of reliable delivery protocols. [Familiarity]
3. Design and implement a simple reliable protocol. [Usage]

NC/Routing and Forwarding

[1.5 Core-Tier2 hours]

Topics:

- Routing versus forwarding
- Static routing
- Internet Protocol (IP)
- Scalability issues (hierarchical addressing)

Learning Outcomes:

1. Describe the organization of the network layer. [Familiarity]
2. Describe how packets are forwarded in an IP network. [Familiarity]
3. List the scalability benefits of hierarchical addressing. [Familiarity]

NC/Local Area Networks

[1.5 Core-Tier2 hours]

Topics:

- Multiple Access Problem
- Common approaches to multiple access (exponential-backoff, time division multiplexing, etc)
- Local Area Networks
- Ethernet
- Switching

Learning Outcomes:

1. Describe how frames are forwarded in an Ethernet network. [Familiarity]
2. Describe the differences between IP and Ethernet. [Familiarity]
3. Describe the interrelations between IP and Ethernet. [Familiarity]
4. Describe the steps used in one common approach to the multiple access problem. [Familiarity]

NC/Resource Allocation

[1 Core-Tier2 hours]

Topics:

- Need for resource allocation
- Fixed allocation (TDM, FDM, WDM) versus dynamic allocation
- End-to-end versus network assisted approaches
- Fairness
- Principles of congestion control
- Approaches to Congestion (e.g., Content Distribution Networks)

Learning Outcomes:

1. Describe how resources can be allocated in a network. [Familiarity]
2. Describe the congestion problem in a large network. [Familiarity]
3. Compare and contrast fixed and dynamic allocation techniques. [Assessment]
4. Compare and contrast current approaches to congestion. [Assessment]

NC/Mobility

[1 Core-Tier2 hours]

Topics:

- Principles of cellular networks
- 802.11 networks
- Issues in supporting mobile nodes (home agents)

Learning Outcomes:

1. Describe the organization of a wireless network. [Familiarity]
2. Describe how wireless networks support mobile users. [Familiarity]

NC/Social Networking

[Elective]

Topics:

- Social networks overview
- Example social network platforms
- Structure of social network graphs
- Social network analysis

Learning Outcomes:

1. Discuss the key principles (such as membership, trust) of social networking. [Familiarity]
2. Describe how existing social networks operate. [Familiarity]
3. Construct a social network graph from network data. [Usage]
4. Analyze a social network to determine who the key people are. [Usage]
5. Evaluate a given interpretation of a social network question with associated data. [Assessment]

Operating Systems (OS)

An operating system defines an abstraction of hardware and manages resource sharing among the computer's users. The topics in this area explain the most basic knowledge of operating systems in the sense of interfacing an operating system to networks, teaching the difference between the kernel and user modes, and developing key approaches to operating system design and implementation. This knowledge area is structured to be complementary to the Systems Fundamentals (SF), Networking and Communication (NC), Information Assurance and Security (IAS), and the Parallel and Distributed Computing (PD) knowledge areas. The Systems Fundamentals and Information Assurance and Security knowledge areas are the new ones to include contemporary issues. For example, Systems Fundamentals includes topics such as performance, virtualization and isolation, and resource allocation and scheduling; Parallel and Distributed Systems includes parallelism fundamentals; and and Information Assurance and Security includes forensics and security issues in depth. Many courses in Operating Systems will draw material from across these knowledge areas.

OS. Operating Systems (4 Core-Tier1 hours; 11 Core Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
OS/Overview of Operating Systems	**2**		**N**
OS/Operating System Principles	**2**		**N**
OS/Concurrency		**3**	**N**
OS/Scheduling and Dispatch		**3**	**N**
OS/Memory Management		**3**	**N**
OS/Security and Protection		**2**	**N**
OS/Virtual Machines			**Y**
OS/Device Management			**Y**
OS/File Systems			**Y**
OS/Real Time and Embedded Systems			**Y**
OS/Fault Tolerance			**Y**
OS/System Performance Evaluation			**Y**

OS/Overview of Operating Systems

[2 Core-Tier1 hours]

Topics:

- Role and purpose of the operating system
- Functionality of a typical operating system
- Mechanisms to support client-server models, hand-held devices
- Design issues (efficiency, robustness, flexibility, portability, security, compatibility)
- Influences of security, networking, multimedia, windowing systems

Learning Outcomes:

1. Explain the objectives and functions of modern operating systems. [Familiarity]
2. Analyze the tradeoffs inherent in operating system design. [Usage]
3. Describe the functions of a contemporary operating system with respect to convenience, efficiency, and the ability to evolve. [Familiarity]
4. Discuss networked, client-server, distributed operating systems and how they differ from single user operating systems. [Familiarity]
5. Identify potential threats to operating systems and the security features design to guard against them. [Familiarity]

OS/Operating System Principles

[2 Core-Tier1 hours]

Topics:

- Structuring methods (monolithic, layered, modular, micro-kernel models)
- Abstractions, processes, and resources
- Concepts of application program interfaces (APIs)
- The evolution of hardware/software techniques and application needs
- Device organization
- Interrupts: methods and implementations
- Concept of user/system state and protection, transition to kernel mode

Learning Outcomes:

1. Explain the concept of a logical layer. [Familiarity]
2. Explain the benefits of building abstract layers in hierarchical fashion. [Familiarity]
3. Describe the value of APIs and middleware. [Assessment]
4. Describe how computing resources are used by application software and managed by system software. [Familiarity]
5. Contrast kernel and user mode in an operating system. [Usage]
6. Discuss the advantages and disadvantages of using interrupt processing. [Familiarity]
7. Explain the use of a device list and driver I/O queue. [Familiarity]

OS/Concurrency

[3 Core-Tier2 hours]

Topics:

- States and state diagrams (cross-reference SF/State and State Machines)
- Structures (ready list, process control blocks, and so forth)
- Dispatching and context switching
- The role of interrupts
- Managing atomic access to OS objects
- Implementing synchronization primitives
- Multiprocessor issues (spin-locks, reentrancy) (cross-reference SF/Parallelism)

Learning Outcomes:

1. Describe the need for concurrency within the framework of an operating system. [Familiarity]
2. Demonstrate the potential run-time problems arising from the concurrent operation of many separate tasks. [Usage]
3. Summarize the range of mechanisms that can be employed at the operating system level to realize concurrent systems and describe the benefits of each. [Familiarity]
4. Explain the different states that a task may pass through and the data structures needed to support the management of many tasks. [Familiarity]
5. Summarize techniques for achieving synchronization in an operating system (e.g., describe how to implement a semaphore using OS primitives). [Familiarity]
6. Describe reasons for using interrupts, dispatching, and context switching to support concurrency in an operating system. [Familiarity]
7. Create state and transition diagrams for simple problem domains. [Usage]

OS/Scheduling and Dispatch

[3 Core-Tier2 hours]

Topics:

- Preemptive and non-preemptive scheduling (cross-reference SF/Resource Allocation and Scheduling, PD/Parallel Performance)
- Schedulers and policies (cross-reference SF/Resource Allocation and Scheduling, PD/Parallel Performance)
- Processes and threads (cross-reference SF/Computational paradigms)
- Deadlines and real-time issues

Learning Outcomes:

1. Compare and contrast the common algorithms used for both preemptive and non-preemptive scheduling of tasks in operating systems, such as priority, performance comparison, and fair-share schemes. [Usage]
2. Describe relationships between scheduling algorithms and application domains. [Familiarity]
3. Discuss the types of processor scheduling such as short-term, medium-term, long-term, and I/O. [Familiarity]
4. Describe the difference between processes and threads. [Usage]
5. Compare and contrast static and dynamic approaches to real-time scheduling. [Usage]
6. Discuss the need for preemption and deadline scheduling. [Familiarity]
7. Identify ways that the logic embodied in scheduling algorithms are applicable to other domains, such as disk I/O, network scheduling, project scheduling, and problems beyond computing. [Usage]

OS/Memory Management

[3 Core-Tier2 hours]

Topics:

- Review of physical memory and memory management hardware
- Working sets and thrashing
- Caching (cross-reference AR/Memory System Organization and Architecture)

Learning Outcomes:

1. Explain memory hierarchy and cost-performance trade-offs. [Familiarity]
2. Summarize the principles of virtual memory as applied to caching and paging. [Familiarity]
3. Evaluate the trade-offs in terms of memory size (main memory, cache memory, auxiliary memory) and processor speed. [Assessment]
4. Defend the different ways of allocating memory to tasks, citing the relative merits of each. [Assessment]
5. Describe the reason for and use of cache memory (performance and proximity, different dimension of how caches complicate isolation and VM abstraction). [Familiarity]
6. Discuss the concept of thrashing, both in terms of the reasons it occurs and the techniques used to recognize and manage the problem. [Familiarity]

OS/Security and Protection

[2 Core-Tier2 hours]

Topics:

- Overview of system security
- Policy/mechanism separation
- Security methods and devices
- Protection, access control, and authentication
- Backups

Learning Outcomes:

1. Articulate the need for protection and security in an OS (cross-reference IAS/Security Architecture and Systems Administration/Investigating Operating Systems Security for various systems). [Assessment]
2. Summarize the features and limitations of an operating system used to provide protection and security (cross-reference IAS/Security Architecture and Systems Administration). [Familiarity]
3. Explain the mechanisms available in an OS to control access to resources (cross-reference IAS/Security Architecture and Systems Administration/Access Control/Configuring systems to operate securely as an IT system). [Familiarity]
4. Carry out simple system administration tasks according to a security policy, for example creating accounts, setting permissions, applying patches, and arranging for regular backups (cross-reference IAS/Security Architecture and Systems Administration). [Usage]

OS/Virtual Machines

[Elective]

Topics:

- Types of virtualization (including Hardware/Software, OS, Server, Service, Network)
- Paging and virtual memory
- Virtual file systems
- Hypervisors
- Portable virtualization; emulation vs. isolation
- Cost of virtualization

Learning Outcomes:

1. Explain the concept of virtual memory and how it is realized in hardware and software. [Familiarity]
5. Differentiate emulation and isolation. [Familiarity]
6. Evaluate virtualization trade-offs. [Assessment]
2. Discuss hypervisors and the need for them in conjunction with different types of hypervisors. [Usage]

OS/Device Management

[Elective]

Topics:

- Characteristics of serial and parallel devices
- Abstracting device differences
- Buffering strategies
- Direct memory access
- Recovery from failures

Learning Outcomes:

1. Explain the key difference between serial and parallel devices and identify the conditions in which each is appropriate. [Familiarity]
2. Identify the relationship between the physical hardware and the virtual devices maintained by the operating system. [Usage]
3. Explain buffering and describe strategies for implementing it. [Familiarity]
4. Differentiate the mechanisms used in interfacing a range of devices (including hand-held devices, networks, multimedia) to a computer and explain the implications of these for the design of an operating system. [Usage]
5. Describe the advantages and disadvantages of direct memory access and discuss the circumstances in which its use is warranted. [Usage]
6. Identify the requirements for failure recovery. [Familiarity]
7. Implement a simple device driver for a range of possible devices. [Usage]

OS/File Systems

[Elective]

Topics:

- Files: data, metadata, operations, organization, buffering, sequential, nonsequential
- Directories: contents and structure
- File systems: partitioning, mount/unmount, virtual file systems
- Standard implementation techniques
- Memory-mapped files
- Special-purpose file systems
- Naming, searching, access, backups
- Journaling and log-structured file systems

Learning Outcomes:

1. Describe the choices to be made in designing file systems. [Familiarity]
2. Compare and contrast different approaches to file organization, recognizing the strengths and weaknesses of each. [Usage]
3. Summarize how hardware developments have led to changes in the priorities for the design and the management of file systems. [Familiarity]
4. Summarize the use of journaling and how log-structured file systems enhance fault tolerance. [Familiarity]

OS/Real Time and Embedded Systems

[Elective]

Topics:

- Process and task scheduling
- Memory/disk management requirements in a real-time environment
- Failures, risks, and recovery
- Special concerns in real-time systems

Learning Outcomes:

1. Describe what makes a system a real-time system. [Familiarity]
2. Explain the presence of and describe the characteristics of latency in real-time systems. [Familiarity]
3. Summarize special concerns that real-time systems present, including risk, and how these concerns are addressed. [Familiarity]

OS/Fault Tolerance

[Elective]

Topics:

- Fundamental concepts: reliable and available systems (cross-reference SF/Reliability through Redundancy)
- Spatial and temporal redundancy (cross-reference SF/Reliability through Redundancy)
- Methods used to implement fault tolerance
- Examples of OS mechanisms for detection, recovery, restart to implement fault tolerance, use of these techniques for the OS's own services

Learning Outcomes:

1. Explain the relevance of the terms fault tolerance, reliability, and availability. [Familiarity]
2. Outline the range of methods for implementing fault tolerance in an operating system. [Familiarity]
3. Explain how an operating system can continue functioning after a fault occurs. [Familiarity]

OS/System Performance Evaluation

[Elective]

Topics:

- Why system performance needs to be evaluated (cross-reference SF/Performance/Figures of performance merit)
- What is to be evaluated (cross-reference SF/Performance/Figures of performance merit)
- Systems performance policies, e.g., caching, paging, scheduling, memory management, and security
- Evaluation models: deterministic, analytic, simulation, or implementation-specific
- How to collect evaluation data (profiling and tracing mechanisms)

Learning Outcomes:

1. Describe the performance measurements used to determine how a system performs. [Familiarity]
2. Explain the main evaluation models used to evaluate a system. [Familiarity]

Platform-Based Development (PBD)

Platform-based development is concerned with the design and development of software applications that reside on specific software platforms. In contrast to general purpose programming, platform-based development takes into account platform-specific constraints. For instance web programming, multimedia development, mobile computing, app development, and robotics are examples of relevant platforms that provide specific services/APIs/hardware that constrain development. Such platforms are characterized by the use of specialized APIs, distinct delivery/update mechanisms, and being abstracted away from the machine level. Platform-based development may be applied over a wide breadth of ecosystems.

While we recognize that some platforms (e.g., web development) are prominent, we are also cognizant of the fact that no particular platform should be specified as a requirement in the CS2013 curricular guidelines. Consequently, this Knowledge Area highlights many of the platforms that have become popular, without including any such platform in the core curriculum. We note that the general skill of developing with respect to an API or a constrained environment is covered in other Knowledge Areas, such as Software Development Fundamentals (SDF). Platform-based development further emphasizes such general skills within the context of particular platforms.

PBD. Platform-Based Development (Elective)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
PBD/Introduction			**Y**
PBD/Web Platforms			**Y**
PBD/Mobile Platforms			**Y**
PBD/Industrial Platforms			**Y**
PBD/Game Platforms			**Y**

PBD/Introduction

[Elective]

This knowledge unit describes the fundamental differences that Platform-Based Development has over traditional software development.

Topics:

- Overview of platforms (e.g., Web, Mobile, Game, Industrial)
- Programming via platform-specific APIs
- Overview of Platform Languages (e.g., Objective C, HTML5)
- Programming under platform constraints

Learning Outcomes:

1. Describe how platform-based development differs from general purpose programming. [Familiarity]
2. List characteristics of platform languages. [Familiarity]
3. Write and execute a simple platform-based program. [Usage]
4. List the advantages and disadvantages of programming with platform constraints. [Familiarity]

PBD/Web Platforms

[Elective]

Topics:

- Web programming languages (e.g., HTML5, Java Script, PHP, CSS)
- Web platform constraints
- Software as a Service (SaaS)
- Web standards

Learning Outcomes:

1. Design and Implement a simple web application. [Usage]
2. Describe the constraints that the web puts on developers. [Familiarity]
3. Compare and contrast web programming with general purpose programming. [Assessment]
4. Describe the differences between Software-as-a-Service and traditional software products. [Familiarity]
5. Discuss how web standards impact software development. [Familiarity]
6. Review an existing web application against a current web standard. [Assessment]

PBD/Mobile Platforms

[Elective]

Topics:

- Mobile programming languages
- Challenges with mobility and wireless communication
- Location-aware applications
- Performance / power tradeoffs
- Mobile platform constraints
- Emerging technologies

Learning Outcomes:

1. Design and implement a mobile application for a given mobile platform. [Usage]
2. Discuss the constraints that mobile platforms put on developers. [Familiarity]
3. Discuss the performance vs. power tradeoff. [Familiarity]
4. Compare and contrast mobile programming with general purpose programming. [Assessment]

PBD/Industrial Platforms

[Elective]

This knowledge unit is related to IS/Robotics.

Topics:

- Types of Industrial Platforms (e.g., Mathematic, Robotic, Industrial Control)
- Robotic software and its architecture
- Domain-specific languages
- Industrial platform constraints

Learning Outcomes:

1. Design and implement an industrial application on a given platform (e.g., using Lego Mindstorms or Matlab). [Usage]
2. Compare and contrast domain specific languages with general purpose programming languages. [Assessment]
3. Discuss the constraints that a given industrial platforms impose on developers. [Familiarity]

PBD/Game Platforms

[Elective]

Topics:

- Types of game platforms (e.g., XBox, Wii, PlayStation)
- Game platform languages (e.g., C++, Java, Lua, Python)
- Game platform constraints

Learning Outcomes:

1. Design and implement a simple application on a game platform. [Usage]
2. Describe the constraints that game platforms impose on developers. [Familiarity]
3. Compare and contrast game programming with general purpose programming. [Assessment]

Parallel and Distributed Computing (PD)

The past decade has brought explosive growth in multiprocessor computing, including multi-core processors and distributed data centers. As a result, parallel and distributed computing has moved from a largely elective topic to become more of a core component of undergraduate computing curricula. Both parallel and distributed computing entail the logically simultaneous execution of multiple processes, whose operations have the potential to interleave in complex ways. Parallel and distributed computing builds on foundations in many areas, including an understanding of fundamental systems concepts such as concurrency and parallel execution, consistency in state/memory manipulation, and latency. Communication and coordination among processes is rooted in the message-passing and shared-memory models of computing and such algorithmic concepts as atomicity, consensus, and conditional waiting. Achieving speedup in practice requires an understanding of parallel algorithms, strategies for problem decomposition, system architecture, detailed implementation strategies, and performance analysis and tuning. Distributed systems highlight the problems of security and fault tolerance, emphasize the maintenance of replicated state, and introduce additional issues that bridge to computer networking.

Because parallelism interacts with so many areas of computing, including at least algorithms, languages, systems, networking, and hardware, many curricula will put different parts of the knowledge area in different courses, rather than in a dedicated course. While we acknowledge that computer science is moving in this direction and may reach that point, in 2013 this process is still in flux and we feel it provides more useful guidance to curriculum designers to aggregate the fundamental parallelism topics in one place. Note, however, that the fundamentals of concurrency and mutual exclusion appear in the Systems Fundamentals (SF) Knowledge Area. Many curricula may choose to introduce parallelism and concurrency in the same course (see below for the distinction intended by these terms). Further, we note that the topics and learning outcomes listed below include only brief mentions of purely elective coverage. At the present time, there is too much diversity in topics that share little in common (including for example, parallel scientific computing, process calculi, and non-blocking data structures) to recommend particular topics be covered in elective courses.

Because the terminology of parallel and distributed computing varies among communities, we provide here brief descriptions of the intended senses of a few terms. This list is not exhaustive or definitive, but is provided for the sake of clarity.

- *Parallelism:* Using additional computational resources simultaneously, usually for speedup.
- *Concurrency:* Efficiently and correctly managing concurrent access to resources.
- *Activity*: A computation that may proceed concurrently with others; for example a program, process, thread, or active parallel hardware component.
- *Atomicity*: Rules and properties governing whether an action is observationally indivisible; for example, setting all of the bits in a word, transmitting a single packet, or completing a transaction.
- *Consensus*: Agreement among two or more activities about a given predicate; for example, the value of a counter, the owner of a lock, or the termination of a thread.
- *Consistency*: Rules and properties governing agreement about the values of variables written, or messages produced, by some activities and used by others (thus possibly exhibiting a *data race*); for example, *sequential consistency*, stating that the values of all variables in a shared memory parallel program are equivalent to that of a single program performing some interleaving of the memory accesses of these activities.
- *Multicast*: A message sent to possibly many recipients, generally without any constraints about whether some recipients receive the message before others. An *event* is a multicast message sent to a designated set of *listeners* or *subscribers*.

As multi-processor computing continues to grow in the coming years, so too will the role of parallel and distributed computing in undergraduate computing curricula. In addition to the guidelines presented here, we also direct the interested reader to the document entitled "NSF/TCPP Curriculum Initiative on Parallel and Distributed Computing - Core Topics for Undergraduates", available from the website: http://www.cs.gsu.edu/~tcpp/curriculum/.

General cross-referencing note: Systems Fundamentals also contains an introduction to parallelism (SF/Computational Paradigms, SF/System Support for Parallelism, SF/Performance).

The introduction to parallelism in SF complements the one here and there is no ordering constraint between them. In SF, the idea is to provide a unified view of the system support for simultaneous execution at multiple levels of abstraction (parallelism is inherent in gates, processors, operating systems, and servers), whereas here the focus is on a preliminary understanding of parallelism as a computing primitive and the complications that arise in parallel and concurrent programming. Given these different perspectives, the hours assigned to each are not redundant: the layered systems view and the high-level computing concepts are accounted for separately in terms of the core hours.

PD. Parallel and Distributed Computing (5 Core-Tier1 hours, 10 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
PD/Parallelism Fundamentals	**2**		**N**
PD/Parallel Decomposition	**1**	**3**	**N**
PD/Communication and Coordination	**1**	**3**	**Y**
PD/Parallel Algorithms, Analysis, and Programming		**3**	**Y**
PD/Parallel Architecture	**1**	**1**	**Y**
PD/Parallel Performance			**Y**
PD/Distributed Systems			**Y**
PD/Cloud Computing			**Y**
PD/Formal Models and Semantics			**Y**

PD/Parallelism Fundamentals

[2 Core-Tier1 hours]

Build upon students' familiarity with the notion of basic parallel execution—a concept addressed in Systems Fundamentals—to delve into the complicating issues that stem from this notion, such as race conditions and liveness.

Cross-reference SF/Computational Paradigms and SF/System Support for Parallelism.

Topics:

- Multiple simultaneous computations
- Goals of parallelism (e.g., throughput) versus concurrency (e.g., controlling access to shared resources)
- Parallelism, communication, and coordination
    - Programming constructs for coordinating multiple simultaneous computations
    - Need for synchronization
- Programming errors not found in sequential programming
    - Data races (simultaneous read/write or write/write of shared state)
    - Higher-level races (interleavings violating program intention, undesired non-determinism)
    - Lack of liveness/progress (deadlock, starvation)

Learning outcomes:

1. Distinguish using computational resources for a faster answer from managing efficient access to a shared resource. (Cross-reference GV/Fundamental Concepts, outcome 5.) [Familiarity]
2. Distinguish multiple sufficient programming constructs for synchronization that may be inter-implementable but have complementary advantages. [Familiarity]
3. Distinguish data races from higher level races. [Familiarity]

PD/Parallel Decomposition

[1 Core-Tier1 hour, 3 Core-Tier2 hours]

(Cross-reference SF/System Support for Parallelism)

Topics:

[Core-Tier1]

- Need for communication and coordination/synchronization
- Independence and partitioning

[Core-Tier2]

- Basic knowledge of parallel decomposition concepts (cross-reference SF/System Support for Parallelism)
- Task-based decomposition
    - Implementation strategies such as threads
- Data-parallel decomposition
    - Strategies such as SIMD and MapReduce
- Actors and reactive processes (e.g., request handlers)

Learning outcomes:

[Core-Tier1]

1. Explain why synchronization is necessary in a specific parallel program. [Usage]
2. Identify opportunities to partition a serial program into independent parallel modules. [Familiarity]

[Core-Tier2]

3. Write a correct and scalable parallel algorithm. [Usage]
4. Parallelize an algorithm by applying task-based decomposition. [Usage]
5. Parallelize an algorithm by applying data-parallel decomposition. [Usage]
6. Write a program using actors and/or reactive processes. [Usage]

PD/Communication and Coordination

[1 Core-Tier1 hour, 3 Core-Tier2 hours]

Cross-reference OS/Concurrency for mechanism implementation issues.

Topics:

[Core-Tier1]

- Shared Memory
- Consistency, and its role in programming language guarantees for data-race-free programs

[Core-Tier2]

- Message passing
    - Point-to-point versus multicast (or event-based) messages
    - Blocking versus non-blocking styles for sending and receiving messages
    - Message buffering (cross-reference PF/Fundamental Data Structures/Queues)
- Atomicity
    - Specifying and testing atomicity and safety requirements
    - Granularity of atomic accesses and updates, and the use of constructs such as critical sections or transactions to describe them
    - Mutual Exclusion using locks, semaphores, monitors, or related constructs
        - Potential for liveness failures and deadlock (causes, conditions, prevention)
    - Composition
        - Composing larger granularity atomic actions using synchronization
        - Transactions, including optimistic and conservative approaches

[Elective]

- Consensus
    - (Cyclic) barriers, counters, or related constructs
- Conditional actions
    - Conditional waiting (e.g., using condition variables)

Learning outcomes:

[Core-Tier1]

1. Use mutual exclusion to avoid a given race condition. [Usage]
2. Give an example of an ordering of accesses among concurrent activities (e.g., program with a data race) that is not sequentially consistent. [Familiarity]

[Core-Tier2]

3. Give an example of a scenario in which blocking message sends can deadlock. [Usage]
4. Explain when and why multicast or event-based messaging can be preferable to alternatives. [Familiarity]
5. Write a program that correctly terminates when all of a set of concurrent tasks have completed. [Usage]
6. Use a properly synchronized queue to buffer data passed among activities. [Usage]
7. Explain why checks for preconditions, and actions based on these checks, must share the same unit of atomicity to be effective. [Familiarity]
8. Write a test program that can reveal a concurrent programming error; for example, missing an update when two activities both try to increment a variable. [Usage]
9. Describe at least one design technique for avoiding liveness failures in programs using multiple locks or semaphores. [Familiarity]
10. Describe the relative merits of optimistic versus conservative concurrency control under different rates of contention among updates. [Familiarity]
11. Give an example of a scenario in which an attempted optimistic update may never complete. [Familiarity]

[Elective]

12. Use semaphores or condition variables to block threads until a necessary precondition holds. [Usage]

PD/Parallel Algorithms, Analysis, and Programming

[3 Core-Tier2 hours]

Topics:

[Core-Tier2]

- Critical paths, work and span, and the relation to Amdahl's law (cross-reference SF/Performance)
- Speed-up and scalability
- Naturally (embarrassingly) parallel algorithms
- Parallel algorithmic patterns (divide-and-conquer, map and reduce, master-workers, others)
    - Specific algorithms (e.g., parallel MergeSort)

[Elective]

- Parallel graph algorithms (e.g., parallel shortest path, parallel spanning tree) (cross-reference AL/Algorithmic Strategies/Divide-and-conquer)
- Parallel matrix computations
- Producer-consumer and pipelined algorithms
- Examples of non-scalable parallel algorithms

Learning outcomes:

[Core-Tier2]

1. Define "critical path", "work", and "span". [Familiarity]
2. Compute the work and span, and determine the critical path with respect to a parallel execution diagram. [Usage]
3. Define "speed-up" and explain the notion of an algorithm's scalability in this regard. [Familiarity]
4. Identify independent tasks in a program that may be parallelized. [Usage]
5. Characterize features of a workload that allow or prevent it from being naturally parallelized. [Familiarity]
6. Implement a parallel divide-and-conquer (and/or graph algorithm) and empirically measure its performance relative to its sequential analog. [Usage]
7. Decompose a problem (e.g., counting the number of occurrences of some word in a document) via map and reduce operations. [Usage]

[Elective]

8. Provide an example of a problem that fits the producer-consumer paradigm. [Familiarity]
9. Give examples of problems where pipelining would be an effective means of parallelization. [Familiarity]
10. Implement a parallel matrix algorithm. [Usage]
11. Identify issues that arise in producer-consumer algorithms and mechanisms that may be used for addressing them. [Familiarity]

PD/Parallel Architecture

[1 Core-Tier1 hour, 1 Core-Tier2 hour]

The topics listed here are related to knowledge units in the Architecture and Organization (AR) knowledge area (AR/Assembly Level Machine Organization and AR/Multiprocessing and Alternative Architectures). Here, we focus on parallel architecture from the standpoint of applications, whereas the Architecture and Organization knowledge area presents the topic from the hardware perspective.

[Core-Tier1]

- Multicore processors
- Shared vs. distributed memory

[Core-Tier2]

- Symmetric multiprocessing (SMP)
- SIMD, vector processing

[Elective]

- GPU, co-processing
- Flynn's taxonomy
- Instruction level support for parallel programming
    - Atomic instructions such as Compare and Set
- Memory issues
    - Multiprocessor caches and cache coherence
    - Non-uniform memory access (NUMA)

- Topologies
  - Interconnects
  - Clusters
  - Resource sharing (e.g., buses and interconnects)

Learning outcomes:

[Core-Tier1]

1. Explain the differences between shared and distributed memory. [Familiarity]

[Core-Tier2]

2. Describe the SMP architecture and note its key features. [Familiarity]
3. Characterize the kinds of tasks that are a natural match for SIMD machines. [Familiarity]

[Elective]

4. Describe the advantages and limitations of GPUs vs. CPUs. [Familiarity]
5. Explain the features of each classification in Flynn's taxonomy. [Familiarity]
6. Describe assembly-level support for atomic operations. [Familiarity]
7. Describe the challenges in maintaining cache coherence. [Familiarity]
8. Describe the key performance challenges in different memory and distributed system topologies. [Familiarity]

PD/Parallel Performance

[Elective]

Topics:

- Load balancing
- Performance measurement
- Scheduling and contention (cross-reference OS/Scheduling and Dispatch)
- Evaluating communication overhead
- Data management
  - Non-uniform communication costs due to proximity (cross-reference SF/Proximity)
  - Cache effects (e.g., false sharing)
  - Maintaining spatial locality
- Power usage and management

Learning outcomes:

1. Detect and correct a load imbalance. [Usage]
2. Calculate the implications of Amdahl's law for a particular parallel algorithm (cross-reference SF/Evaluation for Amdahl's Law). [Usage]
3. Describe how data distribution/layout can affect an algorithm's communication costs. [Familiarity]
4. Detect and correct an instance of false sharing. [Usage]
5. Explain the impact of scheduling on parallel performance. [Familiarity]
6. Explain performance impacts of data locality. [Familiarity]
7. Explain the impact and trade-off related to power usage on parallel performance. [Familiarity]

PD/Distributed Systems

[Elective]

Topics:

- Faults (cross-reference OS/Fault Tolerance)
    - Network-based (including partitions) and node-based failures
    - Impact on system-wide guarantees (e.g., availability)
- Distributed message sending
    - Data conversion and transmission
    - Sockets
    - Message sequencing
    - Buffering, retrying, and dropping messages
- Distributed system design tradeoffs
    - Latency versus throughput
    - Consistency, availability, partition tolerance
- Distributed service design
    - Stateful versus stateless protocols and services
    - Session (connection-based) designs
    - Reactive (IO-triggered) and multithreaded designs
- Core distributed algorithms
    - Election, discovery

Learning outcomes:

1. Distinguish network faults from other kinds of failures. [Familiarity]
2. Explain why synchronization constructs such as simple locks are not useful in the presence of distributed faults. [Familiarity]
3. Write a program that performs any required marshaling and conversion into message units, such as packets, to communicate interesting data between two hosts. [Usage]
4. Measure the observed throughput and response latency across hosts in a given network. [Usage]
5. Explain why no distributed system can be simultaneously consistent, available, and partition tolerant. [Familiarity]
6. Implement a simple server -- for example, a spell checking service. [Usage]
7. Explain the tradeoffs among overhead, scalability, and fault tolerance when choosing a stateful v. stateless design for a given service. [Familiarity]
8. Describe the scalability challenges associated with a service growing to accommodate many clients, as well as those associated with a service only transiently having many clients. [Familiarity]
9. Give examples of problems for which consensus algorithms such as leader election are required. [Usage]

PD/Cloud Computing

[Elective]

Topics:

- Internet-Scale computing
    - Task partitioning (cross-reference PD/Parallel Algorithms, Analysis, and Programming)
    - Data access
    - Clusters, grids, and meshes
- Cloud services
    - Infrastructure as a service
        - Elasticity of resources
        - Platform APIs

    - Software as a service
    - Security
    - Cost management
- Virtualization (cross-reference SF/Virtualization and Isolation and OS/Virtual Machines)
    - Shared resource management
    - Migration of processes
- Cloud-based data storage
    - Shared access to weakly consistent data stores
    - Data synchronization
    - Data partitioning
    - Distributed file systems (cross-reference IM/Distributed Databases)
    - Replication

Learning outcomes:

1. Discuss the importance of elasticity and resource management in cloud computing. [Familiarity]
2. Explain strategies to synchronize a common view of shared data across a collection of devices. [Familiarity]
3. Explain the advantages and disadvantages of using virtualized infrastructure. [Familiarity]
4. Deploy an application that uses cloud infrastructure for computing and/or data resources. [Usage]
5. Appropriately partition an application between a client and resources. [Usage]

PD/Formal Models and Semantics

[Elective]

Topics:

- Formal models of processes and message passing, including algebras such as Communicating Sequential Processes (CSP) and pi-calculus
- Formal models of parallel computation, including the Parallel Random Access Machine (PRAM) and alternatives such as Bulk Synchronous Parallel (BSP)
- Formal models of computational dependencies
- Models of (relaxed) shared memory consistency and their relation to programming language specifications
- Algorithmic correctness criteria including linearizability
- Models of algorithmic progress, including non-blocking guarantees and fairness
- Techniques for specifying and checking correctness properties such as atomicity and freedom from data races

Learning outcomes:

1. Model a concurrent process using a formal model, such as pi-calculus. [Usage]
2. Explain the characteristics of a particular formal parallel model. [Familiarity]
3. Formally model a shared memory system to show if it is consistent. [Usage]
4. Use a model to show progress guarantees in a parallel algorithm. [Usage]
5. Use formal techniques to show that a parallel algorithm is correct with respect to a safety or liveness property. [Usage]
6. Decide if a specific execution is linearizable or not. [Usage]

Programming Languages (PL)

Programming languages are the medium through which programmers precisely describe concepts, formulate algorithms, and reason about solutions. In the course of a career, a computer scientist will work with many different languages, separately or together. Software developers must understand the programming models underlying different languages and make informed design choices in languages supporting multiple complementary approaches. Computer scientists will often need to learn new languages and programming constructs, and must understand the principles underlying how programming language features are defined, composed, and implemented. The effective use of programming languages, and appreciation of their limitations, also requires a basic knowledge of programming language translation and static program analysis, as well as run-time components such as memory management.

PL. Programming Languages (8 Core-Tier1 hours, 20 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
PL/Object-Oriented Programming	**4**	**6**	**N**
PL/Functional Programming	**3**	**4**	**N**
PL/Event-Driven and Reactive Programming		**2**	**N**
PL/Basic Type Systems	**1**	**4**	**N**
PL/Program Representation		**1**	**N**
PL/Language Translation and Execution		**3**	**N**
PL/Syntax Analysis			**Y**
PL/Compiler Semantic Analysis			**Y**
PL/Code Generation			**Y**
PL/Runtime Systems			**Y**
PL/Static Analysis			**Y**
PL/Advanced Programming Constructs			**Y**
PL/Concurrency and Parallelism			**Y**
PL/Type Systems			**Y**
PL/Formal Semantics			**Y**
PL/Language Pragmatics			**Y**
PL/Logic Programming			**Y**

Note:

- Some topics from one or more of the first three Knowledge Units (*Object-Oriented Programming*, *Functional Programming*, *Event-Driven and Reactive Programming*) are likely to be integrated with topics in the SF-Software Development Fundamentals Knowledge Area in a curriculum's introductory courses. Curricula will differ on which topics are integrated in this fashion and which are delayed until later courses on software development and programming languages.
- Some of the most important core learning outcomes are relevant to object-oriented programming, functional programming, and, in fact, all programming. These learning outcomes are *repeated* in the *Object-Oriented Programming* and *Functional Programming* Knowledge Units, with a note to this effect. We do not intend that a

curriculum necessarily needs to cover them multiple times, though some will. We repeat them only because they do not naturally fit in only one Knowledge Unit.

PL/Object-Oriented Programming

[4 Core-Tier1 hours, 6 Core-Tier2 hours]

Topics:

[Core-Tier1]

- Object-oriented design
  - Decomposition into objects carrying state and having behavior
  - Class-hierarchy design for modeling
- Definition of classes: fields, methods, and constructors
- Subclasses, inheritance, and method overriding
- Dynamic dispatch: definition of method-call

[Core-Tier2]

- Subtyping (cross-reference PL/Type Systems)
  - Subtype polymorphism; implicit upcasts in typed languages
  - Notion of behavioral replacement: subtypes acting like supertypes
  - Relationship between subtyping and inheritance
- Object-oriented idioms for encapsulation
  - Privacy and visibility of class members
  - Interfaces revealing only method signatures
  - Abstract base classes
- Using collection classes, iterators, and other common library components

Learning outcomes:

[Core-Tier1]

1. Design and implement a class. [Usage]
2. Use subclassing to design simple class hierarchies that allow code to be reused for distinct subclasses. [Usage]
3. Correctly reason about control flow in a program using dynamic dispatch. [Usage]
4. Compare and contrast (1) the procedural/functional approach (defining a function for each operation with the function body providing a case for each data variant) and (2) the object-oriented approach (defining a class for each data variant with the class definition providing a method for each operation). Understand both as defining a matrix of operations and variants. [Assessment] *This outcome also appears in PL/Functional Programming.*

[Core-Tier2]

5. Explain the relationship between object-oriented inheritance (code-sharing and overriding) and subtyping (the idea of a subtype being usable in a context that expects the supertype). [Familiarity]
6. Use object-oriented encapsulation mechanisms such as interfaces and private members. [Usage]
7. Define and use iterators and other operations on aggregates, including operations that take functions as arguments, in multiple programming languages, selecting the most natural idioms for each language. [Usage] *This outcome also appears in PL/Functional Programming.*

PL/Functional Programming

[3 Core-Tier1 hours, 4 Core-Tier2 hours]

Topics:

[Core-Tier1]

- Effect-free programming
    - Function calls have no side effects, facilitating compositional reasoning
    - Variables are immutable, preventing unexpected changes to program data by other code
    - Data can be freely aliased or copied without introducing unintended effects from mutation
- Processing structured data (e.g., trees) via functions with cases for each data variant
    - Associated language constructs such as discriminated unions and pattern-matching over them
    - Functions defined over compound data in terms of functions applied to the constituent pieces
- First-class functions (taking, returning, and storing functions)

[Core-Tier2]

- Function closures (functions using variables in the enclosing lexical environment)
    - Basic meaning and definition -- creating closures at run-time by capturing the environment
    - Canonical idioms: call-backs, arguments to iterators, reusable code via function arguments
    - Using a closure to encapsulate data in its environment
    - Currying and partial application
- Defining higher-order operations on aggregates, especially map, reduce/fold, and filter

Learning outcomes:

[Core-Tier1]

1. Write basic algorithms that avoid assigning to mutable state or considering reference equality. [Usage]
2. Write useful functions that take and return other functions. [Usage]
3. Compare and contrast (1) the procedural/functional approach (defining a function for each operation with the function body providing a case for each data variant) and (2) the object-oriented approach (defining a class for each data variant with the class definition providing a method for each operation). Understand both as defining a matrix of operations and variants. [Assessment] *This outcome also appears in PL/Object-Oriented Programming.*

[Core-Tier2]

4. Correctly reason about variables and lexical scope in a program using function closures. [Usage]
5. Use functional encapsulation mechanisms such as closures and modular interfaces. [Usage]
6. Define and use iterators and other operations on aggregates, including operations that take functions as arguments, in multiple programming languages, selecting the most natural idioms for each language. [Usage] *This outcome also appears in PL/Object-Oriented Programming.*

PL/Event-Driven and Reactive Programming

[2 Core-Tier2 hours]

This material can stand alone or be integrated with other knowledge units on concurrency, asynchrony, and threading to allow contrasting events with threads.

Topics:

- Events and event handlers
- Canonical uses such as GUIs, mobile devices, robots, servers
- Using a reactive framework
    - Defining event handlers/listeners
    - Main event loop not under event-handler-writer's control
- Externally-generated events and program-generated events
- Separation of model, view, and controller

Learning outcomes:

1. Write event handlers for use in reactive systems, such as GUIs. [Usage]
2. Explain why an event-driven programming style is natural in domains where programs react to external events. [Familiarity]
3. Describe an interactive system in terms of a model, a view, and a controller. [Familiarity]

PL/Basic Type Systems

[1 Core-Tier1 hour, 4 Core-Tier2 hours]

The core-tier2 hours would be profitably spent both on the core-tier2 topics and on a less shallow treatment of the core-tier1 topics and learning outcomes.

Topics:

[Core-Tier1]

- A type as a set of values together with a set of operations
    - Primitive types (e.g., numbers, Booleans)
    - Compound types built from other types (e.g., records, unions, arrays, lists, functions, references)
- Association of types to variables, arguments, results, and fields
- Type safety and errors caused by using values inconsistently given their intended types
- Goals and limitations of static typing
    - Eliminating some classes of errors without running the program
    - Undecidability means static analysis must conservatively approximate program behavior

[Core-Tier2]

- Generic types (parametric polymorphism)
    - Definition
    - Use for generic libraries such as collections
    - Comparison with ad hoc polymorphism (overloading) and subtype polymorphism
- Complementary benefits of static and dynamic typing
    - Errors early vs. errors late/avoided

- Enforce invariants during code development and code maintenance vs. postpone typing decisions while prototyping and conveniently allow flexible coding patterns such as heterogeneous collections
- Avoid misuse of code vs. allow more code reuse
- Detect incomplete programs vs. allow incomplete programs to run

Learning outcomes:

[Core-Tier1]

1. For both a primitive and a compound type, informally describe the values that have that type. [Familiarity]
2. For a language with a static type system, describe the operations that are forbidden statically, such as passing the wrong type of value to a function or method. [Familiarity]
3. Describe examples of program errors detected by a type system. [Familiarity]
4. For multiple programming languages, identify program properties checked statically and program properties checked dynamically. [Usage]
5. Give an example program that does not type-check in a particular language and yet would have no error if run. [Familiarity]
6. Use types and type-error messages to write and debug programs. [Usage]

[Core-Tier2]

7. Explain how typing rules define the set of operations that are legal for a type. [Familiarity]
8. Write down the type rules governing the use of a particular compound type. [Usage]
9. Explain why undecidability requires type systems to conservatively approximate program behavior. [Familiarity]
10. Define and use program pieces (such as functions, classes, methods) that use generic types, including for collections. [Usage]
11. Discuss the differences among generics, subtyping, and overloading. [Familiarity]
12. Explain multiple benefits and limitations of static typing in writing, maintaining, and debugging software. [Familiarity]

PL/Program Representation

[1 Core-Tier2 hour]

Topics:

- Programs that take (other) programs as input such as interpreters, compilers, type-checkers, documentation generators
- Abstract syntax trees; contrast with concrete syntax
- Data structures to represent code for execution, translation, or transmission

Learning outcomes:

1. Explain how programs that process other programs treat the other programs as their input data. [Familiarity]
2. Describe an abstract syntax tree for a small language. [Usage]
3. Describe the benefits of having program representations other than strings of source code. [Familiarity]
4. Write a program to process some representation of code for some purpose, such as an interpreter, an expression optimizer, or a documentation generator. [Usage]

PL/Language Translation and Execution

[3 Core-Tier2 hours]

Topics:

- Interpretation vs. compilation to native code vs. compilation to portable intermediate representation
- Language translation pipeline: parsing, optional type-checking, translation, linking, execution
    - Execution as native code or within a virtual machine
    - Alternatives like dynamic loading and dynamic (or "just-in-time") code generation
- Run-time representation of core language constructs such as objects (method tables) and first-class functions (closures)
- Run-time layout of memory: call-stack, heap, static data
    - Implementing loops, recursion, and tail calls
- Memory management
    - Manual memory management: allocating, de-allocating, and reusing heap memory
    - Automated memory management: garbage collection as an automated technique using the notion of reachability

Learning outcomes:

1. Distinguish a language definition (what constructs mean) from a particular language implementation (compiler vs. interpreter, run-time representation of data objects, etc.). [Familiarity]
2. Distinguish syntax and parsing from semantics and evaluation. [Familiarity]
3. Sketch a low-level run-time representation of core language constructs, such as objects or closures. [Familiarity]
4. Explain how programming language implementations typically organize memory into global data, text, heap, and stack sections and how features such as recursion and memory management map to this memory model. [Familiarity]
5. Identify and fix memory leaks and dangling-pointer dereferences. [Usage]
6. Discuss the benefits and limitations of garbage collection, including the notion of reachability. [Familiarity]

PL/Syntax Analysis

[Elective]

Topics:

- Scanning (lexical analysis) using regular expressions
- Parsing strategies including top-down (e.g., recursive descent, Earley parsing, or LL) and bottom-up (e.g., backtracking or LR) techniques; role of context-free grammars
- Generating scanners and parsers from declarative specifications

Learning outcomes:

1. Use formal grammars to specify the syntax of languages. [Usage]
2. Use declarative tools to generate parsers and scanners. [Usage]
3. Identify key issues in syntax definitions: ambiguity, associativity, precedence. [Familiarity]

PL/Compiler Semantic Analysis

[Elective]

Topics:

- High-level program representations such as abstract syntax trees
- Scope and binding resolution
- Type checking
- Declarative specifications such as attribute grammars

Learning outcomes:

1. Implement context-sensitive, source-level static analyses such as type-checkers or resolving identifiers to identify their binding occurrences. [Usage]
2. Describe semantic analyses using an attribute grammar. [Usage]

PL/Code Generation

[Elective]

Topics:

- Procedure calls and method dispatching
- Separate compilation; linking
- Instruction selection
- Instruction scheduling
- Register allocation
- Peephole optimization

Learning outcomes:

1. Identify all essential steps for automatically converting source code into assembly or other low-level languages. [Familiarity]
2. Generate the low-level code for calling functions/methods in modern languages. [Usage]
3. Discuss why separate compilation requires uniform calling conventions. [Familiarity]
4. Discuss why separate compilation limits optimization because of unknown effects of calls. [Familiarity]
5. Discuss opportunities for optimization introduced by naive translation and approaches for achieving optimization, such as instruction selection, instruction scheduling, register allocation, and peephole optimization. [Familiarity]

PL/Runtime Systems

[Elective]

Topics:

- Dynamic memory management approaches and techniques: malloc/free, garbage collection (mark-sweep, copying, reference counting), regions (also known as arenas or zones)

- Data layout for objects and activation records
- Just-in-time compilation and dynamic recompilation
- Other common features of virtual machines, such as class loading, threads, and security.

Learning outcomes:

1. Compare the benefits of different memory-management schemes, using concepts such as fragmentation, locality, and memory overhead. [Familiarity]
2. Discuss benefits and limitations of automatic memory management. [Familiarity]
3. Explain the use of metadata in run-time representations of objects and activation records, such as class pointers, array lengths, return addresses, and frame pointers. [Familiarity]
4. Discuss advantages, disadvantages, and difficulties of just-in-time and dynamic recompilation. [Familiarity]
5. Identify the services provided by modern language run-time systems. [Familiarity]

PL/Static Analysis

[Elective]

Topics:

- Relevant program representations, such as basic blocks, control-flow graphs, def-use chains, and static single assignment
- Undecidability and consequences for program analysis
- Flow-insensitive analyses, such as type-checking and scalable pointer and alias analyses
- Flow-sensitive analyses, such as forward and backward dataflow analyses
- Path-sensitive analyses, such as software model checking
- Tools and frameworks for defining analyses
- Role of static analysis in program optimization
- Role of static analysis in (partial) verification and bug-finding

Learning outcomes:

1. Define useful static analyses in terms of a conceptual framework such as dataflow analysis. [Usage]
2. Explain why non-trivial sound static analyses must be approximate. [Familiarity]
3. Communicate why an analysis is correct (sound and terminating). [Usage]
4. Distinguish “may” and “must” analyses. [Familiarity]
5. Explain why potential aliasing limits sound program analysis and how alias analysis can help. [Familiarity]
6. Use the results of a static analysis for program optimization and/or partial program correctness. [Usage]

PL/Advanced Programming Constructs

[Elective]

Topics:

- Lazy evaluation and infinite streams
- Control Abstractions: Exception Handling, Continuations, Monads
- Object-oriented abstractions: Multiple inheritance, Mixins, Traits, Multimethods

- Metaprogramming: Macros, Generative programming, Model-based development
- Module systems
- String manipulation via pattern-matching (regular expressions)
- Dynamic code evaluation ("eval")
- Language support for checking assertions, invariants, and pre/post-conditions

Learning outcomes:

1. Use various advanced programming constructs and idioms correctly. [Usage]
2. Discuss how various advanced programming constructs aim to improve program structure, software quality, and programmer productivity. [Familiarity]
3. Discuss how various advanced programming constructs interact with the definition and implementation of other language features. [Familiarity]

PL/Concurrency and Parallelism

[Elective]

Support for concurrency is a fundamental programming-languages issue with rich material in programming language design, language implementation, and language theory. Due to coverage in other Knowledge Areas, this elective Knowledge Unit aims only to complement the material included elsewhere in the Body of Knowledge. Courses on programming languages are an excellent place to include a general treatment of concurrency including this other material.

Cross-reference PD/Parallel and Distributed Computing, SF/Parallelism.

Topics:

- Constructs for thread-shared variables and shared-memory synchronization
- Actor models
- Futures
- Language support for data parallelism
- Models for passing messages between sequential processes
- Effect of memory-consistency models on language semantics and correct code generation

Learning outcomes:

1. Write correct concurrent programs using multiple programming models, such as shared memory, actors, futures, and data-parallelism primitives. [Usage]
2. Use a message-passing model to analyze a communication protocol. [Usage]
3. Explain why programming languages do not guarantee sequential consistency in the presence of data races and what programmers must do as a result. [Familiarity]

PL/Type Systems

[Elective]

Topics:

- Compositional type constructors, such as product types (for aggregates), sum types (for unions), function types, quantified types, and recursive types
- Type checking
- Type safety as preservation plus progress
- Type inference
- Static overloading

Learning outcomes:

1. Define a type system precisely and compositionally. [Usage]
2. For various foundational type constructors, identify the values they describe and the invariants they enforce. [Familiarity]
3. Precisely specify the invariants preserved by a sound type system. [Familiarity]
4. Prove type safety for a simple language in terms of preservation and progress theorems. [Usage]
5. Implement a unification-based type-inference algorithm for a simple language. [Usage]
6. Explain how static overloading and associated resolution algorithms influence the dynamic behavior of programs. [Familiarity]

PL/Formal Semantics

[Elective]

Topics:

- Syntax vs. semantics
- Lambda Calculus
- Approaches to semantics: Operational, Denotational, Axiomatic
- Proofs by induction over language semantics
- Formal definitions and proofs for type systems (cross-reference PL/Type Systems)
- Parametricity (cross-reference PL/Type Systems)
- Using formal semantics for systems modeling

Learning outcomes:

1. Give a formal semantics for a small language. [Usage]
2. Write a lambda-calculus program and show its evaluation to a normal form. [Usage]
3. Discuss the different approaches of operational, denotational, and axiomatic semantics. [Familiarity]
4. Use induction to prove properties of all programs in a language. [Usage]
5. Use induction to prove properties of all programs in a language that are well-typed according to a formally defined type system. [Usage]
6. Use parametricity to establish the behavior of code given only its type. [Usage]
7. Use formal semantics to build a formal model of a software system other than a programming language. [Usage]

PL/Language Pragmatics

[Elective]

Topics:

- Principles of language design such as orthogonality
- Evaluation order, precedence, and associativity
- Eager vs. delayed evaluation
- Defining control and iteration constructs
- External calls and system libraries

Learning outcomes:

1. Discuss the role of concepts such as orthogonality and well-chosen defaults in language design. [Familiarity]
2. Use crisp and objective criteria for evaluating language-design decisions. [Usage]
3. Give an example program whose result can differ under different rules for evaluation order, precedence, or associativity. [Usage]
4. Show uses of delayed evaluation, such as user-defined control abstractions. [Familiarity]
5. Discuss the need for allowing calls to external calls and system libraries and the consequences for language implementation. [Familiarity]

PL/Logic Programming

[Elective]

Topics:

- Clausal representation of data structures and algorithms
- Unification
- Backtracking and search
- Cuts

Learning outcomes:

1. Use a logic language to implement a conventional algorithm. [Usage]
2. Use a logic language to implement an algorithm employing implicit search using clauses, relations, and cuts. [Usage]

Software Development Fundamentals (SDF)

Fluency in the process of software development is a prerequisite to the study of most of computer science. In order to use computers to solve problems effectively, students must be competent at reading and writing programs in multiple programming languages. Beyond programming skills, however, they must be able to design and analyze algorithms, select appropriate paradigms, and utilize modern development and testing tools. This knowledge area brings together those fundamental concepts and skills related to the software development process. As such, it provides a foundation for other software-oriented knowledge areas, most notably Programming Languages, Algorithms and Complexity, and Software Engineering.

It is important to note that this knowledge area is distinct from the old Programming Fundamentals knowledge area from CC2001. Whereas that knowledge area focused exclusively on the programming skills required in an introductory computer science course, this new knowledge area is intended to fill a much broader purpose. It focuses on the entire software development process, identifying those concepts and skills that should be mastered in the first year of a computer science program. This includes the design and simple analysis of algorithms, fundamental programming concepts and data structures, and basic software development methods and tools. As a result of its broader purpose, the Software Development Fundamentals knowledge area includes fundamental concepts and skills that could naturally be listed in other software-oriented knowledge areas (e.g., programming constructs from Programming Languages, simple algorithm analysis from Algorithms & Complexity, simple development methodologies from Software Engineering). Likewise, each of these knowledge areas will contain more advanced material that builds upon the fundamental concepts and skills listed here.

While broader in scope than the old Programming Fundamentals, this knowledge area still allows for considerable flexibility in the design of first-year curricula. For example, the Fundamental Programming Concepts unit identifies only those concepts that are common to all programming paradigms. It is expected that an instructor would select one or more programming paradigms (e.g., object-oriented programming, functional programming, scripting) to illustrate these programming concepts, and would pull paradigm-specific content from the Programming Languages knowledge area to fill out a course. Likewise, an instructor could choose to

emphasize formal analysis (e.g., Big-Oh, computability) or design methodologies (e.g., team projects, software life cycle) early, thus integrating hours from the Programming Languages, Algorithms and Complexity, and/or Software Engineering knowledge areas. Thus, the 43 hours of material in this knowledge area will typically be augmented with core material from one or more of these knowledge areas to form a complete and coherent first-year experience.

When considering the hours allocated to each knowledge unit, it should be noted that these hours reflect the minimal amount of classroom coverage needed to introduce the material. Many software development topics will reappear and be reinforced by later topics (e.g., applying iteration constructs when processing lists). In addition, the mastery of concepts and skills from this knowledge area requires a significant amount of software development experience outside of class.

SDF. Software Development Fundamentals (43 Core-Tier1 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
SDF/Algorithms and Design	**11**		**N**
SDF/Fundamental Programming Concepts	**10**		**N**
SDF/Fundamental Data Structures	**12**		**N**
SDF/Development Methods	**10**		**N**

SDF/Algorithms and Design

[11 Core-Tier1 hours]

This unit builds the foundation for core concepts in the Algorithms and Complexity Knowledge Area, most notably in the Basic Analysis and Algorithmic Strategies knowledge units.

Topics:

- The concept and properties of algorithms
    - Informal comparison of algorithm efficiency (e.g., operation counts)
- The role of algorithms in the problem-solving process
- Problem-solving strategies
    - Iterative and recursive mathematical functions
    - Iterative and recursive traversal of data structures
    - Divide-and-conquer strategies
- Fundamental design concepts and principles
    - Abstraction
    - Program decomposition
    - Encapsulation and information hiding
    - Separation of behavior and implementation

Learning Outcomes:

1. Discuss the importance of algorithms in the problem-solving process. [Familiarity]
2. Discuss how a problem may be solved by multiple algorithms, each with different properties. [Familiarity]
3. Create algorithms for solving simple problems. [Usage]
4. Use a programming language to implement, test, and debug algorithms for solving simple problems. [Usage]
5. Implement, test, and debug simple recursive functions and procedures. [Usage]
6. Determine whether a recursive or iterative solution is most appropriate for a problem. [Assessment]
7. Implement a divide-and-conquer algorithm for solving a problem. [Usage]
8. Apply the techniques of decomposition to break a program into smaller pieces. [Usage]
9. Identify the data components and behaviors of multiple abstract data types. [Usage]
10. Implement a coherent abstract data type, with loose coupling between components and behaviors. [Usage]
11. Identify the relative strengths and weaknesses among multiple designs or implementations for a problem. [Assessment]

SDF/Fundamental Programming Concepts

[10 Core-Tier1 hours]

This knowledge unit builds the foundation for core concepts in the Programming Languages Knowledge Area, most notably in the paradigm-specific units: Object-Oriented Programming, Functional Programming, and Event-Driven & Reactive Programming.

Topics:

- Basic syntax and semantics of a higher-level language
- Variables and primitive data types (e.g., numbers, characters, Booleans)
- Expressions and assignments
- Simple I/O including file I/O
- Conditional and iterative control structures
- Functions and parameter passing
- The concept of recursion

Learning Outcomes:

1. Analyze and explain the behavior of simple programs involving the fundamental programming constructs variables, expressions, assignments, I/O, control constructs, functions, parameter passing, and recursion. [Assessment]
2. Identify and describe uses of primitive data types. [Familiarity]
3. Write programs that use primitive data types. [Usage]
4. Modify and expand short programs that use standard conditional and iterative control structures and functions. [Usage]
5. Design, implement, test, and debug a program that uses each of the following fundamental programming constructs: basic computation, simple I/O, standard conditional and iterative structures, the definition of functions, and parameter passing. [Usage]
6. Write a program that uses file I/O to provide persistence across multiple executions. [Usage]
7. Choose appropriate conditional and iteration constructs for a given programming task. [Assessment]
8. Describe the concept of recursion and give examples of its use. [Familiarity]
9. Identify the base case and the general case of a recursively-defined problem. [Assessment]

SDF/Fundamental Data Structures

[12 Core-Tier1 hours]

This unit builds the foundation for core concepts in the Algorithms and Complexity Knowledge Area, most notably in the Fundamental Data Structures and Algorithms and Basic Computability and Complexity knowledge units.

Topics:

- Arrays
- Records/structs (heterogeneous aggregates)
- Strings and string processing
- Abstract data types and their implementation
    - Stacks
    - Queues
    - Priority queues
    - Sets
    - Maps
- References and aliasing
- Linked lists
- Strategies for choosing the appropriate data structure

Learning Outcomes:

1. Discuss the appropriate use of built-in data structures. [Familiarity]
2. Describe common applications for each of the following data structures: stack, queue, priority queue, set, and map. [Familiarity]
3. Write programs that use each of the following data structures: arrays, records/structs, strings, linked lists, stacks, queues, sets, and maps. [Usage]
4. Compare alternative implementations of data structures with respect to performance. [Assessment]
5. Describe how references allow for objects to be accessed in multiple ways. [Familiarity]
6. Compare and contrast the costs and benefits of dynamic and static data structure implementations. [Assessment]
7. Choose the appropriate data structure for modeling a given problem. [Assessment]

SDF/Development Methods

[10 Core-Tier1 hours]

This unit builds the foundation for core concepts in the Software Engineering knowledge area, most notably in the Software Processes, Software Design and Software Evolution knowledge units.

Topics:

- Program comprehension
- Program correctness
    - Types of errors (syntax, logic, run-time)
    - The concept of a specification
    - Defensive programming (e.g. secure coding, exception handling)
    - Code reviews
    - Testing fundamentals and test-case generation
    - The role and the use of contracts, including pre- and post-conditions
    - Unit testing
- Simple refactoring
- Modern programming environments
    - Code search
    - Programming using library components and their APIs
- Debugging strategies
- Documentation and program style

Learning Outcomes:

1. Trace the execution of a variety of code segments and write summaries of their computations. [Assessment]
2. Explain why the creation of correct program components is important in the production of high-quality software. [Familiarity]
3. Identify common coding errors that lead to insecure programs (e.g., buffer overflows, memory leaks, malicious code) and apply strategies for avoiding such errors. [Usage]
4. Conduct a personal code review (focused on common coding errors) on a program component using a provided checklist. [Usage]
5. Contribute to a small-team code review focused on component correctness. [Usage]
6. Describe how a contract can be used to specify the behavior of a program component. [Familiarity]
7. Refactor a program by identifying opportunities to apply procedural abstraction. [Usage]
8. Apply a variety of strategies to the testing and debugging of simple programs. [Usage]
9. Construct, execute and debug programs using a modern IDE and associated tools such as unit testing tools and visual debuggers. [Usage]
10. Construct and debug programs using the standard libraries available with a chosen programming language. [Usage]
11. Analyze the extent to which another programmer's code meets documentation and programming style standards. [Assessment]
12. Apply consistent documentation and program style standards that contribute to the readability and maintainability of software. [Usage]

Software Engineering (SE)

In every computing application domain, professionalism, quality, schedule, and cost are critical to producing software systems. Because of this, the elements of software engineering are applicable to developing software in all areas of computing. A wide variety of software engineering practices have been developed and utilized since the need for a discipline of software engineering was first recognized. Many trade-offs between these different practices have also been identified. Practicing software engineers have to select and apply appropriate techniques and practices to a given development effort in order to maximize value. To learn how to do so, they study the elements of software engineering.

Software engineering is the discipline concerned with the application of theory, knowledge, and practice to effectively and efficiently build reliable software systems that satisfy the requirements of customers and users. This discipline is applicable to small, medium, and large-scale systems. It encompasses all phases of the lifecycle of a software system, including requirements elicitation, analysis and specification; design; construction; verification and validation; deployment; and operation and maintenance. Whether small or large, following a traditional plan-driven development process, an agile approach, or some other method, software engineering is concerned with the best way to build good software systems.

Software engineering uses engineering methods, processes, techniques, and measurements. It benefits from the use of tools for managing software development; analyzing and modeling software artifacts; assessing and controlling quality; and for ensuring a disciplined, controlled approach to software evolution and reuse. The software engineering toolbox has evolved over the years. For instance, the use of contracts, with requires and ensure clauses and class invariants, is one good practice that has become more common. Software development, which can involve an individual developer or a team or teams of developers, requires choosing the most appropriate tools, methods, and approaches for a given development environment.

Students and instructors need to understand the impacts of specialization on software engineering approaches. For example, specialized systems include:

- Real time systems
- Client-server systems
- Distributed systems
- Parallel systems
- Web-based systems
- High integrity systems
- Games
- Mobile computing
- Domain specific software (e.g., scientific computing or business applications)

Issues raised by each of these specialized systems demand specific treatments in each phase of software engineering. Students must become aware of the differences between general software engineering techniques and principles and the techniques and principles needed to address issues specific to specialized systems.

An important effect of specialization is that different choices of material may need to be made when teaching applications of software engineering, such as between different process models, different approaches to modeling systems, or different choices of techniques for carrying out any of the key activities. This is reflected in the assignment of core and elective material, with the core topics and learning outcomes focusing on the principles underlying the various choices, and the details of the various alternatives from which the choices have to be made being assigned to the elective material.

Another division of the practices of software engineering is between those concerned with the fundamental need to develop systems that implement correctly the functionality that is required for them and those concerned with other qualities for systems and the trade-offs needed to balance these qualities. This division too is reflected in the assignment of core and elective material, so that topics and learning outcomes concerned with the basic methods for developing

such system are assigned to the core and those that are concerned with other qualities and trade-offs between them are assigned to the elective material.

In general, students can best learn to apply much of the material defined in the Sofware Engineering KA by participating in a project. Such projects should require students to work on a team to develop a software system through as much of its lifecycle as is possible. Much of software engineering is devoted to effective communication among team members and stakeholders. Utilizing project teams, projects can be sufficiently challenging to require students to use effective software engineering techniques and to develop and practice their communication skills. While organizing and running effective projects within the academic framework can be challenging, the best way to learn to apply software engineering theory and knowledge is in the practical environment of a project. The minimum hours specified for some knowledge units in this document may appear insufficient to accomplish associated application-level learning outcomes. It should be understood that these outcomes are to be achieved through project experience that may even occur later in the curriculum than when the topics within the knowledge unit are introduced.

Further, there is increasing evidence that students learn to apply software engineering principles more effectively through an iterative approach, where students have the opportunity to work through a development cycle, assess their work, and then apply the knowledge gained through their assessment to another development cycle. Agile and iterative lifecycle models inherently afford such opportunities.

Software lifecycle terminology in this document is based on that used in earlier sources, such as the Software Engineering Body of Knowledge (SWEBOK) and the ACM/IEEE-CS Software Engineering 2004 Curriculum Guidelines (SE2004). While some terms were originally defined in the context of plan-driven development processes, they are treated here as generic, and thus equally applicable to agile processes.

Note: The SDF/Development Methods knowledge unit includes 9 Core-Tier1 hours that constitute an introduction to certain aspects of software engineering. The knowledge units, topics and core hour specifications in this Software Engineering Knowledge Area must be understood as assuming previous exposure to the material described in SDF/Development Methods.

SE. Software Engineering (6 Core-Tier1 hours; 21 Core-Tier2 hours)

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
SE/Software Processes	**2**	**1**	**Y**
SE/Software Project Management		**2**	**Y**
SE/Tools and Environments		**2**	**N**
SE/Requirements Engineering	**1**	**3**	**Y**
SE/Software Design	**3**	**5**	**Y**
SE/Software Construction		**2**	**Y**
SE/Software Verification and Validation		**4**	**Y**
SE/Software Evolution		**2**	**Y**
SE/Software Reliability		**1**	**Y**
SE/Formal Methods			**Y**

SE/Software Processes

[2 Core-Tier1 hours; 1 Core-Tier2 hour]

Topics:

[Core-Tier1]

- Systems level considerations, i.e., the interaction of software with its intended environment (cross-reference IAS/Secure Software Engineering)
- Introduction to software process models (e.g., waterfall, incremental, agile)
    - Activities within software lifecycles
- Programming in the large vs. individual programming

[Core-Tier2]

- Evaluation of software process models

[Elective]

- Software quality concepts
- Process improvement
- Software process capability maturity models
- Software process measurements

Learning Outcomes:

[Core-Tier1]

1. Describe how software can interact with and participate in various systems including information management, embedded, process control, and communications systems. [Familiarity]
2. Describe the relative advantages and disadvantages among several major process models (e.g., waterfall, iterative, and agile). [Familiarity]
3. Describe the different practices that are key components of various process models. [Familiarity]
4. Differentiate among the phases of software development. [Familiarity]
5. Describe how programming in the large differs from individual efforts with respect to understanding a large code base, code reading, understanding builds, and understanding context of changes. [Familiarity]

[Core-Tier2]

6. Explain the concept of a software lifecycle and provide an example, illustrating its phases including the deliverables that are produced. [Familiarity]
7. Compare several common process models with respect to their value for development of particular classes of software systems taking into account issues such as requirement stability, size, and non-functional characteristics. [Usage]

[Elective]

8. Define software quality and describe the role of quality assurance activities in the software process. [Familiarity]
9. Describe the intent and fundamental similarities among process improvement approaches. [Familiarity]
10. Compare several process improvement models such as CMM, CMMI, CQI, Plan-Do-Check-Act, or ISO9000. [Assessment]
11. Assess a development effort and recommend potential changes by participating in process improvement (using a model such as PSP) or engaging in a project retrospective. [Usage]
12. Explain the role of process maturity models in process improvement. [Familiarity]
13. Describe several process metrics for assessing and controlling a project. [Familiarity]
14. Use project metrics to describe the current state of a project. [Usage]

SE/Software Project Management

[2 Core-Tier2 hours]

Topics:

[Core-Tier2]

- Team participation
    - Team processes including responsibilities for tasks, meeting structure, and work schedule
    - Roles and responsibilities in a software team
    - Team conflict resolution
    - Risks associated with virtual teams (communication, perception, structure)
- Effort Estimation (at the personal level)
- Risk (cross reference IAS/Secure Software Engineering)
    - The role of risk in the lifecycle
    - Risk categories including security, safety, market, financial, technology, people, quality, structure and process

[Elective]

- Team management
    - Team organization and decision-making

    - Role identification and assignment
    - Individual and team performance assessment
- Project management
    - Scheduling and tracking
    - Project management tools
    - Cost/benefit analysis
- Software measurement and estimation techniques
- Software quality assurance and the role of measurements
- Risk
    - Risk identification and management
    - Risk analysis and evaluation
    - Risk tolerance (e.g., risk-adverse, risk-neutral, risk-seeking)
    - Risk planning
- System-wide approach to risk including hazards associated with tools

Learning Outcomes:

[Core-Tier2]

1. Discuss common behaviors that contribute to the effective functioning of a team. [Familiarity]
2. Create and follow an agenda for a team meeting. [Usage]
3. Identify and justify necessary roles in a software development team. [Usage]
4. Understand the sources, hazards, and potential benefits of team conflict. [Usage]
5. Apply a conflict resolution strategy in a team setting. [Usage]
6. Use an *ad hoc* method to estimate software development effort (e.g., time) and compare to actual effort required. [Usage]
7. List several examples of software risks. [Familiarity]
8. Describe the impact of risk in a software development lifecycle. [Familiarity]
9. Describe different categories of risk in software systems. [Familiarity]

[Elective]

10. Demonstrate through involvement in a team project the central elements of team building and team management. [Usage]
11. Describe how the choice of process model affects team organizational structures and decision-making processes. [Familiarity]
12. Create a team by identifying appropriate roles and assigning roles to team members. [Usage]
13. Assess and provide feedback to teams and individuals on their performance in a team setting. [Usage]
14. Using a particular software process, describe the aspects of a project that need to be planned and monitored, (e.g., estimates of size and effort, a schedule, resource allocation, configuration control, change management, and project risk identification and management). [Familiarity]
15. Track the progress of some stage in a project using appropriate project metrics. [Usage]
16. Compare simple software size and cost estimation techniques. [Usage]
17. Use a project management tool to assist in the assignment and tracking of tasks in a software development project. [Usage]
18. Describe the impact of risk tolerance on the software development process. [Assessment]
19. Identify risks and describe approaches to managing risk (avoidance, acceptance, transference, mitigation), and characterize the strengths and shortcomings of each. [Familiarity]
20. Explain how risk affects decisions in the software development process. [Usage]
21. Identify security risks for a software system. [Usage]
22. Demonstrate a systematic approach to the task of identifying hazards and risks in a particular situation. [Usage]
23. Apply the basic principles of risk management in a variety of simple scenarios including a security situation. [Usage]
24. Conduct a cost/benefit analysis for a risk mitigation approach. [Usage]
25. Identify and analyze some of the risks for an entire system that arise from aspects other than the software. [Usage]

SE/Tools and Environments

[2 Core-Tier2 hours]

Topics:

- Software configuration management and version control
- Release management
- Requirements analysis and design modeling tools
- Testing tools including static and dynamic analysis tools
- Programming environments that automate parts of program construction processes (e.g., automated builds)
    - Continuous integration
- Tool integration concepts and mechanisms

Learning Outcomes:

1. Describe the difference between centralized and distributed software configuration management. [Familiarity]
2. Describe how version control can be used to help manage software release management. [Familiarity]
3. Identify configuration items and use a source code control tool in a small team-based project. [Usage]
4. Describe how available static and dynamic test tools can be integrated into the software development environment. [Familiarity]
5. Describe the issues that are important in selecting a set of tools for the development of a particular software system, including tools for requirements tracking, design modeling, implementation, build automation, and testing. [Familiarity]
6. Demonstrate the capability to use software tools in support of the development of a software product of medium size. [Usage]

SE/Requirements Engineering

[1 Core-Tier1 hour; 3 Core-Tier2 hours]

The purpose of requirements engineering is to develop a common understanding of the needs, priorities, and constraints relevant to a software system. Many software failures arise from an incomplete understanding of requirements for the software to be developed or inadequate management of those requirements.

Specifications of requirements range in formality from completely informal (e.g., spoken) to rigorously mathematical (e.g., written in a formal specification language such as Z or first-order logic). In practice, successful software engineering efforts use requirements specifications to reduce ambiguity and improve the consistency and completeness of the development team's understanding of the vision of the intended software. Plan-driven approaches tend to produce formal documents with numbered requirements. Agile approaches tend to favor less formal specifications that include user stories, use cases, and test cases.

Topics:

[Core-Tier1]

- Describing functional requirements using, for example, use cases or users stories
- Properties of requirements including consistency, validity, completeness, and feasibility

[Core-Tier2]

- Software requirements elicitation
- Describing system data using, for example, class diagrams or entity-relationship diagrams
- Non-functional requirements and their relationship to software quality (cross-reference IAS/Secure Software Engineering)
- Evaluation and use of requirements specifications

[Elective]

- Requirements analysis modeling techniques
- Acceptability of certainty / uncertainty considerations regarding software / system behavior
- Prototyping
- Basic concepts of formal requirements specification
- Requirements specification
- Requirements validation
- Requirements tracing

Learning Outcomes:

[Core-Tier1]

1. List the key components of a use case or similar description of some behavior that is required for a system. [Familiarity]
2. Describe how the requirements engineering process supports the elicitation and validation of behavioral requirements. [Familiarity]
3. Interpret a given requirements model for a simple software system. [Familiarity]

[Core-Tier2]

4. Describe the fundamental challenges of and common techniques used for requirements elicitation. [Familiarity]
5. List the key components of a data model (e.g., class diagrams or ER diagrams). [Familiarity]
6. Identify both functional and non-functional requirements in a given requirements specification for a software system. [Usage]
7. Conduct a review of a set of software requirements to determine the quality of the requirements with respect to the characteristics of good requirements. [Usage]

[Elective]

8. Apply key elements and common methods for elicitation and analysis to produce a set of software requirements for a medium-sized software system. [Usage]
9. Compare the plan-driven and agile approaches to requirements specification and validation and describe the benefits and risks associated with each. [Familiarity]
10. Use a common, non-formal method to model and specify the requirements for a medium-size software system. [Usage]
11. Translate into natural language a software requirements specification (e.g., a software component contract) written in a formal specification language. [Usage]
12. Create a prototype of a software system to mitigate risk in requirements. [Usage]
13. Differentiate between forward and backward tracing and explain their roles in the requirements validation process. [Familiarity]

SE/Software Design

[3 Core-Tier1 hours; 5 Core-Tier2 hours]

Topics:

[Core-Tier1]

- System design principles: levels of abstraction (architectural design and detailed design), separation of concerns, information hiding, coupling and cohesion, re-use of standard structures
- Design Paradigms such as structured design (top-down functional decomposition), object-oriented analysis and design, event driven design, component-level design, data-structured centered, aspect oriented, function oriented, service oriented
- Structural and behavioral models of software designs
- Design patterns

[Core-Tier2]

- Relationships between requirements and designs: transformation of models, design of contracts, invariants
- Software architecture concepts and standard architectures (e.g. client-server, n-layer, transform centered, pipes-and-filters)
- Refactoring designs using design patterns
- The use of components in design: component selection, design, adaptation and assembly of components, components and patterns, components and objects (for example, building a GUI using a standard widget set)

[Elective]

- Internal design qualities, and models for them: efficiency and performance, redundancy and fault tolerance, traceability of requirements
- External design qualities, and models for them: functionality, reliability, performance and efficiency, usability, maintainability, portability
- Measurement and analysis of design quality
- Tradeoffs between different aspects of quality
- Application frameworks
- Middleware: the object-oriented paradigm within middleware, object request brokers and marshalling, transaction processing monitors, workflow systems
- Principles of secure design and coding (cross-reference IAS/Principles of Secure Design)
    - Principle of least privilege
    - Principle of fail-safe defaults
    - Principle of psychological acceptability

Learning Outcomes:

[Core-Tier1]

1. Articulate design principles including separation of concerns, information hiding, coupling and cohesion, and encapsulation. [Familiarity]
2. Use a design paradigm to design a simple software system, and explain how system design principles have been applied in this design. [Usage]
3. Construct models of the design of a simple software system that are appropriate for the paradigm used to design it. [Usage]
4. Within the context of a single design paradigm, describe one or more design patterns that could be applicable to the design of a simple software system. [Familiarity]

[Core-Tier2]

5. For a simple system suitable for a given scenario, discuss and select an appropriate design paradigm. [Usage]
6. Create appropriate models for the structure and behavior of software products from their requirements specifications. [Usage]
7. Explain the relationships between the requirements for a software product and its design, using appropriate models. [Assessment]
8. For the design of a simple software system within the context of a single design paradigm, describe the software architecture of that system. [Familiarity]
9. Given a high-level design, identify the software architecture by differentiating among common software architectures such as 3-tier, pipe-and-filter, and client-server. [Familiarity]
10. Investigate the impact of software architectures selection on the design of a simple system. [Assessment]
11. Apply simple examples of patterns in a software design. [Usage]
12. Describe a form of refactoring and discuss when it may be applicable. [Familiarity]
13. Select suitable components for use in the design of a software product. [Usage]
14. Explain how suitable components might need to be adapted for use in the design of a software product. [Familiarity]
15. Design a contract for a typical small software component for use in a given system. [Usage]

[Elective]

16. Discuss and select appropriate software architecture for a simple system suitable for a given scenario. [Usage]
17. Apply models for internal and external qualities in designing software components to achieve an acceptable tradeoff between conflicting quality aspects. [Usage]
18. Analyze a software design from the perspective of a significant internal quality attribute. [Assessment]
19. Analyze a software design from the perspective of a significant external quality attribute. [Assessment]
20. Explain the role of objects in middleware systems and the relationship with components. [Familiarity]
21. Apply component-oriented approaches to the design of a range of software, such as using components for concurrency and transactions, for reliable communication services, for database interaction including services for remote query and database management, or for secure communication and access. [Usage]
22. Refactor an existing software implementation to improve some aspect of its design. [Usage]
23. State and apply the principles of least privilege and fail-safe defaults. [Familiarity]

SE/Software Construction

[2 Core-Tier2 hours]

Topics:

[Core-Tier2]

- Coding practices: techniques, idioms/patterns, mechanisms for building quality programs (cross-reference IAS/Defensive Programming; SDF/Development Methods)
    - Defensive coding practices
    - Secure coding practices
    - Using exception handling mechanisms to make programs more robust, fault-tolerant
- Coding standards
- Integration strategies
- Development context: “green field” vs. existing code base
    - Change impact analysis
    - Change actualization

[Elective]

- Potential security problems in programs
    - Buffer and other types of overflows
    - Race conditions
    - Improper initialization, including choice of privileges
    - Checking input
    - Assuming success and correctness
    - Validating assumptions

Learning Outcomes:

[Core-Tier2]

1. Describe techniques, coding idioms and mechanisms for implementing designs to achieve desired properties such as reliability, efficiency, and robustness. [Familiarity]
2. Build robust code using exception handling mechanisms. [Usage]
3. Describe secure coding and defensive coding practices. [Familiarity]
4. Select and use a defined coding standard in a small software project. [Usage]
5. Compare and contrast integration strategies including top-down, bottom-up, and sandwich integration. [Familiarity]
6. Describe the process of analyzing and implementing changes to code base developed for a specific project. [Familiarity]
7. Describe the process of analyzing and implementing changes to a large existing code base. [Familiarity]

[Elective]

8. Rewrite a simple program to remove common vulnerabilities, such as buffer overflows, integer overflows and race conditions. [Usage]
9. Write a software component that performs some non-trivial task and is resilient to input and run-time errors. [Usage]

SE/Software Verification and Validation

[4 Core-Tier2 hours]

Topics:

[Core-Tier2]

- Verification and validation concepts
- Inspections, reviews, audits
- Testing types, including human computer interface, usability, reliability, security, conformance to specification (cross-reference IAS/Secure Software Engineering)
- Testing fundamentals (cross-reference SDF/Development Methods)
    - Unit, integration, validation, and system testing
    - Test plan creation and test case generation
    - Black-box and white-box testing techniques
    - Regression testing and test automation
- Defect tracking
- Limitations of testing in particular domains, such as parallel or safety-critical systems

[Elective]

- Static approaches and dynamic approaches to verification
- Test-driven development
- Validation planning; documentation for validation
- Object-oriented testing; systems testing
- Verification and validation of non-code artifacts (documentation, help files, training materials)
- Fault logging, fault tracking and technical support for such activities
- Fault estimation and testing termination including defect seeding

Learning Outcomes:

[Core-Tier2]

1. Distinguish between program validation and verification. [Familiarity]
2. Describe the role that tools can play in the validation of software. [Familiarity]
3. Undertake, as part of a team activity, an inspection of a medium-size code segment. [Usage]
4. Describe and distinguish among the different types and levels of testing (unit, integration, systems, and acceptance). [Familiarity]
5. Describe techniques for identifying significant test cases for integration, regression and system testing. [Familiarity]
6. Create and document a set of tests for a medium-size code segment. [Usage]
7. Describe how to select good regression tests and automate them. [Familiarity]
8. Use a defect tracking tool to manage software defects in a small software project. [Usage]
9. Discuss the limitations of testing in a particular domain. [Familiarity]

[Elective]

10. Evaluate a test suite for a medium-size code segment. [Usage]
11. Compare static and dynamic approaches to verification. [Familiarity]
12. Identify the fundamental principles of test-driven development methods and explain the role of automated testing in these methods. [Familiarity]
13. Discuss the issues involving the testing of object-oriented software. [Usage]
14. Describe techniques for the verification and validation of non-code artifacts. [Familiarity]
15. Describe approaches for fault estimation. [Familiarity]
16. Estimate the number of faults in a small software application based on fault density and fault seeding. [Usage]
17. Conduct an inspection or review of software source code for a small or medium sized software project. [Usage]

SE/Software Evolution

[2 Core-Tier2 hour]

Topics:

- Software development in the context of large, pre-existing code bases
    - Software change
    - Concerns and concern location
    - Refactoring
- Software evolution
- Characteristics of maintainable software
- Reengineering systems
- Software reuse

- Code segments
- Libraries and frameworks
- Components
- Product lines

Learning Outcomes:

1. Identify the principal issues associated with software evolution and explain their impact on the software lifecycle. [Familiarity]
2. Estimate the impact of a change request to an existing product of medium size. [Usage]
3. Use refactoring in the process of modifying a software component. [Usage]
4. Discuss the challenges of evolving systems in a changing environment. [Familiarity]
5. Outline the process of regression testing and its role in release management. [Familiarity]
6. Discuss the advantages and disadvantages of different types of software reuse. [Familiarity]

SE/Software Reliability

[1 Core-Tier2]

Topics:

[Core-Tier2]

- Software reliability engineering concepts
- Software reliability, system reliability and failure behavior (cross-reference SF/Reliability Through Redundancy)
- Fault lifecycle concepts and techniques

[Elective]

- Software reliability models
- Software fault tolerance techniques and models
- Software reliability engineering practices
- Measurement-based analysis of software reliability

Learning Outcomes:

[Core-Tier2]

1. Explain the problems that exist in achieving very high levels of reliability. [Familiarity]
2. Describe how software reliability contributes to system reliability. [Familiarity]
3. List approaches to minimizing faults that can be applied at each stage of the software lifecycle. [Familiarity]

[Elective]

4. Compare the characteristics of three different reliability modeling approaches. [Familiarity]
5. Demonstrate the ability to apply multiple methods to develop reliability estimates for a software system. [Usage]
6. Identify methods that will lead to the realization of a software architecture that achieves a specified level of reliability. [Usage]
7. Identify ways to apply redundancy to achieve fault tolerance for a medium-sized application. [Usage]

SE/Formal Methods

[Elective]

The topics listed below have a strong dependency on core material from the Discrete Structures (DS) Knowledge Area, particularly knowledge units DS/Functions Relations and Sets, DS/Basic Logic and DS/Proof Techniques.

***Topics*:**

- Role of formal specification and analysis techniques in the software development cycle
- Program assertion languages and analysis approaches (including languages for writing and analyzing pre- and post-conditions, such as OCL, JML)
- Formal approaches to software modeling and analysis
    - Model checkers
    - Model finders
- Tools in support of formal methods

Learning Outcomes:

1. Describe the role formal specification and analysis techniques can play in the development of complex software and compare their use as validation and verification techniques with testing. [Familiarity]
2. Apply formal specification and analysis techniques to software designs and programs with low complexity. [Usage]
3. Explain the potential benefits and drawbacks of using formal specification languages. [Familiarity]
4. Create and evaluate program assertions for a variety of behaviors ranging from simple through complex. [Usage]
5. Using a common formal specification language, formulate the specification of a simple software system and derive examples of test cases from the specification. [Usage]

Systems Fundamentals (SF)

The underlying hardware and software infrastructure upon which applications are constructed is collectively described by the term "computer systems." Computer systems broadly span the sub-disciplines of operating systems, parallel and distributed systems, communications networks, and computer architecture. Traditionally, these areas are taught in a non-integrated way through independent courses. However these sub-disciplines increasingly share important common fundamental concepts within their respective cores. These concepts include computational paradigms, parallelism, cross-layer communications, state and state transition, resource allocation and scheduling, and so on. The Systems Fundamentals Knowledge Area is designed to present an integrative view of these fundamental concepts in a unified albeit simplified fashion, providing a common foundation for the different specialized mechanisms and policies appropriate to the particular domain area.

SF. Systems Fundamentals. [18 Core-Tier1 hours, 9 Core-Tier2 hours]

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
SF/Computational Paradigms	**3**		**N**
SF/Cross-Layer Communications	**3**		**N**
SF/State and State Machines	**6**		**N**
SF/Parallelism	**3**		**N**
SF/Evaluation	**3**		**N**
SF/Resource Allocation and Scheduling		**2**	**N**
SF/Proximity		**3**	**N**
SF/Virtualization and Isolation		**2**	**N**
SF/Reliability through Redundancy		**2**	**N**
SF/Quantitative Evaluation			**Y**

SF/Computational Paradigms

[3 Core-Tier1 hours]

The view presented here is the multiple representations of a system across layers, from hardware building blocks to application components, and the parallelism available in each representation. Cross-reference PD/Parallelism Fundamentals.

***Topics**:*

- Basic building blocks and components of a computer (gates, flip-flops, registers, interconnections; Datapath + Control + Memory)
- Hardware as a computational paradigm: Fundamental logic building blocks; Logic expressions, minimization, sum of product forms
- Application-level sequential processing: single thread
- Simple application-level parallel processing: request level (web services/client-server/distributed), single thread per server, multiple threads with multiple servers
- Basic concept of pipelining, overlapped processing stages
- Basic concept of scaling: going faster vs. handling larger problems

Learning Outcomes:

1. List commonly encountered patterns of how computations are organized. [Familiarity]
2. Describe the basic building blocks of computers and their role in the historical development of computer architecture. [Familiarity]
3. Articulate the differences between single thread vs. multiple thread, single server vs. multiple server models, motivated by real world examples (e.g., cooking recipes, lines for multiple teller machines and couples shopping for food). [Familiarity]
4. Articulate the concept of strong vs. weak scaling, i.e., how performance is affected by scale of problem vs. scale of resources to solve the problem. This can be motivated by the simple, real-world examples. [Familiarity]
5. Design a simple logic circuit using the fundamental building blocks of logic design. [Usage]
6. Use tools for capture, synthesis, and simulation to evaluate a logic design. [Usage]
7. Write a simple sequential problem and a simple parallel version of the same program. [Usage]
8. Evaluate performance of simple sequential and parallel versions of a program with different problem sizes, and be able to describe the speed-ups achieved. [Assessment]

SF/Cross-Layer Communications

Cross-reference NC/Introduction, OS/Operating Systems Principles

[3 Core-Tier1 hours]

***Topics**:*

- Programming abstractions, interfaces, use of libraries
- Distinction between Application and OS services, Remote Procedure Call
- Application-Virtual Machine Interaction
- Reliability

***Learning Outcomes**:*

1. Describe how computing systems are constructed of layers upon layers, based on separation of concerns, with well-defined interfaces, hiding details of low layers from the higher layers. [Familiarity]

2. Describe how hardware, VM, OS, and applications are additional layers of interpretation/processing. [Familiarity]
3. Describe the mechanisms of how errors are detected, signaled back, and handled through the layers. [Familiarity]
4. Construct a simple program using methods of layering, error detection and recovery, and reflection of error status across layers. [Usage]
5. Find bugs in a layered program by using tools for program tracing, single stepping, and debugging. [Usage]

SF/State and State Machines

[6 Core-Tier1 hours]

Cross-reference AL/Basic Computability and Complexity, OS/State and State Diagrams, NC/Protocols

Topics:

- Digital vs. Analog/Discrete vs. Continuous Systems
- Simple logic gates, logical expressions, Boolean logic simplification
- Clocks, State, Sequencing
- Combinational Logic, Sequential Logic, Registers, Memories
- Computers and Network Protocols as examples of state machines

Learning Outcomes:

1. Describe computations as a system characyterized by a known set of configurations with transitions from one unique configuration (state) to another (state). [Familiarity]
2. Describe the distinction between systems whose output is only a function of their input (Combinational) and those with memory/history (Sequential). [Familiarity]
3. Describe a computer as a state machine that interprets machine instructions. [Familiarity]
4. Explain how a program or network protocol can also be expressed as a state machine, and that alternative representations for the same computation can exist. [Familiarity]
5. Develop state machine descriptions for simple problem statement solutions (e.g., traffic light sequencing, pattern recognizers). [Usage]
6. Derive time-series behavior of a state machine from its state machine representation. [Assessment]

SF/Parallelism

[3 Core-Tier1 hours]

Cross-reference PD/Parallelism Fundamentals.

Topics*:*

- Sequential vs. parallel processing
- Parallel programming vs. concurrent programming
- Request parallelism vs. Task parallelism
- Client-Server/Web Services, Thread (Fork-Join), Pipelining
- Multicore architectures and hardware support for synchronization

***Learning Outcomes**:*

1. For a given program, distinguish between its sequential and parallel execution, and the performance implications thereof. [Familiarity]
2. Demonstrate on an execution time line that parallelism events and operations can take place simultaneously (i.e., at the same time). Explain how work can be performed in less elapsed time if this can be exploited. [Familiarity]
3. Explain other uses of parallelism, such as for reliability/redundancy of execution. [Familiarity]
4. Define the differences between the concepts of Instruction Parallelism, Data Parallelism, Thread Parallelism/Multitasking, Task/Request Parallelism. [Familiarity]
5. Write more than one parallel program (e.g., one simple parallel program in more than one parallel programming paradigm; a simple parallel program that manages shared resources through synchronization primitives; a simple parallel program that performs simultaneous operation on partitioned data through task parallel (e.g., parallel search terms; a simple parallel program that performs step-by-step pipeline processing through message passing). [Usage]
6. Use performance tools to measure speed-up achieved by parallel programs in terms of both problem size and number of resources. [Assessment]

SF/Evaluation

[3 Core-Tier1 hours]

Cross-reference PD/Parallel Performance.

***Topics**:*

- Performance figures of merit
- Workloads and representative benchmarks, and methods of collecting and analyzing performance figures of merit
- CPI (Cycles per Instruction) equation as tool for understanding tradeoffs in the design of instruction sets, processor pipelines, and memory system organizations.
- Amdahl's Law: the part of the computation that cannot be sped up limits the effect of the parts that can

***Learning Outcomes**:*

1. Explain how the components of system architecture contribute to improving its performance. [Familiarity]
2. Describe Amdahl's law and discuss its limitations. [Familiarity]
3. Design and conduct a performance-oriented experiment. [Usage]
4. Use software tools to profile and measure program performance. [Assessment]

SF/Resource Allocation and Scheduling

[2 Core-Tier2 hours]

***Topics**:*

- Kinds of resources (e.g., processor share, memory, disk, net bandwidth)
- Kinds of scheduling (e.g., first-come, priority)
- Advantages of fair scheduling, preemptive scheduling

***Learning Outcomes**:*

1. Define how finite computer resources (e.g., processor share, memory, storage and network bandwidth) are managed by their careful allocation to existing entities. [Familiarity]

2. Describe the scheduling algorithms by which resources are allocated to competing entities, and the figures of merit by which these algorithms are evaluated, such as fairness. [Familiarity]
3. Implement simple schedule algorithms. [Usage]
4. Use figures of merit of alternative scheduler implementations. [Assessment]

SF/Proximity

[3 Core-Tier2 hours]

Cross-reference AR/Memory Management, OS/Virtual Memory.

***Topics**:*

- Speed of light and computers (one foot per nanosecond vs. one GHz clocks)
- Latencies in computer systems: memory vs. disk latencies vs. across the network memory
- Caches and the effects of spatial and temporal locality on performance in processors and systems
- Caches and cache coherency in databases, operating systems, distributed systems, and computer architecture
- Introduction into the processor memory hierarchy and the formula for average memory access time

***Learning Outcomes**:*

1. Explain the importance of locality in determining performance. [Familiarity]
2. Describe why things that are close in space take less time to access. [Familiarity]
3. Calculate average memory access time and describe the tradeoffs in memory hierarchy performance in terms of capacity, miss/hit rate, and access time. [Assessment]

SF/Virtualization and Isolation

[2 Core-Tier2 hours]

***Topics**:*

- Rationale for protection and predictable performance
- Levels of indirection, illustrated by virtual memory for managing physical memory resources
- Methods for implementing virtual memory and virtual machines

***Learning Outcomes**:*

1. Explain why it is important to isolate and protect the execution of individual programs and environments that share common underlying resources. [Familiarity]
2. Describe how the concept of indirection can create the illusion of a dedicated machine and its resources even when physically shared among multiple programs and environments. [Familiarity]
3. Measure the performance of two application instances running on separate virtual machines, and determine the effect of performance isolation. [Assessment]

SF/Reliability through Redundancy

[2 Core-Tier2 hours]

***Topics**:*

- Distinction between bugs and faults
- Redundancy through check and retry

- Redundancy through redundant encoding (error correcting codes, CRC, FEC)
- Duplication/mirroring/replicas
- Other approaches to fault tolerance and availability

***Learning Outcomes**:*

1. Explain the distinction between program errors, system errors, and hardware faults (e.g., bad memory) and exceptions (e.g., attempt to divide by zero). [Familiarity]
2. Articulate the distinction between detecting, handling, and recovering from faults, and the methods for their implementation. [Familiarity]
3. Describe the role of error correcting codes in providing error checking and correction techniques in memories, storage, and networks. [Familiarity]
4. Apply simple algorithms for exploiting redundant information for the purposes of data correction. [Usage]
5. Compare different error detection and correction methods for their data overhead, implementation complexity, and relative execution time for encoding, detecting, and correcting errors. [Assessment]

SF/Quantitative Evaluation

[Elective]

***Topics**:*

- Analytical tools to guide quantitative evaluation
- Order of magnitude analysis (Big-Oh notation)
- Analysis of slow and fast paths of a system
- Events on their effect on performance (e.g., instruction stalls, cache misses, page faults)
- Understanding layered systems, workloads, and platforms, their implications for performance, and the challenges they represent for evaluation
- Microbenchmarking pitfalls

***Learning Outcomes**:*

1. Explain the circumstances in which a given figure of system performance metric is useful. [Familiarity]
2. Explain the inadequacies of benchmarks as a measure of system performance. [Familiarity]
3. Use limit studies or simple calculations to produce order-of-magnitude estimates for a given performance metric in a given context. [Usage]
4. Conduct a performance experiment on a layered system to determine the effect of a system parameter on figure of system performance. [Assessment]

Social Issues and Professional Practice (SP)

While technical issues are central to the computing curriculum, they do not constitute a complete educational program in the field. Students must also be exposed to the larger societal context of computing to develop an understanding of the relevant social, ethical, legal and professional issues. This need to incorporate the study of these non-technical issues into the ACM curriculum was formally recognized in 1991, as can be seen from the following excerpt [2]:

> *Undergraduates also need to understand the basic cultural, social, legal, and ethical issues inherent in the discipline of computing. They should understand where the discipline has been, where it is, and where it is heading. They should also understand their individual roles in this process, as well as appreciate the philosophical questions, technical problems, and aesthetic values that play an important part in the development of the discipline.*
>
> *Students also need to develop the ability to ask serious questions about the social impact of computing and to evaluate proposed answers to those questions. Future practitioners must be able to anticipate the impact of introducing a given product into a given environment. Will that product enhance or degrade the quality of life? What will the impact be upon individuals, groups, and institutions?*
>
> *Finally, students need to be aware of the basic legal rights of software and hardware vendors and users, and they also need to appreciate the ethical values that are the basis for those rights. Future practitioners must understand the responsibility that they will bear, and the possible consequences of failure. They must understand their own limitations as well as the limitations of their tools. All practitioners must make a long-term commitment to remaining current in their chosen specialties and in the discipline of computing as a whole.*

As technological advances continue to significantly impact the way we live and work, the critical importance of social issues and professional practice continues to increase; new computer-based products and venues pose ever more challenging problems each year. It is our students who must enter the workforce and academia with intentional regard for the identification and resolution of these problems.

Computer science educators may opt to deliver this core and elective material in stand-alone courses, integrated into traditional technical and theoretical courses, or as special units in capstone and professional practice courses. The material in this familiarity area is best covered through a combination of one required course along with short modules in other courses. On the one hand, some units listed as Core Tier-1 (in particular, Social Context, Analytical Tools, Professional Ethics, and Intellectual Property) do not readily lend themselves to being covered in other traditional courses. Without a standalone course, it is difficult to cover these topics appropriately. On the other hand, if ethical and social considerations are covered only in the standalone course and not "in context," it will reinforce the false notion that technical processes are void of these other relevant issues. Because of this broad relevance, it is important that several traditional courses include modules with case studies that analyze the ethical, legal, social and professional considerations in the context of the technical subject matter of the course. Courses in areas such as software engineering, databases, computer networks, information assurance and security, and introduction to computing provide obvious context for analysis of ethical issues. However, an ethics-related module could be developed for almost any course in the curriculum. It would be explicitly against the spirit of the recommendations to have only a standalone course. Running through all of the issues in this area is the need to speak to the computing practitioner's responsibility to proactively address these issues by both moral and technical actions. The ethical issues discussed in any class should be directly related to and arise naturally from the subject matter of that class. Examples include a discussion in the database course of data aggregation or data mining, or a discussion in the software engineering course of the potential conflicts between obligations to the customer and obligations to the user and others affected by their work. Programming assignments built around applications such as controlling the movement of a laser during eye surgery can help to address the professional, ethical and social impacts of computing. Computing faculty who are unfamiliar with the content and/or pedagogy of applied ethics are urged to take advantage of the considerable resources from ACM, IEEE-CS, SIGCAS (special interest group on computers and society), and other organizations.

It should be noted that the application of ethical analysis underlies every subsection of this Social and Professional knowledge area in computing. The ACM Code of Ethics and Professional Conduct (http://www.acm.org/about/code-of-ethics) provides guidelines that serve as the basis for the conduct of our professional work. The General Moral Imperatives provide an

understanding of our commitment to personal responsibility, professional conduct, and our leadership roles.

SP. Social Issues and Professional Practice. [11 Core-Tier1 hours, 5 Core-Tier2 hours]

	Core-Tier1 hours	Core-Tier2 hours	Includes Electives
SP/Social Context	**1**	**2**	**N**
SP/Analytical Tools	**2**		**N**
SP/Professional Ethics	**2**	**2**	**N**
SP/Intellectual Property	**2**		**Y**
SP/Privacy and Civil Liberties	**2**		**Y**
SP/Professional Communication	**1**		**Y**
SP/Sustainability	**1**	**1**	**Y**
SP/History			**Y**
SP/Economies of Computing			**Y**
SP/Security Policies, Laws and Computer Crimes			**Y**

SP/Social Context

[1 Core-Tier1 hour, 2 Core-Tier2 hours]

Computers and the Internet, perhaps more than any other technologies, have transformed society over the past 75 years, with dramatic increases in human productivity; an explosion of options for news, entertainment, and communication; and fundamental breakthroughs in almost every branch of science and engineering. Social Context provides the foundation for all other SP knowledge units, especially Professional Ethics. Also see cross-referencing with Human-Computer Interaction (HCI) and Networking and Communication (NC) Knowledge Areas.

Topics:

[Core-Tier1]

- Social implications of computing in a networked world (cross-reference HCI/Foundations/social models; IAS/Fundamental Concepts/social issues)
- Impact of social media on individualism, collectivism and culture.

[Core-Tier2]

- Growth and control of the Internet (cross-reference NC/Introduction/organization of the Internet)
- Often referred to as the digital divide, differences in access to digital technology resources and its resulting ramifications for gender, class, ethnicity, geography, and/or underdeveloped countries.
- Accessibility issues, including legal requirements
- Context-aware computing (cross-reference HCI/Design for non-mouse interfaces/ ubiquitous and context-aware)

Learning Outcomes:

[Core-Tier1]

1. Describe positive and negative ways in which computer technology (networks, mobile computing, cloud computing) alters modes of social interaction at the personal level. [Familiarity]
2. Identify developers' assumptions and values embedded in hardware and software design, especially as they pertain to usability for diverse populations including under-represented populations and the disabled. [Familiarity]
3. Interpret the social context of a given design and its implementation. [Familiarity]
4. Evaluate the efficacy of a given design and implementation using empirical data. [Assessment]
5. Summarize the implications of social media on individualism versus collectivism and culture. [Usage]

[Core-Tier2]

6. Discuss how Internet access serves as a liberating force for people living under oppressive forms of government; explain how limits on Internet access are used as tools of political and social repression. [Familiarity]
7. Analyze the pros and cons of reliance on computing in the implementation of democracy (e.g. delivery of social services, electronic voting). [Assessment]
8. Describe the impact of the under-representation of diverse populations in the computing profession (e.g., industry culture, product diversity). [Familiarity]
9. Explain the implications of context awareness in ubiquitous computing systems. [Familiarity]

SP/Analytical Tools

[2 Core-Tier1 hours]

Ethical theories and principles are the foundations of ethical analysis because they are the viewpoints from which guidance can be obtained along the pathway to a decision. Each theory emphasizes different points such as predicting the outcome and following one's duties to others in order to reach an ethically guided decision. However, in order for an ethical theory to be useful, the theory must be directed towards a common set of goals. Ethical principles are the common goals that each theory tries to achieve in order to be successful. These goals include beneficence, least harm, respect for autonomy, and justice.

Topics:

- Ethical argumentation
- Ethical theories and decision-making
- Moral assumptions and values

Learning Outcomes:

1. Evaluate stakeholder positions in a given situation. [Assessment]
2. Analyze basic logical fallacies in an argument. [Assessment]
3. Analyze an argument to identify premises and conclusion. [Assessment]
4. Illustrate the use of example and analogy in ethical argument. [Usage]
5. Evaluate ethical/social tradeoffs in technical decisions. [Assessment]

SP/Professional Ethics

[2 Core-Tier1 hours, 2 Core-Tier2 hours]

Computer ethics is a branch of practical philosophy that deals with how computing professionals should make decisions regarding professional and social conduct. There are three primary influences: 1) an individual's own personal code; 2) any informal code of ethical behavior existing in the work place; and 3) exposure to formal codes of ethics. See cross-referencing with the Information Assurance and Security (IAS) Knowledge Area.

Topics:

[Core-Tier1]

- Community values and the laws by which we live
- The nature of professionalism including care, attention and discipline, fiduciary responsibility, and mentoring
- Keeping up-to-date as a computing professional in terms of familiarity, tools, skills, legal and professional framework as well as the ability to self-assess and progress in the computing field
- Professional certification, codes of ethics, conduct, and practice, such as the ACM/IEEE-CS, SE, AITP, IFIP and international societies (cross-reference IAS/Fundamental Concepts/ethical issues)
- Accountability, responsibility and liability (e.g. software correctness, reliability and safety, as well as ethical confidentiality of cybersecurity professionals)

[Core-Tier2]

- The role of the computing professional in public policy
- Maintaining awareness of consequences
- Ethical dissent and whistle-blowing
- The relationship between regional culture and ethical dilemmas
- Dealing with harassment and discrimination
- Forms of professional credentialing
- Acceptable use policies for computing in the workplace
- Ergonomics and healthy computing environments
- Time to market and cost considerations versus quality professional standards

Learning Outcomes:

[Core-Tier1]

1. Identify ethical issues that arise in software development and determine how to address them technically and ethically. [Familiarity]
2. Explain the ethical responsibility of ensuring software correctness, reliability and safety. [Familiarity]
3. Describe the mechanisms that typically exist for a professional to keep up-to-date. [Familiarity]

4. Describe the strengths and weaknesses of relevant professional codes as expressions of professionalism and guides to decision-making. [Familiarity]
5. Analyze a global computing issue, observing the role of professionals and government officials in managing this problem. [Assessment]
6. Evaluate the professional codes of ethics from the ACM, the IEEE Computer Society, and other organizations. [Assessment]

[Core-Tier2]

7. Describe ways in which professionals may contribute to public policy. [Familiarity]
8. Describe the consequences of inappropriate professional behavior. [Familiarity]
9. Identify progressive stages in a whistle-blowing incident. [Familiarity]
10. Identify examples of how regional culture interplays with ethical dilemmas. [Familiarity]
11. Investigate forms of harassment and discrimination and avenues of assistance. [Usage]
12. Examine various forms of professional credentialing. [Usage]
13. Explain the relationship between ergonomics in computing environments and people's health. [Familiarity]
14. Develop a computer usage/acceptable use policy with enforcement measures. [Assessment]
15. Describe issues associated with industries' push to focus on time to market versus enforcing quality professional standards. [Familiarity]

SP/Intellectual Property

[2 Core-Tier1 hours]

Intellectual property refers to a range of intangible rights of ownership in an asset such as a software program. Each intellectual property "right" is itself an asset. The law provides different methods for protecting these rights of ownership based on their type. There are essentially four types of intellectual property rights relevant to software: patents, copyrights, trade secrets and trademarks. Each affords a different type of legal protection. See cross-referencing with the Information Management (IM) Knowledge Area.

Topics:

[Core-Tier1]

- Philosophical foundations of intellectual property
- Intellectual property rights (cross-reference IM/Information Storage and Retrieval/intellectual property and protection)
- Intangible digital intellectual property (IDIP)
- Legal foundations for intellectual property protection
- Digital rights management
- Copyrights, patents, trade secrets, trademarks
- Plagiarism

[Elective]

- Foundations of the open source movement
- Software piracy

Learning Outcomes:

[Core-Tier1]

1. Discuss the philosophical bases of intellectual property. [Familiarity]
2. Discuss the rationale for the legal protection of intellectual property. [Familiarity]
3. Describe legislation aimed at digital copyright infringements. [Familiarity]
4. Critique legislation aimed at digital copyright infringements. [Assessment]
5. Identify contemporary examples of intangible digital intellectual property. [Familiarity]
6. Justify uses of copyrighted materials. [Assessment]
7. Evaluate the ethical issues inherent in various plagiarism detection mechanisms. [Assessment]
8. Interpret the intent and implementation of software licensing. [Familiarity]
9. Discuss the issues involved in securing software patents. [Familiarity]
10. Characterize and contrast the concepts of copyright, patenting and trademarks. [Assessment]

[Elective]

11. Identify the goals of the open source movement. [Familiarity]
12. Identify the global nature of software piracy. [Familiarity]

SP/Privacy and Civil Liberties

[2 Core-Tier1 hours]

Electronic information sharing highlights the need to balance privacy protections with information access. The ease of digital access to many types of data makes privacy rights and civil liberties more complex, differing among the variety of cultures worldwide. See cross-referencing with the Human-Computer Interaction (HCI), Information Assurance and Security (IAS), Information Management (IM), and Intelligent Systems (IS) Knowledge Areas.

Topics:

[Core-Tier1]

- Philosophical foundations of privacy rights (cross-reference IS/Fundamental Issues/philosophical issues)
- Legal foundations of privacy protection
- Privacy implications of widespread data collection for transactional databases, data warehouses, surveillance systems, and cloud computing (cross-reference IM/Database Systems/data independence; IM/Data Mining/data cleaning)
- Ramifications of differential privacy
- Technology-based solutions for privacy protection (cross-reference IAS/Threats and Attacks/attacks on privacy and anonymity)

[Elective]

- Privacy legislation in areas of practice
- Civil liberties and cultural differences
- Freedom of expression and its limitations

Learning Outcomes:

[Core-Tier1]

1. Discuss the philosophical basis for the legal protection of personal privacy. [Familiarity]
2. Evaluate solutions to privacy threats in transactional databases and data warehouses. [Assessment]

3. Describe the role of data collection in the implementation of pervasive surveillance systems (e.g., RFID, face recognition, toll collection, mobile computing). [Familiarity]
4. Describe the ramifications of differential privacy. [Familiarity]
5. Investigate the impact of technological solutions to privacy problems. [Usage]

[Elective]

6. Critique the intent, potential value and implementation of various forms of privacy legislation. [Assessment]
7. Identify strategies to enable appropriate freedom of expression. [Familiarity]

SP/Professional Communication

[1 Core-Tier1 hour]

Professional communication conveys technical information to various audiences who may have very different goals and needs for that information. Effective professional communication of technical information is rarely an inherited gift, but rather needs to be taught in context throughout the undergraduate curriculum. See cross-referencing with Human-Computer Interaction (HCI) and Software Engineering (SE) Knowledge Areas.

Topics:

[Core-Tier1]

- Reading, understanding and summarizing technical material, including source code and documentation
- Writing effective technical documentation and materials
- Dynamics of oral, written, and electronic team and group communication (cross-reference HCI/Collaboration and Communication/group communication; SE/Project Management/team participation)
- Communicating professionally with stakeholders
- Utilizing collaboration tools (cross-reference HCI/Collaboration and Communication/online communities; IS/Agents/collaborative agents)

[Elective]

- Dealing with cross-cultural environments (cross-reference HCI/User-Centered Design and Testing/cross-cultural evaluation)
- Tradeoffs of competing risks in software projects, such as technology, structure/process, quality, people, market and financial (cross-reference SE/Software Project Management/Risk)

Learning Outcomes:

[Core-Tier1]

1. Write clear, concise, and accurate technical documents following well-defined standards for format and for including appropriate tables, figures, and references. [Usage]
2. Evaluate written technical documentation to detect problems of various kinds. [Assessment]
3. Develop and deliver a good quality formal presentation. [Assessment]
4. Plan interactions (e.g. virtual, face-to-face, shared documents) with others in which they are able to get their point across, and are also able to listen carefully and appreciate the points of others, even when they disagree, and are able to convey to others what they have heard. [Usage]
5. Describe the strengths and weaknesses of various forms of communication (e.g. virtual, face-to-face, shared documents). [Familiarity]
6. Examine appropriate measures used to communicate with stakeholders involved in a project. [Usage]
7. Compare and contrast various collaboration tools. [Assessment]

[Elective]

8. Discuss ways to influence performance and results in cross-cultural teams. [Familiarity]
9. Examine the tradeoffs and common sources of risk in software projects regarding technology, structure/process, quality, people, market and financial. [Usage]
10. Evaluate personal strengths and weaknesses to work remotely as part of a multinational team. [Assessment]

SP/Sustainability

[1 Core-Tier1 hour, 1 Core-Tier2 hour]

Sustainability is characterized by the United Nations [1] as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainability was first introduced in the CS2008 curricular guidelines. Topics in this emerging area can be naturally integrated into other familiarity areas and units, such as human-computer interaction and software evolution. See cross-referencing with the Human-Computer Interaction (HCI) and Software Engineering (SE) Knowledge Areas.

Topics:

[Core-Tier1]

- Being a sustainable practitioner by taking into consideration cultural and environmental impacts of implementation decisions (e.g. organizational policies, economic viability, and resource consumption).
- Explore global social and environmental impacts of computer use and disposal (e-waste)

[Core-Tier2]

- Environmental impacts of design choices in specific areas such as algorithms, operating systems, networks, databases, or human-computer interaction (cross-reference SE/Software Evaluation/software evolution; HCI/Design-Oriented HCI/sustainability)

[Elective]

- Guidelines for sustainable design standards
- Systemic effects of complex computer-mediated phenomena (e.g. telecommuting or web shopping)
- Pervasive computing; information processing integrated into everyday objects and activities, such as smart energy systems, social networking and feedback systems to promote sustainable behavior, transportation, environmental monitoring, citizen science and activism.
- Research on applications of computing to environmental issues, such as energy, pollution, resource usage, recycling and reuse, food management, farming and others.
- The interdependence of the sustainability of software systems with social systems, including the knowledge and skills of its users, organizational processes and policies, and its societal context (e.g., market forces, government policies).

Learning Outcomes:

[Core-Tier1]

1. Identify ways to be a sustainable practitioner. [Familiarity]
2. Illustrate global social and environmental impacts of computer use and disposal (e-waste). [Usage]

[Core-Tier2]

3. Describe the environmental impacts of design choices within the field of computing that relate to algorithm design, operating system design, networking design, database design, etc. [Familiarity]
4. Investigate the social and environmental impacts of new system designs through projects. [Usage]

[Elective]

5. Identify guidelines for sustainable IT design or deployment. [Familiarity]
6. List the sustainable effects of telecommuting or web shopping. [Familiarity]
7. Investigate pervasive computing in areas such as smart energy systems, social networking, transportation, agriculture, supply-chain systems, environmental monitoring and citizen activism. [Usage]
8. Develop applications of computing and assess through research areas pertaining to environmental issues (e.g. energy, pollution, resource usage, recycling and reuse, food management, farming). [Assessment]

SP/History

[Elective]

This history of computing is taught to provide a sense of how the rapid change in computing impacts society on a global scale. It is often taught in context with foundational concepts, such as system fundamentals and software developmental fundamentals.

Topics:

- Prehistory—the world before 1946
- History of computer hardware, software, networking (cross-reference AR/Digital logic and digital systems/ history of computer architecture)
- Pioneers of computing
- History of the Internet

Learning Outcomes:

1. Identify significant continuing trends in the history of the computing field. [Familiarity]
2. Identify the contributions of several pioneers in the computing field. [Familiarity]
3. Discuss the historical context for several programming language paradigms. [Familiarity]
4. Compare daily life before and after the advent of personal computers and the Internet. [Assessment]

SP/Economies of Computing

[Elective]

Economics of computing encompasses the metrics and best practices for personnel and financial management surrounding computer information systems.

Topics:

- Monopolies and their economic implications
- Effect of skilled labor supply and demand on the quality of computing products
- Pricing strategies in the computing domain
- The phenomenon of outsourcing and off-shoring software development; impacts on employment and on economics
- Consequences of globalization for the computer science profession

- Differences in access to computing resources and the possible effects thereof
- Cost/benefit analysis of jobs with considerations to manufacturing, hardware, software, and engineering implications
- Cost estimates versus actual costs in relation to total costs
- Entrepreneurship: prospects and pitfalls
- Network effect or demand-side economies of scale
- Use of engineering economics in dealing with finances

Learning Outcomes:

1. Summarize the rationale for antimonopoly efforts. [Familiarity]
2. Identify several ways in which the information technology industry is affected by shortages in the labor supply. [Familiarity]
3. Identify the evolution of pricing strategies for computing goods and services. [Familiarity]
4. Discuss the benefits, the drawbacks and the implications of off-shoring and outsourcing. [Familiarity]
5. Investigate and defend ways to address limitations on access to computing. [Usage]
6. Describe the economic benefits of network effects. [Familiarity]

SP/Security Policies, Laws and Computer Crimes

[Elective]

While security policies, laws and computer crimes are important subjects, it is essential they are viewed with the foundation of other Social and Professional knowledge units, such as Intellectual Property, Privacy and Civil Liberties, Social Context, and Professional Ethics. Computers and the Internet, perhaps more than any other technology, have transformed society over the past 75 years. At the same time, they have contributed to unprecedented threats to privacy; whole new categories of crime and anti-social behavior; major disruptions to organizations; and the large-scale concentration of risk into information systems. See cross-referencing with the Human-Computer Interaction (HCI) and Information Assurance and Security (IAS) Knowledge Areas.

Topics:

- Examples of computer crimes and legal redress for computer criminals (cross-reference IAS/Digital Forensics/rules of evidence)
- Social engineering, identity theft and recovery (cross-reference HCI/Human Factors and Security/trust, privacy and deception)
- Issues surrounding the misuse of access and breaches in security
- Motivations and ramifications of cyber terrorism and criminal hacking, “cracking”
- Effects of malware, such as viruses, worms and Trojan horses
- Crime prevention strategies
- Security policies (cross-reference IAS/Security Policy and Governance/policies)

Learning Outcomes:

1. List classic examples of computer crimes and social engineering incidents with societal impact. [Familiarity]
2. Identify laws that apply to computer crimes. [Familiarity]
3. Describe the motivation and ramifications of cyber terrorism and criminal hacking. [Familiarity]
4. Examine the ethical and legal issues surrounding the misuse of access and various breaches in security. [Usage]

5. Discuss the professional's role in security and the trade-offs involved. [Familiarity]
6. Investigate measures that can be taken by both individuals and organizations including governments to prevent or mitigate the undesirable effects of computer crimes and identity theft. [Usage]
7. Write a company-wide security policy, which includes procedures for managing passwords and employee monitoring. [Usage]

References

[1] "Our Common Future." http://grawemeyer.org/worldorder/previous-winners/1991-the-united-nations-world-commission-on-environment-and-development.html

[2] Tucker, A. (ed), B. Barnes, R. Aiken, K. Barker, K. Bruce, J. Cain, S. Conry, G. Engel, R. Epstein, D. Lidtke, M. Mulder, J. Rogers, E. Spafford, A. Turner, *Computing Curricula 1991: Report of the Joint Curriculum Task Force*, ACM Press and IEEE-CS Press, 1991.

Appendix B: Migrating to CS2013

A goal of CS2013 is to create guidelines that are realistic and implementable. One question that often arises is, "How are these guidelines different from what we already do?" While it is not possible in this document to answer that question for each institution, it is possible to describe in general terms how these guidelines differ from previous versions in order to provide assistance to curriculum developers in moving towards the CS2013 recommendations.

Due to advancements in the field and the increased needs of stakeholders, CS2013 has reorganized and expanded the number of topics. However, few institutions have the luxury of expanding their programs to accommodate a larger body of knowledge. CS2013 has taken the following approaches to managing the size of curricula:

- The core material has been divided into Core-Tier1 and Core-Tier2, providing more guidance to programs about the relative importance of material.
- Sets of knowledge areas have been restructured where common themes were identified.
- The expected depth of coverage has been made explicit. Outcomes listed at the Familiarity level will typically require less coverage than topics at the Usage level, which in turn require less coverage time than Assessment outcomes.
- Topic emphasis has changed within individual knowledge areas to reflect the state of the art and practice.

To assist programs in migrating towards CS2013, we first compare the CC2001 Core with the CS2013 Core (Tier1 and Tier2 combined). We include brief descriptions of how the content in the KAs has changed, what outcomes were removed, and what outcomes have emerged.

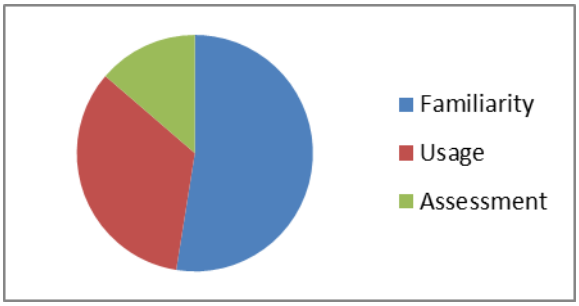
Outcomes

CS2013 lists 1110 outcomes, just over half of which are in the core. Core-Tier1 comprises just over one-fifth of the total outcomes. As shown in Figure B-1, over half of the learning outcomes are at the Familiarity level, and one-third are at the Usage level.

Table B-1: Count of Outcomes by Category

	Tier1	Tier2	Elective
Familiarity	118	192	273
Usage	93	92	191
Assessment	43	23	86

Figure B-1: Distribution of Outcomes by Knowledge Level



Over 160 of the 560 core outcomes are substantially new and another approximately 150 are significantly different than what is implied by CC2001. These new learning outcomes are identified in Table B-4, which appears at the end of this appendix. Over two dozen topics from CC2001 have been removed from the core, either by moving them to elective material or by elimination entirely. These are summarized in Table B-3.

Changes in Knowledge Area Structure

Several knowledge areas have been significantly changed from the CC2001 and CS2008 Guidelines. Specifically, Systems Fundamentals has been added to capture the common themes in previously distinct systems knowledge areas. The new Software Development Fundamentals KA provides students with a view of software beyond programming skills, including topics from Algorithms and Complexity (e.g., basic analysis, fundamental data structures), Software Engineering (e.g., small scale reviews, basic development tools), and Programming Languages (e.g., paradigm-independent constructs). Topics related to specific programming paradigms are now covered in the Programming Languages and Platform-Based Development KAs.

A comparison of learning outcomes between CS2013 and CC2001 leads to several general observations:

- The Systems Fundamentals knowledge area was created to capture the fundamental principles common among operating systems, networking, and distributed systems.
- Digital logic and numerical methods are de-emphasized. A fundamental coverage of digital logic can be found in Systems Fundamentals, but more advanced coverage is considered to be the domain of computer engineering and electrical engineering. Numerical methods are elective material in the Computational Science Knowledge Area

and are treated as a topic geared towards a more selected group of students entering into computational sciences.

- Similarly, foundational topics related to software development have been reorganized to produce a more coherent grouping and encourage curricular flexibility.
- There is increased emphasis on Parallel and Distributed Computing, as evidenced by the new Knowledge Area with that name.
- There is a significant new emphasis on security. To this end, a new KA has been developed, Information Assurance and Security (IAS). Much of the material described in the KA is also mentioned in other KAs. The IAS KA cross-lists these topics. Some institutions may choose to distribute the core IAS topics among existing courses. In addition, privacy is a topic of growing concern, and is described in IAS as well as being represented in the core content of the Social Issues and Professional Practice KA.
- There is no distinguished emphasis on building web pages or search engine use. We assume that students entering undergraduate study in this decade are familiar with internet search, email, and social networking, an assumption that was not universally true in 2001.
- The Programming Languages core in CC2001 had a significant emphasis on language translation. The CS2013 core material in PL is more focused on language paradigms and tradeoffs, rather than implementation. The implementation content is elective.
- The Intelligent Systems, Architecture and Organization, and Discrete Structures Knowledge Areas have many topics in common with CC2001, but also have a number of new topics. Emphases have changed. Some topics have been de-emphasised to allow for inclusion of new topics.
- The Social Issues and Professional Practice Knowledge Area has changed to a great degree, particularly with respect to contemporary issues.

Core Comparison

There is significant overlap between the CC2001 Core and the CS2013 Core, particularly in the more theoretical and fundamental content. This is an indication of growing maturity in the fundamentals of the field. Knowledge Areas such as Discrete Structures, Algorithms and Complexity, and Programming Languages are updated in CS2013, but the central material is largely unchanged. Two new knowledge areas, Systems Fundamentals and Software Development Fundamentals, are constructed from cross-cutting, foundational material from

existing knowledge areas. There are significant differences in applied and rapidly-changing areas such as information assurance and security, intelligent systems, parallel and distributed computing, and topics related to professionalism and society. This, too, is to be expected of a field that is vibrant and expanding. The comparison is complicated by the fact that in CS2013, we have augmented the topic list with explicit student outcomes and levels of understanding. To compare CC2001 directly, we had to make some reasonable assumptions about what CC2001 intended. The changes are summarized in Table B-2 by knowledge area in CS2013.

Table B-2: Summary of Changes by Knowledge Area

KA	Changes in CS2013
AL	This knowledge area now includes a basic understanding of the classes P and NP, the P vs NP problem, and examples of NP-complete problems. It also includes empirical studies for the purposes of comparing algorithm performance. Note that Distributed Algorithms have been moved to the Parallel and Distributed Computing KA.
AR	In this knowledge area, multi-core parallelism, virtual machine support, and power as a constraint are more significant considerations now than a decade ago. The use of CAD tools is prescribed rather than suggested.
CN	The topics in the core of this area are central to "computational thinking" and are at the heart of using computational power to solve problems in domains both inside and outside of traditional CS boundaries. The elective material covers topics that prepare students to contribute to efforts such as computational biology, bioinformatics, eco-informatics, computational finance, and computational chemistry.
DS	The concepts covered in the core are not new, but some coverage time has shifted from logic to discrete probability, reflecting the growing use of probability as a mathematical tool in computing. Many learning outcomes are also more explicit in CS2013.

GV	The storage of analog signals in digital form is a general computing idea, as is storing information vs. re-computing. (This outcome appears in System Fundamentals, also.)
HCI	Although the core hours have not increased, there is a change in emphasis within this knowledge area to recognize the increased importance of design methods and interdisciplinary approaches within the specialty.
IAS	This is a new knowledge area. All of these outcomes reflect the growing emphasis in the profession on security. The IAS knowledge area contains specific security and assurance knowledge units; however, it is also heavily integrated with many other knowledge areas. For example defensive programming is addressed in Core-Tier1 and Core-Tier2 hours within the Programming Languages, System Fundamentals, Software Engineering, and Operating Systems Knowledge Areas.
IM	The core outcomes in this Knowledge Area reflect topics that are broader than a typical database course. They can easily be covered in a traditional database course, but they must be explicitly addressed.
IS	Greater emphasis has been placed on machine learning than in the past. Additional guidance has been provided on what is expected of students with respect to understanding the challenges of implementing and using intelligent systems.
NC	There is greater focus on the comparison of IP and Ethernet networks, and increased attention to wireless networking. A related topic is reliable delivery. Here there is also added emphasis on implementation of protocols and applications.

OS	This knowledge area is structured to be complementary to Systems Fundamentals, Networking and Communication, Information Assurance and Security, and the Parallel and Distributed Computing Knowledge Areas. While some argue that system administration is the realm of IT and not CS, the working group believes that every student should have the capability to carry out basic administrative activities, especially those impact access control. Security and protection were electives in CC2001, while they were included in the core in CS2008. They appear in the core here as well. Realization of virtual memory using hardware and software has been moved to be an elective learning outcome (OS/Virtual Machines). Details of deadlocks and their prevention, including detailed concurrency is left to the Parallel and Distributed Computing Knowledge Area.
PD	This is a new knowledge area, which demonstrates the need for students to be able to work in parallel and distributed environments. This trend was initially identified, but not included, in the CS2008 Body of Knowledge. It is made explicit here to reflect that some familiarity with this topic has become essential for all undergraduates in CS.
PL	For the core material, the outcomes were made more uniform and general by refactoring material on object-oriented programming, functional programming, and event-oriented programming that was in multiple knowledge areas in CC2001. Programming with less mutable state and with more use of higher-order functions (like map and reduce) have greater emphasis. For the elective material, there is greater depth on advanced language constructs, type systems, static analysis for purposes other than compiler optimization, and run-time systems particularly garbage collection.

SDF	This new knowledge area pulls together foundational concepts and skills needed for software development. It is derived from the Programming Fundamentals Knowledge Area in CC2001, but also draws basic analysis material from Algorithms and Complexity, development process from Software Engineering, fundamental data structures from Discrete Structures, and programming language concepts from Programming Languages. Material specific to particular programming paradigms (e.g. object-oriented, functional) has been moved to Programming Languages to allow for a more uniform treatment with complementary material.
SE	The changes in this knowledge area introduce or require topics such as refactoring, secure programming, code modeling, code reviews, contracts, and team participation and process improvement. These topics, which reflect the growing awareness of software process in industry, are central to any level of modern software development, and should be used for software development projects throughout the curriculum. Agile process models have been added.
SF	This is a new knowledge area. Its outcomes reflect the refactoring of the knowledge areas to identify common themes across previously existing systems-related knowledge areas (in particular, operating systems, networks, and computer architecture). The new cross-cutting thematic areas include parallelism, communications, performance, proximity, virtualization/isolation, and reliability.
SP	These outcomes in this knowledge area reflect a shift in the past decade toward understanding intellectual property as related to digital intellectual property and digital rights management, the need for global awareness, and a growing concern for privacy in the digital age. They further recognize the enormous impact that computing has had on society at large emphasizing a sustainable future and placing added responsibilities on computing professionals. The outcomes also identify the vital needs for professional ethics, professional development, professional communication, and the ability to collaborate in person as well as remotely across time zones.

Conclusions

The changes from CC2001 to CS2013 are significant. Approximately one-half of the outcomes are new or significantly changed from those implied by CC2001. Many of these changes were suggested in the CS2008 revision, and reflect current practice in CS programs. Programs may be in a position to migrate their curricula incrementally towards the CS2013 guidelines. In other cases it will be preferable for faculty to revisit the structure of their curriculum to address the changing landscape of computing.

Table B-3: Core Learning Topics and Objectives in CC2001 not found in the CS2013 Core

KA	Topic From CC2001	Comment
AL	Design and implement an appropriate hashing function for an application.	This is elective material in C2013.
AL	Distributed Algorithms	Topics in this section have been updated and moved to the CS2013 Parallel and Distributed knowledge unit.
AR	Logic gates, flip flops, PLA, minimization, sum-of-product form, fan-out	This material has been moved to Systems Fundamentals/Computational Paradigms.
AR	VLIW, EPIC, Systolic architecture; hypercube, shuffle-exchange, mesh, crossbar as examples of interconnection networks	These topics are elective in CS2013.
GV	Raster and vector graphics systems; video display devices; physical and logical input devices; issues facing the developer of graphical systems	These topics have been updated significantly.
GV	Affine transformations, homogeneous coordinates, clipping; raster and vector graphics, physical and logical input devices	This is elective material in C2013.
IM	Information storage and retrieval	This is elective material in C2013.
IM	Summarize the evolution of information systems from early visions up through modern offerings, distinguishing their respective capabilities and future potential.	The history of information systems has been removed.
NC	Evolution of early networks; use of common networked applications (e-mail, telnet, FTP, newsgroups, and web browsers, online web courses, and instant messaging); streams and datagrams; CGI, applets, web servers	The evolution of early networks is elective material in C2013. Use of common applications has been removed. We assume that students enter programs familiar with common web applications.
NC	Discuss important network standards in their historical context.	The history of networking has been removed.
NC	Install a simple network with two clients and a single server using standard host configuration software tools such as DHCP.	System administration outcomes are described in Operating Systems/Security and Protection.

OS	Describe how operating systems have evolved over time from primitive batch systems to sophisticated multiuser systems.	The history of operating systems has been removed.
OS	Describe how issues such as open source software and the increased use of the Internet are influencing operating system design.	No core outcomes explicitly mention the use of open source software.
OS	Discuss the utility of data structures, such as stacks and queues, in managing concurrency.	Concurrency topics are now located in Parallel and Distributed Computing.
PF	Describe the mechanics of parameter passing	Implementation specifics are elective topics in CS2013.
PF	Describe how recursion can be implemented using a stack.	Recursion remains a significant topic, much of which is described in Programming Languages now.
PL	Summarize the evolution of programming languages illustrating how this history has led to the paradigms available today.	The history of programming languages has been removed.
PL	Activation records, type parameters, internal representations of objects and methods	Most implementation specifics are elective topics in CS2013, with a basic familiarity with the implementation of key language constructs appearing in Core-Tier-2.
SE	Class browsers, programming by example, API debugging; tools.	Covered without listing a necessary and sufficient list of tools.
SP	History	This is elective material in C2013.
SP	Gender-related issues	This material has been expanded to include all under-represented populations.
SP	Growth of the internet	This material has been subsumed by topics in Social Context with an understanding that students entering undergraduate study no longer consider the Internet to be a novel concept.
SP	Freedom of expression	This is elective material in C2013.

Table B-4: New and Expanded Core Learning Outcomes in CS2013

KA	Core Learning Outcomes as described in CS2013
AL	Core-Tier1: • Explain what is meant by "best", "expected", and "worst" case behavior of an algorithm. • In the context of specific algorithms, identify the characteristics of data and/or other conditions or assumptions that lead to different behaviors. • Perform empirical studies to validate hypotheses about runtime stemming from mathematical analysis. Run algorithms on input of various sizes and compare performance. • Give examples that illustrate time-space trade-offs of algorithms. • Use dynamic programming to solve an appropriate problem. • Explain how tree balance affects the efficiency of various binary search tree operations. Core-Tier2: • Define the classes P and NP. • Explain the significance of NP-completeness. • Discuss factors other than computational efficiency that influence the choice of algorithms, such as programming time, maintainability, and the use of application-specific patterns in the input data.
AR	Core-Tier2: • Comprehend the trend of modern computer architectures towards multi-core and that parallelism is inherent in all hardware systems. • Explain the implications of the "power wall" in terms of further processor performance improvements and the drive towards harnessing parallelism. • Design the basic building blocks of a computer: arithmetic-logic unit (gate-level), registers (gate-level), central processing unit (register transfer-level), and memory (register transfer-level). • Use CAD tools for capture, synthesis, and simulation to evaluate simple building blocks (e.g., arithmetic-logic unit, registers, movement between registers) of a simple computer design. • Evaluate the functional and timing diagram behavior of a simple processor implemented at the logic circuit level. • Compute Average Memory Access Time under a variety of cache and memory configurations and mixes of instruction and data references.

CN	Core-Tier1: • Explain the concept of modeling and the use of abstraction that allows the use of a machine to solve a problem. • Describe the relationship between modeling and simulation, ie, thinking of simulation as dynamic modeling. • Create a simple, formal mathematical model of a real-world situation and use that model in a simulation. • Differentiate among the different types of simulations, including physical simulations, human-guided simulations, and virtual reality. • Describe several approaches to validating models.
DS	Core-Tier1: • Apply the pigeonhole principle in the context of a formal proof. • Perform computations involving modular arithmetic. • Identify a case of the binomial distribution and compute a probability using that distribution. • Compute the variance for a given probability distribution. Core-Tier2: • Compute the variance for a given probability distribution. • Explain how events that are independent can be conditionally dependent (and vice-versa). Identify real-world examples of such cases. • Determine if two graphs are isomorphic.
GV	Core-Tier1: • Explain in general terms how analog signals can be reasonably represented by discrete samples, for example, how images can be represented by pixels. • Explain how the limits of human perception affect choices about the digital representation of analog signals. • Describe the differences between lossy and lossless image compression techniques, for example as reflected in common graphics image file formats such as JPG, PNG, MP3, MP4, and GIF. Core-Tier2: • Describe color models and their use in graphics display devices. • Describe the tradeoffs between storing information vs storing enough information to reproduce the information, as in the difference between vector and raster rendering.
HCI	Core-Tier2: • For an identified user group, undertake and document an analysis of their needs. • Create a simple application, together with help and documentation, that supports a graphical user interface. • Discuss at least one national or international user interface design standard.

IAS	Core-Tier1: • Analyze the tradeoffs of balancing key security properties (Confidentiality, Integrity, Availability). • Describe the concepts of risk, threats, vulnerabilities and attack vectors (including the fact that there is no such thing as perfect security). • Explain the concept of trust and trustworthiness. • Recognize that there are important ethical issues to consider in computer security, including ethical issues associated with fixing or not fixing vulnerabilities and disclosing or not disclosing vulnerabilities. • Describe the principle of least privilege and isolation as applied to system design. • Summarize the principle of fail-safe and deny-by-default. • Recognize not to rely on the secrecy of design for security (but also that open design alone does not imply security). • Explain the goals of end-to-end data security. • Discuss the benefits of having multiple layers of defenses. • Recognize that security has to be a consideration from the point of initial design and throughout the lifecycle of a product. • Recognize that security imposes costs and tradeoffs. • Explain why input validation and data sanitization is necessary in the face of adversarial control of the input channel. • Explain why you might choose to develop a program in a type-safe language like Java, in contrast to an unsafe programming language like C/C++. • Classify common input validation errors, and write correct input validation code. • Demonstrate using a high-level programming language how to prevent a race condition from occurring and how to handle an exception. • Demonstrate the identification and graceful handling of error conditions. Core-Tier2: • Describe the concept of mediation and the principle of complete mediation. • Be aware of standard components for security operations, instead of re-inventing fundamentals operations. • Explain the concept of trusted computing including trusted computing base and attack surface and the principle of minimizing trusted computing base. • Discuss the importance of usability in security mechanism design. • Recognize that security does not compose by default; security issues can arise at boundaries between multiple components. • Identify the different roles of prevention mechanisms and detection/deterrence mechanisms. • Explain the risks with misusing interfaces with third-party code and how to correctly use third-party code. • Discuss the need to update software to fix security vulnerabilities and the lifecycle management of the fix. • List examples of direct and indirect information flows.

	• Describe likely attacker types against a particular system. • Discuss the limitations of malware countermeasures (eg, signature-based detection, behavioral detection). • Identify instances of social engineering attacks and Denial of Service attacks. • Discuss how Denial of Service attacks can be identified and mitigated. • Describe risks to privacy and anonymity in commonly used applications. • Discuss the concepts of covert channels and other data leakage procedures. • Describe the different categories of network threats and attacks. • Describe virtues and limitations of security technologies at each layer of the network stack. • Identify the appropriate defense mechanism(s) and its limitations given a network threat. • Discuss security properties and limitations of other non-wired networks. • Define the following terms: cipher, cryptanalysis, cryptographic algorithm, and cryptology and describe the two basic methods (ciphers) for transforming plain text in cipher text. • Discuss the importance of prime numbers in cryptography and explain their use in cryptographic algorithms. • Use cryptographic primitives and their basic properties.
IM	Core-Tier1: • Describe how humans gain access to information and data to support their needs. • Understand advantages and disadvantages of central organizational control over data. • Identify the careers/roles associated with information management (e.g., database administrator, data modeler, application developer, end-user). • Demonstrate uses of explicitly stored metadata/schema associated with data. • Identify issues of data persistence for an organization. Core-Tier2: • Explain uses of declarative queries. • Give a declarative version for a navigational query. • Identify vulnerabilities and failure scenarios in common forms of information systems. • Describe the most common designs for core database system components including the query optimizer, query executor, storage manager, access methods, and transaction processor. • Describe facilities that databases provide supporting structures and/or stream (sequence) data, e.g., text. • Compare and contrast appropriate data models, including internal structures, for different types of data. • Describe the differences between relational and semi-structured data models. • Give a semi-structured equivalent (e.g., in DTD or XML Schema) for a given relational schema.

IS	Core-Tier2: • Translate a natural language (e.g., English) sentence into predicate logic statement. • Convert a logic statement into clause form. • Apply resolution to a set of logic statements to answer a query. • Make a probabilistic inference in a real-world problem using Bayes' theorem to determine the probability of a hypothesis given evidence. • List the differences among the three main styles of learning: supervised, reinforcement, and unsupervised. • Identify examples of classification tasks, including the available input features and output to be predicted. • Explain the difference between inductive and deductive learning. • Describe over-fitting in the context of a problem. • Apply the simple statistical learning algorithm such as Naive Bayesian Classifier to a classification task and measure the classifier's accuracy.
NC	Core-Tier1: • Articulate the organization of the Internet. • List and define the appropriate network terminology. • Identify the different types of complexity in a network (edges, core, etc). • List the differences and the relations between names and addresses in a network. • Define the principles behind naming schemes and resource location. Core-Tier2: • List the factors that affect the performance of reliable delivery protocols. • Design and implement a simple reliable protocol. • Describe the organization of the network layer. • Describe how packets are forwarded in an IP network. • List the scalability benefits of hierarchical addressing. • Describe how frames are forwarded in an Ethernet network. • Describe the steps used in one common approach to the multiple access problem. • Describe how resources can be allocated in a network. • Describe the congestion problem in a large network. • Compare and contrast fixed and dynamic allocation techniques. • Compare and contrast current approaches to congestion. • Describe the organization of a wireless network. • Describe how wireless networks support mobile users.

OS	Core-Tier2: • Articulate the need for protection and security in an OS (cross-reference IAS/Security Architecture and Systems Administration/Investigating Operating Systems Security for various systems). • Summarize the features and limitations of an operating system used to provide protection and security (cross-reference IAS/Security Architecture and Systems Administration). • Explain the mechanisms available in an OS to control access to resources (cross-reference IAS/Security Architecture and Systems Administration/Access Control/Configuring systems to operate securely as an IT system). • Carry out simple system administration tasks according to a security policy, for example, creating accounts, setting permissions, applying patches, and arranging for regular backups (cross-reference IAS/Security Architecture and Systems Administration).
PD	Core-Tier1: • Distinguish using computational resources for a faster answer from managing efficient access to a shared resource. • Distinguish multiple sufficient programming constructs for synchronization that may be inter-implementable but have complementary advantages. • Distinguish data races from higher level races. • Explain why synchronization is necessary in a specific parallel program. • Use mutual exclusion to avoid a given race condition. • Explain the differences between shared and distributed memory. Core-Tier2: • Identify opportunities to partition a serial program into independent parallel modules. • Write a correct and scalable parallel algorithm. • Parallelize an algorithm by applying task-based decomposition. • Parallelize an algorithm by applying data-parallel decomposition. • Write a program using actors and/or reactive processes. • Give an example of an ordering of accesses among concurrent activities (eg, program with a data race) that is not sequentially consistent. • Give an example of a scenario in which blocking message sends can deadlock. • Explain when and why multicast or event-based messaging can be preferable to alternatives. • Write a program that correctly terminates when all of a set of concurrent tasks have completed. • Use a properly synchronized queue to buffer data passed among activities. • Explain why checks for preconditions, and actions based on these checks, must share the same unit of atomicity to be effective. • Write a test program that can reveal a concurrent programming error, for example, missing an update when two activities both try to increment a variable.

	• Describe at least one design technique for avoiding liveness failures in programs using multiple locks or semaphores. • Describe the relative merits of optimistic versus conservative concurrency control under different rates of contention among updates. • Give an example of a scenario in which an attempted optimistic update may never complete. • Define "critical path", "work", and "span". • Compute the work and span, and determine the critical path with respect to a parallel execution diagram. • Define "speed-up" and explain the notion of an algorithm's scalability in this regard. • Identify independent tasks in a program that may be parallelized. • Characterize features of a workload that allow or prevent it from being naturally parallelized. • Implement a parallel divide-and-conquer (and/or graph algorithm) and empirically measure its performance relative to its sequential analog. • Decompose a problem (e.g., counting the number of occurrences of some word in a document) via map and reduce operations. • Describe the SMP architecture and note its key features. • Characterize the kinds of tasks that are a natural match for SIMD machines.
PL	Core-Tier1: • Write basic algorithms that avoid assigning to mutable state or considering reference equality. • Write useful functions that take and return other functions. • Compare and contrast (1) the procedural/functional approach (defining a function for each operation with the function body providing a case for each data variant) and (2) the object-oriented approach (defining a class for each data variant with the class definition providing a method for each operation). Understand both as defining a matrix of operations and variants. • For both a primitive and a compound type, informally describe the values that have that type. • For a language with a static type system, describe the operations that are forbidden statically, such as passing the wrong type of value to a function or method. • Describe examples of program errors detected by a type system. • For multiple programming languages, identify program properties checked statically and program properties checked dynamically. • Give an example program that does not type-check in a particular language and yet would have no error if run. • Use types and type-error messages to write and debug programs. Core-Tier2: • Correctly reason about variables and lexical scope in a program using function closures.

	• Use functional encapsulation mechanisms such as closures and modular interfaces. • Define and use iterators and other operations on aggregates, including operations that take functions as arguments, in multiple programming languages, selecting the most natural idioms for each language. • Explain why an event-driven programming style is natural in domains where programs react to external events. • Describe an interactive system in terms of a model, a view, and a controller. • Explain how typing rules define the set of operations that are legal for a type. • Write down the type rules governing the use of a particular compound type. • Explain why undecidability requires type systems to conservatively approximate program behavior. • Define and use program pieces (such as functions, classes, methods) that use generic types, including for collections. • Discuss the differences among generics, subtyping, and overloading. • Explain multiple benefits and limitations of static typing in writing, maintaining, and debugging software. • Explain how programs that process other programs treat the other programs as their input data. • Describe an abstract syntax tree for a small language. • Describe the benefits of having program representations other than strings of source code. • Write a program to process some representation of code for some purpose, such as an interpreter, an expression optimizer, or a documentation generator. • Distinguish syntax and parsing from semantics and evaluation. • Sketch a low-level run-time representation of core language constructs, such as objects or closures. • Explain how programming language implementations typically organize memory into global data, text, heap, and stack sections and how features such as recursion and memory management map to this memory model. • Identify and fix memory leaks and dangling-pointer dereferences. • Discuss the benefits and limitations of garbage collection, including the notion of reachability.
SDF	Core-Tier1: • Discuss how a problem may be solved by multiple algorithms, each with different properties. • Identify the data components and behaviors of multiple abstract data types. • Implement a coherent abstract data type, with loose coupling between components and behaviors. • Identify the relative strengths and weaknesses among multiple designs or implementations for a problem. • Trace the execution of a variety of code segments and write summaries of their computations.

	• Explain why the creation of correct program components is important in the production of high-quality software. • Identify common coding errors that lead to insecure programs (eg, buffer overflows, memory leaks, malicious code) and apply strategies for avoiding such errors. • Conduct a personal code review (focused on common coding errors) on a program component using a provided checklist. • Describe how a contract can be used to specify the behavior of a program component. • Refactor a program by identifying opportunities to apply procedural abstraction. • Analyze the extent to which another programmer's code meets documentation and programming style standards. • Apply consistent documentation and program style standards that contribute to the readability and maintainability of software.
SE	Core-Tier1: • List the key components of a use case or similar description of some behavior that is required for a system. • Describe how the requirements engineering process supports the elicitation and validation of behavioral requirements. • Interpret a given requirements model for a simple software system. • Use a design paradigm to design a simple software system, and explain how system design principles have been applied in this design. • Within the context of a single design paradigm, describe one or more design patterns that could be applicable to the design of a simple software system. Core-Tier2: • Discuss common behaviors that contribute to the effective functioning of a team. • Create and follow an agenda for a team meeting. • Identify and justify necessary roles in a software development team. • Understand the sources, hazards, and potential benefits of team conflict. • Apply a conflict resolution strategy in a team setting. • Use an ad hoc method to estimate software development effort (e.g., time) and compare to actual effort required. • List several examples of software risks. • Describe the impact of risk in a software development lifecycle. • Describe different categories of risk in software systems. • Describe the difference between centralized and distributed software configuration management. • Describe how version control can be used to help manage software release management. • Identify configuration items and use a source code control tool in a small team-based project.

	• Describe how available static and dynamic test tools can be integrated into the software development environment. • Describe the issues that are important in selecting a set of tools for the development of a particular software system, including tools for requirements tracking, design modeling, implementation, build automation, and testing. • Demonstrate the capability to use software tools in support of the development of a software product of medium size. • Describe the fundamental challenges of and common techniques used for requirements elicitation. • List the key components of a data model (eg, class diagrams or ER diagrams). • Identify both functional and non-functional requirements in a given requirements specification for a software system. • For a simple system suitable for a given scenario, discuss and select an appropriate design paradigm. • Create appropriate models for the structure and behavior of software products from their requirements specifications. • Explain the relationships between the requirements for a software product and its design, using appropriate models. • For the design of a simple software system within the context of a single design paradigm, describe the software architecture of that system. • Given a high-level design, identify the software architecture by differentiating among common software architectures such as 3-tier, pipe-and-filter, and client-server. • Investigate the impact of software architectures selection on the design of a simple system. • Describe a form of refactoring and discuss when it may be applicable. • Select suitable components for use in the design of a software product. • Explain how suitable components might need to be adapted for use in the design of a software product. • Design a contract for a typical small software component for use in a given system. • Describe techniques, coding idioms and mechanisms for implementing designs to achieve desired properties such as reliability, efficiency, and robustness. • Describe secure coding and defensive coding practices. • Select and use a defined coding standard in a small software project. • Compare and contrast integration strategies including top-down, bottom-up, and sandwich integration. • Describe the process of analyzing and implementing changes to code base developed for a specific project. • Describe the process of analyzing and implementing changes to a large existing code base. • Describe how to select good regression tests and automate them. • Use a defect tracking tool to manage software defects in a small software project. • Discuss the limitations of testing in a particular domain.

	• Use refactoring in the process of modifying a software component. • Explain the problems that exist in achieving very high levels of reliability. • Describe how software reliability contributes to system reliability. • List approaches to minimizing faults that can be applied at each stage of the software lifecycle.
SF	Core-Tier1: • List commonly encountered patterns of how computations are organized. • Articulate the differences between single thread vs. multiple thread, single server vs multiple server models, motivated by real world examples (e.g., cooking recipes, lines for multiple teller machines and couples shopping for food). • Articulate the concept of strong vs. weak scaling, i.e., how performance is affected by scale of problem vs. scale of resources to solve the problem. This can be motivated by the simple, real-world examples. • Use tools for capture, synthesis, and simulation to evaluate a logic design. • Write a simple sequential problem and a simple parallel version of the same program. • Evaluate performance of simple sequential and parallel versions of a program with different problem sizes, and be able to describe the speed-ups achieved. • Describe how computing systems are constructed of layers upon layers, based on separation of concerns, with well-defined interfaces, hiding details of low layers from the higher layers. • Describe that hardware, VM, OS, application are additional layers of interpretation/processing. • Describe the mechanisms of how errors are detected, signaled back, and handled through the layers. • Construct a simple program using methods of layering, error detection and recovery, and reflection of error status across layers. • Find bugs in a layered program by using tools for program tracing, single stepping, and debugging. • Describe computations as a system characterized by a known set of configurations with transitions from one unique configuration (state) to another (state). • Describe the distinction between systems whose output is only a function of their input (combinational) and those with memory/history (sequential). • Describe a computer as a state machine that interprets machine instructions. • Explain how a program or network protocol can also be expressed as a state machine, and that alternative representations for the same computation can exist. • Develop state machine descriptions for simple problem statement solutions (eg, traffic light sequencing, pattern recognizers). • Derive time-series behavior of a state machine from its state machine representation. • For a given program, distinguish between its sequential and parallel execution, and the performance implications thereof.

	• Demonstrate on an execution time line that parallelism events and operations can take place simultaneously (ie, at the same time) Explain how work can be performed in less elapsed time if this can be exploited. • Explain other uses of parallelism, such as for reliability/redundancy of execution. • Define the differences between the concepts of Instruction Parallelism, Data Parallelism, Thread Parallelism/Multitasking, and Task/Request Parallelism. • Write more than one parallel program (e.g., one simple parallel program in more than one parallel programming paradigm; a simple parallel program that manages shared resources through synchronization primitives; a simple parallel program that performs simultaneous operation on partitioned data through task parallelism (e.g., parallel search terms); a simple parallel program that performs step-by-step pipeline processing through message passing). • Use performance tools to measure speed-up achieved by parallel programs in terms of both problem size and number of resources. • Explain how the components of system architecture contribute to improving its performance. • Describe Amdahl's law and discuss its limitations. • Design and conduct a performance-oriented experiment. • Use software tools to profile and measure program performance. Core-Tier2: • Define how finite computer resources (e.g., processor share, memory, storage, and network bandwidth) are managed by their careful allocation to existing entities. • Describe the scheduling algorithms by which resources are allocated to competing entities, and the figures of merit by which these algorithms are evaluated, such as fairness. • Implement simple schedule algorithms. • Use figures of merit of alternative scheduler implementations. • Explain the importance of locality in determining performance. • Describe why things that are close in space take less time to access. • Calculate average memory access time and describe the tradeoffs in memory hierarchy performance in terms of capacity, miss/hit rate, and access time. • Describe how the concept of indirection can create the illusion of a dedicated machine and its resources even when physically shared among multiple programs and environments. • Measure the performance of two application instances running on separate virtual machines, and determine the effect of performance isolation. • Explain the distinction between program errors, system errors, and hardware faults (e.g., bad memory) and exceptions (e.g., attempt to divide by zero). • Articulate the distinction between detecting, handling, and recovering from faults, and the methods for their implementation. • Describe the role of error correcting codes in providing error checking and correction techniques in memories, storage, and networks.

	• Apply simple algorithms for exploiting redundant information for the purposes of data correction. • Compare different error detection and correction methods for their data overhead, implementation complexity, and relative execution time for encoding, detecting, and correcting errors.
SP	Core-Tier1: • Summarize the implications of social media on individualism versus collectivism and culture. • Recognize the ethical responsibility of ensuring software correctness, reliability and safety. • Describe the mechanisms that typically exist for a professional to keep up-to-date. • Discuss the philosophical bases of intellectual property. • Discuss the rationale for the legal protection of intellectual property. • Describe legislation aimed at digital copyright infringements. • Critique legislation aimed at digital copyright infringements. • Identify contemporary examples of intangible digital intellectual property. • Justify uses of copyrighted materials. • Evaluate the ethical issues inherent in various plagiarism detection mechanisms. • Interpret the intent and implementation of software licensing. • Discuss the issues involved in securing software patents. • Evaluate solutions to privacy threats in transactional databases and data warehouses. • Recognize the fundamental role of data collection in the implementation of pervasive surveillance systems (e.g., RFID, face recognition, toll collection, mobile computing). • Recognize the ramifications of differential privacy. • Investigate the impact of technological solutions to privacy problems. • Write clear, concise, and accurate technical documents following well-defined standards for format and for including appropriate tables, figures, and references. • Evaluate written technical documentation to detect problems of various kinds. • Develop and deliver a good quality formal presentation. • Plan interactions (e.g., virtual, face-to-face, shared documents) with others in which they are able to get their point across, and are also able to listen carefully and appreciate the points of others, even when they disagree, and are able to convey to others that they have heard. • Describe the strengths and weaknesses of various forms of communication (e.g., virtual, face-to-face, shared documents). • Examine appropriate measures used to communicate with stakeholders involved in a project. • Compare and contrast various collaboration tools. • Identify ways to be a sustainable practitioner.

	• Illustrate global social and environmental impacts of computer use and disposal (e-waste). Core-Tier2: • Discuss how Internet access serves as a liberating force for people living under oppressive forms of government; explain how limits on Internet access are used as tools of political and social repression. • Analyze the pros and cons of reliance on computing in the implementation of democracy (e.g., delivery of social services, electronic voting). • Describe the impact of the under-representation of diverse populations in the computing profession (e.g., industry culture, product diversity). • Explain the implications of context awareness in ubiquitous computing systems. • Describe ways in which professionals may contribute to public policy. • Describe the consequences of inappropriate professional behavior. • Identify examples of how regional culture interplays with ethical dilemmas. • Investigate forms of harassment and discrimination and avenues of assistance. • Examine various forms of professional credentialing. • Explain the relationship between ergonomics in computing environments and people's health. • Describe issues associated with industries' push to focus on time to market versus enforcing quality professional standards. • Describe the environmental impacts of design choices within the field of computing that relate to algorithm design, operating system design, networking design, database design, etc. • Investigate the social and environmental impacts of new system designs through projects.

Appendix C: Course Exemplars

While the Body of Knowledge lists the topics that should be included in undergraduate programs in computer science and their associated learning outcomes, there are many different ways in which these topics may be packaged into courses. In this appendix we present a collection of *course exemplars* gathered from a wide variety of institutions. These take different approaches in how they cover portions of the CS2013 Body of Knowledge. To allow easy comparison, the exemplars were all written following a common template, which is included before the actual course exemplars. These exemplars are not generalized models, artificially created from abstract features, but are rather examples of real courses. Thus they are written from a variety of viewpoints and in many voices. In the writing, each one embodies the traditions and practices of its own institution.

Table C1 provides a list of exemplars organized by the Knowledge Area that they most significantly cover. The courses listed first with respect to each Knowledge Area devote the majority of their time to the specific Knowledge Area. Courses listed in parentheses have significant coverage of topics in the Knowledge Area, but have primary emphasis in a different Knowledge Area. As can be seen from these exemplars, a course often includes material from multiple Knowledge Areas and, equally, that multiple courses are often used to cover all the material from one Knowledge Area.

These exemplars are not meant to be prescriptive with respect to curricular design, nor are they meant to define a standard curriculum for all institutions. Rather they are provided to give educators examples of different ways that the Body of Knowledge may be organized into courses, to provide comparative breadth, and to spur new thinking for future course design.

Table C1: Exemplars by Knowledge Area

NOTE: Courses listed below in parentheses have a secondary emphasis in this area.

SDF	***Also see Introductory Sequences (at end of table)***		449
	Portland Community College	CIS133J: Java Programming I	388
	Harvey Mudd College	CS5: Introduction to Computer Science	391
	Clemson University	215 Software Development Foundations	394
	Worchester Polytechnic Inst.	CS1101: Introduction to Program Design	397
	(U. of Pennsylvania	Programming Languages and Techniques I)	377
	(Miami University	Data Abstraction)	400
	(Princeton University	COS126: General Computer Science)	443
	(Brown Univ.	CSCI 0190: Accelerated Intro. to Computer Science)	447
SE	Embry Riddle Aeronautical U.	Software Engineering Practices	402
	U. California Berkeley	CS169 Software Engineering	406
	Milwaukee School of Engineering	SE 2890:Software Engineering Practices	409
	Quinnipiac University	Software Development	411
	(Clemson University	215 Software Development Foundations)	394
	(Colorado State University	CS453: Introduction to Compilers)	348
	(Harvard	CS175 Computer Graphics)	274
	(Williams College	CS371: Computer Graphics)	277
	(Brown University	CSCI 0190: Accelerated Intro. to Computer Science)	447
SF	Georgia Tech	CS 2200: Computer Systems and Networks	414
	UC Berkeley	CS 61c: Great Ideas in Computer Architecture	418
	U. Washington	CSE 333: System Programming	420
SP	U. of Maryland, Univ. College	IFSM 304 Ethics in Technology	423
	Carnegie Mellon University	Technology Consulting in the Community	426
	Saint Xavier University	Issues in Computing	430
	Anne Arundel Community College	Ethics & the Information Age (CSI 194)	433
	Miami University (Oxford, OH)	Technology, Ethics, and Global Society	301
	Northwest Missouri State U.	Professional Development Seminar	433
	(Grinnell College	The Digital Age)	439
Introductory Sequences	Creighton University		449
	CSC221: Introduction to Programming		450
	CSC222: Object-Oriented Programming		452
	Grinnell College		454
	CSC207: Algorithms and Object-Oriented Design		460
	CSC161: Imperative Problem Solving and Data Structures		458
	CSC151: Functional problem solving		456

ACM/IEEE-CS CS2013 Course-Exemplar Template:
Total length should not exceed 4 pages, 2-3 pages preferred

Course Exemplar Template (Name of Course, Institution)

Location of Institution
Your Name
Email Address

Permanent URL where additional materials and information are available (this may be course website for a recent offering assuming it is public)

Knowledge Areas that contain topics and learning outcomes covered in the course
[List Knowledge Area(s) and associated acronym. It might be easier to complete this table last – especially the total hours]

Knowledge Area	**Total Hours of Coverage**
Name (e.g., Systems Fundamentals (SF))	*Number*

Where does the course fit in your curriculum?
[*In what year do students commonly take the course? Is it compulsory? Does it have pre-requisites, required following courses? How many students take it?*]

What is covered in the course?
[A short description, and/or a concise list of topics - possibly from your course syllabus.(This is likely to be your longest answer)]

What is the format of the course?
[*Is it face-to-face, online or blended? How many contact hours? Does it have lectures, lab sessions, discussion classes?*]

How are students assessed?
[*What type, and number, of assignments are students are expected to do? (papers, problem sets, programming projects, etc.). How long do you expect students to spend on completing assessed work?]*

Course textbooks and materials
[A brief description of materials used (e.g., textbooks, programming languages, environments etc.)]

Why do you teach the course this way?
[*A description of the course rationale and goals. If you know, please indicate the history and background of the course and when it was last reviewed/revised. Do students typically consider this course to be challenging?*]

Body of Knowledge coverage
[List the Knowledge Units covered in whole or in part in the course. If in part, please indicate which topics and/or learning outcomes are covered. For those not covered, you might want to indicate whether they are covered in another course or not covered in your curriculum at all. This section will likely be the most time-consuming to complete, but is the most valuable for educators planning to adopt the CS2013 guidelines.]

KA	Knowledge Unit	Topics Covered	Hours
XY	*Full name of KU*	*[Include explanation as needed]*	*Num*

Additional topics
[List notable topics covered in the course that you do not find in the CS2013 Body of Knowledge]

Other comments
[optional]

CSCI 140: Algorithms, Pomona College

Claremont, CA 91711, USA
Tzu-Yi Chen
tzuyi@cs.pomona.edu
http://www.cs.pomona.edu/~tzuyi/Classes/CC2013/Algorithms/index.html

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Algorithms and Complexity (AL)	29 - 32
Software Development Fundamentals (SDF)	1.5
Parallel and Distributed Computing (PD)	0 - 3

Where does the course fit in your curriculum?

This is a required course in the CS major that is typically taken by juniors and seniors. The official prerequisites are Data Structures (CSCI 062, the 3rd course in the introductory sequence) and Discrete Math (CSCI 055). However, we regularly make exceptions for students who have had only the first 2 courses in the introductory sequence as long as they have also taken a proof-based math class such as Real Analysis or Combinatorics. Algorithms is not a prerequisite for any other required classes, but is a prerequisite for electives such as Applied Algorithms.

What is covered in the course?

This class covers basic techniques used to analyze problems and algorithms (including asymptotics, upper/lower bounds, best/average/worst case analysis, amortized analysis, complexity), basic techniques used to design algorithms (including divide & conquer / greedy / dynamic programming / heuristics, choosing appropriate data structures), and important classical algorithms (including sorting, string, matrix, and graph algorithms). The goal is for students to be able to apply all of the above to designing solutions for real-world problems.

What is the format of the course?

This is a one semester (14 week) face-to-face class with 2.5 hours of lecture a week.

How are students assessed?

There is a written assignment (written up individually) due almost every class as well as 1 or 2 programming assignments (done in groups of 1-3) due during the semester; solutions are evaluated on clarity, correctness, and (when appropriate) efficiency. Students are expected to spend 6-10 hours a week outside of class on course material. There are also 1 or 2 midterms and a final exam. Students are expected to attend lectures and to demonstrate engagement either by asking/answering questions in class or by going to office hours (the professor's or the TAs').

Course textbooks and materials

The textbook is *Introduction to Algorithms, 3rd Edition* by Cormen, Leiserson, Rivest, and Stein. For the programming assignments students are strongly encouraged to use their choice of C, C++, Java, or Python, though other languages may be used with permission. Students are required to use LaTeX to format their first 2-3 weeks of assignments, after which its use is encouraged but not required.

Why do you teach the course this way?

This course serves as a bridge between theory and practice. Lectures cover classical algorithms and techniques for reasoning about their correctness and efficiency. Assignments allow students to practice skills necessary for

developing, describing, and justifying algorithmic solutions for new problems. The 1 or 2 programming assignments go a step further by also requiring an implementation; these assignments help students better appreciate both what it means to describe an algorithm clearly and what issues can remain in implementation. To encourage students not to fall behind in the material, two problem sets are due every week (one every lecture). By the end of the semester students should also have a strong appreciation for the role of algorithms.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SDF	algorithms and design	concept and properties of algorithms, role of algorithms, problem-solving strategies, separation of behavior and implementation	1.5
AL	basic analysis	all core-tier1 all core-tier2	1 1.5
AL	algorithmic strategies	core-tier1: brute-force, greedy, divide-and-conquer, dynamic programming core-tier2: heuristics	6 .5
AL	fundamental data structures and algorithms	all core-tier1 core-tier2: heaps, graph algorithms (minimum spanning tree, single source shortest path, all pairs shortest path), string algorithms (longest common subsequence)	3 6
AL	basic automata computability and complexity	no core-tier1 (covered in other required courses), core-tier2: introduction to P/NP/NPC with examples	0 1
AL	advanced computational complexity	P/NP/NPC, Cook-Levin, classic NPC problems, reductions	2
AL	advanced automata theory and computability	none (covered in other required courses)	0
AL	advanced data structures algorithms and analysis	balanced trees (1-2 examples), graphs (topological sort, strongly connected components), advanced data structures (disjoint sets, mergeable heaps), network flows, linear programming (formulating, duality, overview of techniques), approximation algorithms (2-approx for metric-TSP, vertex cover), amortized analysis	8

Additional topics

The above table covers approximately 30 hours of lecture and gives the material that is covered every semester. The remaining hours can be used for review sessions, to otherwise allow extra time for topics that students that semester find particularly confusing, for in-class midterms, or to cover a range of additional topics. In the past these additional topics have included:

KA	Knowledge Unit	Topics Covered
AL	advanced computational complexity	P-space, EXP

AL	advanced data structures algorithms and analysis	more approximation algorithms (e.g., Christofides, subset-sum), geometric algorithms, randomized algorithms, online algorithms and competitive analysis, more data structures (e.g., log* analysis for disjoint-sets)
PD	parallel algorithms, analysis, and programming	critical path, work and span, naturally parallel algorithms, specific algorithms (e.g., mergesort, parallel prefix)
PD	formal models and semantics	PRAM

Other comments

Starting in the Fall of 2013 approximately 2-3 hours of the currently optional material on parallel algorithms will become a standard part of the class.

COS 226: Algorithms and Data Structures, Princeton University

Princeton, NJ
Robert Sedgewick and Kevin Wayne
rs@cs.princeton.edu wayne@cs.princeton.edu
http://www.cs.princeton.edu/courses/archive/spring12/cos226/info.php
http://algs4.cs.princeton.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Algorithms and Complexity (AL)	29
Software Development Fundamentals (SDF)	3
Programming Languages (PL)	1

Where does the course fit in your curriculum?

This course introduces fundamental algorithms in the context of significant applications in science, engineering, and commerce. It has evolved from a traditional "second course for CS majors" to a course that is taken by over one-third of all Princeton students. The prerequisite is a one-semester course in programming, preferably in Java and preferably at the college level. Our students nearly all fulfill the prerequisite with our introductory course. This course is a prerequisite for all later courses in computer science, but is taken by many students in other fields of science and engineering (only about one-quarter of the students in the course are majors).

What is covered in the course?

Classical algorithms and data structures, with an emphasis on implementing them in modern programming environments, and using them to solve real-world problems. Particular emphasis is given to algorithms for sorting, searching, string processing, and graph algorithms. Fundamental algorithms in a number of other areas are covered as well, including geometric algorithms and some algorithms from operations research. The course concentrates on developing implementations, understanding their performance characteristics, and estimating their potential effectiveness in applications.

- Analysis of algorithms, with an emphasis on using the scientific method to validate hypotheses about algorithm performance.
- Data types, APIs, encapsulation.
- Linked data structures, resizing arrays, and implementations of container types such as stacks and queues.
- Sorting algorithms, including insertion sort, selection sort, shellsort, mergesort, randomized quicksort, heapsort.
- Priority queue data types and implementations, including binary heaps.
- Symbol table data types and implementations (searching algorithms), including binary search trees, red-black trees, and hash tables.
- Geometric algorithms (searching in point sets and intersection).
- Graph algorithms (breadth-first search, depth-first search, MST, shortest paths, topological sort, strong components, maxflow)
- Tries, string sorting, substring search, regular expression pattern matching.
- Data compression (Huffman, LZW).
- Reductions, combinatorial search, P vs. NP, and NP-completeness.

What is the format of the course?
The material is presented in two 1.5 hour lectures per week with weekly quizzes and a programming assignment, supported by a one-hour section where details pertinent to assignments and exams are covered by TAs teaching smaller groups of students. An alternative format is to use online lectures supplemented by two 1.5 hour sections, one devoted to discussion of lecture material, the other devoted to assignments.

How are students assessed?
The bulk of the assessment is weekly programming assignments, which usually involve solving an interesting application problem using an efficient algorithm learned in lecture. Students spend 10-20 hours per week on these assignments and often consult frequently with section instructors for help.

- Monte Carlo simulation to address the percolation problem from physical chemistry, based on efficient algorithms for the union-find problem.
- Develop generic data types for deques and randomized queues.
- Find collinear points in a point set, using an efficient generic sorting algorithm implementation.
- Implement A* search to solve a combinatorial problem, based on an efficient priority queue implementation.
- Implement a data type that supports range search and near-neighbor search in point sets, using kD trees.
- Build and search a "WordNet" directed acyclic graph.
- Use maxflow to solve the "baseball elimination" problem.
- Develop an efficient implementation of Burrow-Wheeler data compression.

Exercises for self-assessment are available on the web, are a topic of discussion in sections, and are good preparation for exams. A mid-term exam and a final exam account for a significant portion of the grade.

Course textbooks and materials
The course is based on the textbook *Algorithms, 4th Edition* by Robert Sedgewick and Kevin Wayne (Addison-Wesley Professional, 2011, ISBN 0-321-57351-X). The book is supported by a public "booksite" (http://algs4.cs.princeton.edu), which contains a condensed version of the text narrative (for reference while online) Java code for the algorithms and clients in the book, and many related algorithms and clients, test data sets, simulations, exercises, and solutions to selected exercises. The booksite also has lecture slides and other teaching material for use by faculty at other universities.

A separate website specific to each offering of the course contains detailed information about schedule, grading policies, and programming assignments.

Why do you teach the course this way?
The motivation for this course is the idea that knowledge of classical algorithms is fundamental to any computer science curriculum, but it is not just for programmers and computer science students. Everyone who uses a computer wants it to run faster or to solve larger problems. The algorithms in the course represent a body of knowledge developed over the last 50 years that has become indispensable. As the scope of computer applications continues to grow, so grows the impact of these basic methods. Our experience in developing this course over several decades has shown that the most effective way to teach these methods is to integrate them with applications as students are first learning to tackle significant programming problems, as opposed to the oft-used alternative where they are taught in a theory course. With this approach, we are reaching four times as many students as do typical algorithms courses. Furthermore, our CS majors have a solid knowledge of the algorithms when they later learn more about their theoretical underpinnings, and all our students have an understanding that efficient algorithms are necessary in many contexts.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SDF	Algorithms and Design	Encapsulation, separation of behavior and implementation.	1
PL	Object-oriented programming	Object-oriented design, encapsulation, iterators.	1

SDF	Fundamental data structures	Stacks, queues, priority queues, references, linked structures, resizable arrays.	2
AL	Basic Analysis	Asymptotic analysis, empirical measurements. Differences among best, average, and worst case behaviors of an algorithm. Complexity classes, such as constant, logarithmic, linear, quadratic, and exponential. Time and space trade-offs in algorithms.	1
AL	Algorithmic Strategies	Brute-force, greedy, divide-and-conquer, and recursive algorithms. Dynamic programming, reduction.	2
AL	Fundamental Data Structures and Algorithms	Binary search. Insertion sort, selection sort, shellsort, quicksort, mergesort, heapsort. Binary heaps. Binary search trees, hashing. Representations of graphs. Graph search, union-find, minimum spanning trees, shortest paths. Substring search, pattern matching.	13
AL	Basic Automata, Computability and Complexity	Finite-state machines, regular expressions, P vs. NP, NP-completeness, NP-complete problems	3
AL	Advanced Automata, Computability and Complexity	Languages, DFAs, NFAs, equivalence of NFAs and DFAs.	1
AL	Advanced Data Structures and Algorithms	Balanced trees, B-trees. Topological sort, strong components, network flow. Convex hull. Geometric search and intersection. String sorts, tries, Data compression.	9

Additional topics

Use of scientific method to validate hypotheses about an algorithm's time and space usage.

CS 256 Algorithm Design and Analysis, Williams College

Williamstown, MA
Brent Heeringa
heeringa@cs.williams.edu
www.cs.williams.edu/~heeringa/classes/cs256

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Algorithms and Complexity (AL)	28
Discrete Structures (DS)	2

Where does the course fit in your curriculum?

Students commonly take this course in their second year. It is required. The course has two prerequisites: Discrete Mathematics (taken in the Department of Mathematics) and Data Structures. Over the past five years, the course averages 20 students per year. In 2013 there are 38 students enrolled.

What is covered in the course?

Analysis: asymptotic analysis including lower bounds on sorting, recurrence relations and their solutions.

Graphs: directed, undirected, planar, and bipartite.

Greedy Algorithms: shortest paths, minimum spanning trees, and the union-find data structure (including amortized analysis).

Divide and Conquer Algorithms: integer and matrix multiplication, the fast-fourier transform.

Dynamic Programming: matrix parenthesization, subset sum, RNA secondary structure, DP on trees.

Network Flow: Max-Flow, Min-Cut (equivalence, duality, algorithms).

Randomization: randomized quicksort, median, min-cut, universal hashing, skip lists.

String Algorithms: string matching, suffix trees and suffix arrays.

Complexity Theory: Complexity classes, reductions, and approximation algorithms.

What is the format of the course?

The course format is face-to-face lecture. The lectures last 50 minutes and happen 3 times a week for 12 weeks for a total of 30 contact hours. Office hours often increase contact hours significantly. There is no lab or discussion section.

How are students assessed?

Nine problem sets, each worth 5% of the total grade. I drop the lowest score. One take-home midterm exam worth 25% of the grade. One take-home final exam worth 25% of the grade. 6 pop quizzes, each worth 1% of the grade. I drop the lowest score. A class participation grade based on attendance, promptness, and participation worth 5% of the grade. I expect students will spend 7-10 hours on the problem sets and exams.

Course textbooks and materials

Algorithm Design by Kleinberg and Tardos, supplemented liberally with my own lecture notes. There are two programming assignments, one in Python and one in Java.

Why do you teach the course this way?

The goal of *Algorithms* is for students to learn and practice a variety of problem solving strategies and analysis techniques. Students develop algorithmic maturity. They learn how to think about problems, their solutions, and the quality of those solutions.

I have taught Algorithms since 2007 except for 2010 when I was on sabbatical. My sense is that my course is non-trivial revision of the offering pre-2007. Students consider the course challenging in a rewarding way.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Asymptotic analysis including definitions of asymptotic upper, lower, and tight bounds. Discussion of worst, best, and expected running time (Monte Carlo and Las Vegas for randomized algorithms and a brief discussion about making assumptions about the distribution of the input). Natural complexity classes in P (log n, linear quadratic, etc.), recurrence relations and their solutions (mostly via the recursion tree and master method although we mention generating functions as a more general solution).	5
AL	Algorithmic Strategies	Brute-force algorithms (i.e., try-'em-all), divide and conquer, greedy algorithms, dynamic programming, and transformations. We do not cover recursive backtracking, branch and bound, or heuristic programming although these topics are given some attention in Artificial Intelligence.	6
AL	Fundamental Data Structures and Algorithms	Order statistics including deterministic median, We do not cover heaps directly in this course although we mention various heap implementations and their trade-offs (e.g., Fibonacci heaps, soft heaps, etc.) when discussing shortest path and spanning tree algorithms. Undirected and directed graphs, bipartite graphs, graph representations and trade-offs, fundamental graph algorithms including BFS and DFS, shortest-path algorithms, and spanning tree algorithms. Many of the topic areas included in this knowledge unit are covered in Data Structures so we review them quickly and use them as a launching point for more advanced material.	4
AL	Basic Automata, Computability and Complexity	Algorithm Design and Analysis contains very little complexity theory–these topics are all covered in detail in our Theory of Computation course. However, we do spend 1 lecture on the complexity classes P and NP, and approaches to dealing with intractability including approximation algorithms (mentioned below).	1
AL	Advanced Data Structures, Algorithms and Analysis	A quick review of ordered dynamic dictionaries (including balanced BSTs like Red-Black Trees and AVL-Trees) as a way of motivating Skip Lists. Graph algorithms to find a maximum matching and connected components. Some advanced data structures like union-find (including the log*n amortized analysis). Suffix trees, suffix arrays (we follow the approach of Karkkainen and Sanders that recursively builds a suffix array and then transforms it into a suffix tree). Network flow including max-flow, min-cut, bipartite matching	12

		and other applications including Baseball Elimination. Randomized algorithms including randomized median, randomized min-cut, randomized quicksort, and Rabin-Karp string matching. We cover the geometric problem of finding the closest pair of points in the plane and develop the standard randomized solution based on hashing. Sometimes we cover linear programming. Very little number theoretic and geometric algorithms are covered due to time. We spend two lectures on approximation algorithms because it is my research area.	
DS	Discrete Probability	We review concepts from discrete probability in support of randomized algorithms. This includes expectation, variance, and (very quickly) concentration bounds (we use these to prove that many of our algorithms run in their expected time with very high probability)	2

Other comments
There is some overlap with the topics covered here and DS/Graphs and Trees.

CSE332: Data Abstractions, University of Washington

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(Description below based on, for example, the Spring 2012 offering)

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Algorithms and Complexity (AL)	19
Parallel and Distributed Computing (PD)	9
Discrete Structures (DS)	3
Software Development Fundamentals (SDF)	2

Where does the course fit in your curriculum?

This is a required course taken by students mostly in their second year, following at least CS1, CS2, and a "Foundations" course that covers much of Discrete Structures. This course is approximately 70% classic data structures and 30% an introduction to shared-memory parallelism and concurrency. It is a prerequisite for many senior-level courses.

What is covered in the course?

The core of this course is fundamental "classical" data structures and algorithms including balanced trees, hashtables, sorting, priority queues, graphs and graph algorithms like shortest paths, etc. The course includes asymptotic complexity (e.g., big-O notation). The course also includes an introduction to concurrency and parallelism grounded in the data structure material. Concurrent access to shared data motivates mutual exclusion. Independent subcomputations (e.g., recursive calls to mergesort) motivate parallelism and cost models that account for time-to-completion in the presence of parallelism.

More general goals of the course include (1) exposing students to non-obvious algorithms (to make the point that algorithm selection and design is an important and non-trivial part of computer science & engineering) and (2) giving students substantial programming experience in a modern high-level programming language such as Java (to continue developing their software-development maturity).

Course topics:

- Asymptotic complexity, algorithm analysis, recurrence relations
- Review of stacks, queues, and binary search trees (covered in CS2)
- Priority queues and binary heaps
- Dictionaries and AVL trees, B trees, and hashtables
- Insertion sort, selection sort, heap sort, merge sort, quicksort, bucket sort, radix sort
- Lower bound for comparison sorting
- Graphs, graph representations, graph traversals, topological sort, shortest paths, minimum spanning trees
- Simple examples of amortized analysis (e.g., resizing arrays)
- Introduction to multiple explicit threads of execution
- Parallelism via fork-join computations
- Basic parallel algorithms: maps, reduces, parallel-prefix computations
- Parallel-algorithm analysis: Amdahl's Law, work, span
- Concurrent use of shared resources, mutual exclusion via locks

- Data races and higher-level race conditions
- Deadlock
- Condition variables

What is the format of the course?

This is a fairly conventional course with 3 weekly 1-hour lectures and 1 weekly recitation section led by a teaching assistant. The recitation section often covers software-tool details not covered in lecture. It is a 10-week course because the university uses a "quarter system" with 10-week terms.

How are students assessed?

Students complete 8 written homework assignments, 3 programming projects in Java (1 using parallelism), a midterm, and a final exam.

Course textbooks and materials

For the classic data structures material, the textbook is *Data Structures and Algorithm Analysis in Java* by Weiss. For parallelism and concurrency, materials were developed originally for this course and are now used by several other institutions (see URL below). Programming assignments use Java, in particular Java's Fork-Join Framework for parallelism.

Why do you teach the course this way?

Clearly the most novel feature of this course is the integration of multithreading, parallelism, and concurrency. The paper "Introducing Parallelism and Concurrency in the Data Structures Course" by Dan Grossman and Ruth E. Anderson, published in SIGCSE2012, provides additional rationale and experience for this approach. In short, data structures provides a rich source of canonical examples to motivate both parallelism and concurrency. Moreover, an introduction to parallelism benefits from the same mix of algorithms, analysis, programming, and practical considerations that is the main ethos of the data structures course.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	All except the Master Theorem	3
AL	Fundamental Data Structures and Algorithms	All topics except string/text algorithms. Also, the preceding CS2 course covers some of the simpler topics, which are then quickly reviewed	10
AL	Advanced Data Structures Algorithms and Analysis	Only these: AVL trees, topological sort, B-trees, and a brief introduction to amortized analysis	6
DS	Graphs and Trees	All topics except graph isomorphism	3
PD	Parallelism Fundamentals	All	2
PD	Parallel Decomposition	All topics except actors and reactive processes, but at only a cursory level	1
PD	Communication and Coordination	All topics except Consistency in shared memory models, Message passing, Composition, Transactions, Consensus, Barriers, and Conditional actions. (The treatment of atomicity and deadlock is also very elementary.)	2
PD	Parallel Algorithms, Analysis, and Programming	All Core-Tier-2 topics; none of the Elective topics	4

SDF	Fundamental Data Structures	Only priority queues (all other topics are in CS1 and CS2)	2

Additional topics
The parallel-prefix algorithm

Other comments
The parallelism and concurrency materials are freely available at
http://www.cs.washington.edu/homes/djg/teachingMaterials/spac/

CS/ECE 552: Introduction to Computer Architecture, University of Wisconsin

Computer Sciences Department
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http://pages.cs.wisc.edu/~karu/courses/cs552/spring2011/wiki/index.php/Main/Syllabus

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Architecture and Organization (AR)	39

Where does the course fit in your curriculum?

This is taken by juniors, seniors, and beginning graduate students in computer science and computer engineering. Prerequisites include courses that cover assembly language and logic design. This course is a (recommended) prerequisite for a graduate course on advanced computer architecture. Approximately 60 students take the course per offering; it is offered two times per year (once each semester).

What is covered in the course?

The goal of the course is to teach the design and operation of a digital computer. It serves students in two ways. First, for those who want to continue studying computer architecture, embedded systems, and other low-level aspects of computer systems, it lays the foundation of detailed implementation experience needed to make the quantitative tradeoffs in more advanced courses meaningful. Second, for those students interested in other areas of computer science, it solidifies an intuition about why hardware is as it is and how software interacts with hardware.

The subject matter covered in the course includes technology trends and their implications, performance measurement, instruction sets, computer arithmetic, design and control of a datapath, pipelining, memory hierarchies, input and output, and brief introduction to multiprocessors.

The full list of course topics is:
Introduction and Performance

- Technology trends
- Measuring CPU performance
- Amdahl's law and averaging performance metrics

Instruction Sets

- Components of an instruction set
- Understanding instruction sets from an implementation perspective
- RISC and CISC and example instruction sets

Computer Arithmetic

- Ripple carry, carry lookahead, and other adder designs
- ALU and Shifters
- Floating-point arithmetic and floating-point hardware design

Datapath and Control

- Single-cycle and multi-cycle datapaths
- Control of datapaths and implementing control finite-state machines

Pipelining

- Basic pipelined datapath and control
- Data dependences, data hazards, bypassing, code scheduling
- Branch hazards, delayed branches, branch prediction

Memory Hierarchies

- Caches (direct mapped, fully associative, set associative)
- Main memories
- Memory hierarchy performance metrics and their use
- Virtual memory, address translation, TLBs

Input and Output

- Common I/O device types and characteristics
- Memory mapped I/O, DMA, program-controlled I/O, polling, interrupts
- Networks

Multiprocessors

- Introduction to multiprocessors
- Cache coherence problem

What is the format of the course?

The course is 15 weeks long, with students meeting for three 50-minute lectures per week or two 75-minute lectures per week. If the latter, the course is typically "front loaded" so that lecture material is covered earlier in the semester and students are able to spend more time later in the semester working on their projects.

How are students assessed?

Assessment is a combination of homework, class project, and exams. There are typically six homework assignments. The project is a detailed implementation of a 16-bit computer for an example instruction set. The project requires both an unpipelined as well as a pipelined implementation and typically takes close to a hundred hours of work to complete successfully. The project and homeworks are typically done by teams of 2 students. There is a midterm exam and a final exam, each of which is typically 2 hours long.

Course textbooks and materials

David A. Patterson and John L. Hennessy, Computer Organization and Design: The Hardware and Software Interface Morgan Kaufmann Publishers,
Fourth Edition. ISBN: 978-0-12-374493-7

Why do you teach the course this way?

Since the objective is to teach how a digital computer is designed and built and how it executes programs, we want to show how basic logic gates could be combined to construct building blocks which are then combined to work together to execute programs written in a machine language. The students learn the concepts of how to do so in the classroom, and then apply them in their project. Having taken this course a student can go into an industrial environment and be ready to participate in the design of complex digital.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AR	Introductory Material and Performance	Technology trends, measuring CPU performance, Amdahl's law and averaging performance metrics	3
AR	Instruction Set Architecture	Components of instruction sets, understanding instruction sets from an implementation perspective, RISC and CISC and example instruction sets	3
AR	Computer Arithmetic	Ripple carry, carry lookahead, and other adder designs, ALU and Shifters, floating-point arithmetic and floating-point hardware design	6
AR	Datapath and Control	Single-cycle and multi-cycle datapaths, control of datapaths and implementing control finite-state machines	4
AR	Pipelined Datapaths and Control	Basic pipelined datapath and control, data dependences, data hazards, bypassing, code scheduling, branch hazards, delayed branches, branch prediction	8
AR	Memory Hierarchies	Caches (direct mapped, fully associative, set associative), main memories, memory hierarchy performance metrics and their use, virtual memory, address translation, TLBs	9
AR	Input and Output	Common I/O device types and characteristics, memory mapped I/O, DMA, program-controlled I/O, polling, interrupts, networks	3
AR	Multiprocessors	Introduction to multiprocessors, cache coherence problem	3

CS150: Digital Components and Design, University of California, Berkeley

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Architecture and Organization (AR)	37.5

Where does the course fit in your curriculum?
This is a junior-level course in the computer science curriculum for computer engineering students interested in digital system design and implementation.

What is covered in the course?
Design of synchronous digital systems using modern tools and methodologies, in particular, digital logic synthesis tools, digital hardware simulation tools, and field programmable gate array architectures.

What is the format of the course?
Lecture, discussion section, laboratory

How are students assessed?
Laboratories, examinations, and an independent design project

Course textbook and materials
Harris and Harris, Digital Design and Computer Architecture

Why do you teach the course this way?
Understand the principles and methodology of digital logic design at the gate and switch level, including both combinational and sequential logic elements. Gain experience developing a relatively large and complex digital system. Gain experience with modern computer-aided design tools for digital logic design. Understand clocking methodologies used to control the flow of information and manage circuit state. Appreciate methods for specifying digital logic, as well as the process by which a high-level specification of a circuit is synthesized into logic networks. Appreciate the tradeoffs between hardware and software implementations of a given function. Appreciate the uses and capabilities of a modern FPGA platform.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AR	Digital Logic and Digital Systems	Combinational /Sequential Logic Design and CAD Tools; State Machines, Counters; Digital Building Blocks; High Level Design w/Verilog	4.5 4.5 3 4.5 4.5
AR	Machine Level Representation of Data	N/A	0

AR	Assembly Level Machine Organization	MIPS Architecture & Project	3
AR	Memory System Organization and Architecture	CMOS/SRAM/DRAM, Video/Frame Buffers	6
AR	Interfacing and Communication	Timing; Synchronization	3 1.5
AR	Functional Organization	N/A	0
AR	Multprocessing and Alternative Architecture	Graphics Processing Chips	1.5
AR	Performance Enhancements	Power and Energy	1.5

CC152: Computer Architecture and Engineering, University of California, Berkeley

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Architecture and Organization (AR)	33

Where does the course fit in your curriculum?
This is a senior-level course in the computer science curriculum for computer engineering students interested in computer design.

What is covered in the course?
Historical Perspectives: RISC vs. CISC, Pipelining, Memory Hierarchy, Virtual Memory, Complex Pipelines and Out-of-Order Execution, Superscaler and VLIW Architecture, Synchronization, Cache Coherency.

What is the format of the course?
Lectures, Discussion, Laboratories, and Examinations

How are students assessed?
Examinations, homeworks, and hands-on laboratory exercises

Course textbook and materials
J. L. Hennessy and D. A. Patterson, *Computer Architecture: A Quantitative Approach*, 5th Edition, Morgan Kaufmann Publishing Co., Menlo Park, CA. 2012.

Why do you teach the course this way?
The course is intended to provide a foundation for students interested in performance programming, compilers, and operating systems, as well as computer architecture and engineering. Our goal is for you to better understand how software interacts with hardware, and to understand how trends in technology, applications, and economics drive continuing changes in the field. The course will cover the different forms of parallelism found in applications (instruction-level, data-level, thread-level, gate-level) and how these can be exploited with various architectural features. We will cover pipelining, superscalar, speculative and out-of-order execution, vector machines, VLIW machines, multithreading, graphics processing units, and parallel microprocessors. We will also explore the design of memory systems including caches, virtual memory, and DRAM. An important part of the course is a series of lab assignments using detailed simulation tools to evaluate and develop architectural ideas while running real applications and operating systems. Our objective is that you will understand all the major concepts used in modern microprocessors by the end of the semester.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AR	Digital Logic and Digital Systems	N/A	0
AR	Machine Level Representation of Data	N/A	0
AR	Assembly Level Machine Organization	Historical Perspectives	6
AR	Memory System Organization and Architecture	Memory Hierarchy, Virtual Memory, Snooping Caches	9
AR	Interfacing and Communication	Synchronization, Sequential Consistency	3
AR	Functional Organization	Pipelining	3
AR	Multprocessing and Alternative Architecture	Superscalar, VLIW, Vector Processing	6
AR	Performance Enhancements	Complex Pipelining	3

Additional topics

Case Study: Intel Sandy Bridge & AMD Bulldozer (1.5); Warehouse-Scale Computing (1.5)

eScience, University of North Carolina at Charlotte

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Computational Science (CN)	42
Intelligent Systems (IS)	15
Topics outside Body of Knowledge	33

Where does the course fit in your curriculum?

The University of North Carolina at Charlotte's (UNCC) College of Computing and Informatics (CCI) has recently introduced its first laboratory-based science course, designed to partially satisfy the science portion of the University College's general education requirements[2] [3]. The University College General Education program's curriculum reflects UNCC's commitment to the principles of a liberal arts education, a broad training that develops analytic, problem solving, and communications skills and also awareness of bodies of knowledge and new perspectives that prepare students for success in their careers and communities in the 21st century. In the General Education curriculum, eScience is positioned alongside other introductory "Inquiry into the Sciences" courses[4] such as Astronomy, Bioinformatics, Biological Anthropology, Biology, Chemistry, Earth Sciences, Geology, Physics, and Psychology.

This course is commonly taken by freshmen and sophomores, occasionally juniors and seniors have attended. Although this course is not compulsory, it does satisfy the requirement for a science class with lab. There are no course pre-requisites and no follow-on courses are required. (Starting in the Fall 2013, a related and optional Agent-Based Modeling course will be offered for undergraduate and graduate students.) Typically, anywhere from 15 to 40 students will take this course per semester.

What is covered in the course?

eScience's basic premise is that in addition to the two accepted scientific inquiry methods: theoretical/mathematical formulation and experimentation, computational simulation/modeling has become the third method for doing science. eScience introduces the application of computational methods to scientific exploration and discovery in the social and natural sciences. Both the class and the laboratory include a broad range of well-defined experiments, verified data inputs, predictable/repeatable outcomes, and open questions to be explored. We begin with an Introduction to eScience, Scientific Method, and Models. Thereafter, we have weekly topics including Spread of Epidemics, Spread of Fire, Movement of Ants and Problem Solving, Predator-prey relationships,

[2] http://ucol.uncc.edu/

[3] http://ucol.uncc.edu/gened/requirements.htm

[4] https://ucol.uncc.edu/general-education/requirements/inquiry-sciences

Altruism/Collaboration/Competition, Economics, Art and Music, Climate Change, E. coli metabolism of lactose, Cancer and Tumors, Games, Complex Systems and Chaos, Networks, and Fractals. Both theory and practice of computational simulation and modeling techniques are examined as tools to support the scientific method. No computer programming knowledge or calculus is required. By popular student demand, Netlogo[5] is predominantly used as the modeling tool for this course due to its ease of use and extensive library of relevant models. Such tools have the advantage of embodying principles of a systems approach to non-linear, self-organizing, and emergent phenomena that characterize most interesting problems that societies face today. They also offer a bottom-up approach to problem-solution and experimentation in a non-threatening way that does not require the knowledge of programming. At the same time, these tools also provide more adventurous students with the opportunity to modify the natural language-like computer code to test their own ideas about modeling the societal challenge under consideration.

The course includes up to fifteen knowledge units per semester. Each week in the semester is devoted to one knowledge unit. There are two 75-minute lessons per week/knowledge unit. The first lesson of the week uncovers the nature of the societal problem targeted in that particular knowledge unit. The second lesson of the week offers examples of computer-based simulations and models of the problem. Both lessons include many team-based exercises that encourage self-exploration, innovation, and creativity. The lessons are followed by a laboratory session that uses well-defined protocols to guide students through hands-on exploration of computer simulations and models. In the Spring 2013 semester we introduced the use of Audience Response Systems[6] (clickers) for quizzes at the end of each lesson or topic; each quiz consisted of four to five questions about the current topic plus one or two review questions from previous topics. We also experimented with "flipped classroom" methods during some of the clicker quizzes. When responses to questions were diverse and mostly incorrect, we had students discuss their responses amongst themselves and then we re-tested them; as expected, student scores improved on those questions after they had an opportunity to discuss amongst themselves.

Some knowledge units incorporate student projects. Projects are two to three weeks long. They are team-based. Each team includes two to four students. Students are assigned to teams based on their declared major/discipline. Every effort is made to ensure that teams are interdisciplinary.

At the conclusion of this one-semester, 4-hour course, students should be able to:

1. Have an enhanced appreciation for the use of science in addressing real-world problems
2. Apply critical thinking in solving science-related problems
3. Survey literature on current and relevant science-related issues
4. Comfortably communicate scientific concepts with others
5. Perform basic inquiry-based science experimentation using computational models
6. Have fun doing all of the above!

What is the format of the course?

eScience is taught as a traditional face-to-face, four credit-hour course consisting of three hours of class instruction and one three-hour lab per week for about 15 weeks.

[5] http://ccl.northwestern.edu/netlogo/

[6] http://www.turningtechnologies.com/response-solutions

How are students assessed?

eScience students are assessed using various methods: two or three member team-based project assignments (30%), eight to ten lab exercises (20%), class participation including weekly quizzes (10%), mid-term and final exams (20% each). On average, students are expected to spend about two to three hours per week on assessed work plus class attendance.

Course textbooks and materials

There is currently no textbook for this course. Course materials consist of PowerPoint presentations, online YouTube videos, and links to other online resources. All course materials, assignments, communications, quizzes, and exams are available on Moodle[7], an open source Learning Management System (LMS) available to students 24 x 7. Netlogo is predominantly used as the modeling tool for this course due to its ease of use and extensive library of relevant models.

Why do you teach the course this way?

The initial offering of this course in the Fall 2010 and Spring 2011 semesters made use of dynamical systems and data-driven simulation/modeling paradigms; the textbook we used ("Introduction to Computational Science: Modeling and Simulation for the Sciences," by Shiflet, A. B. and Shiflet, G. W., Princeton University Press, 2006) was heavily based on calculus and mathematical formalisms. The topics covered were: Rate of Change, Constrained Growth, Unconstrained Growth and Decay, Drug Dosage, Modeling Falling and Skydiving, Competition, Spread of SARS, Predator-Prey, Errors, Euler's Method, Runge-Kutta Method, Empirical Models, Simulations, Area Through Monte Carlo Simulation, Random Walk, Spreading of Fire, and Movement of Ants. We used Mathematica[8] and Vensim[9] for lab experiments. Teaching this course in this manner was instrumental in helping us understand what is wrong with current approaches to teaching science, including ours. For example, the eScience course attracted a diverse group of students the first time it was offered, including those majoring in communications, business, computer science, and information systems. However, early on in the semester eight of the twenty students dropped the class, citing the heavy use of calculus as the reason for doing so. We can only speculate that these students have conveyed their experience to their academic advisors and fellow students, and the 75% drop in the course enrollment the following semester seemed to indicate such a possibility. In conversations with students who stayed in the class, we learned that they expected a class that was very different from the one that was offered. They were hoping for a class that would demonstrate the utility of science in many areas of everyday life, including social interactions, economy, stock market, diseases, weather, poverty, population growth, ecology, global warming, war, politics, social unrests, and nature in general. They wanted to be able to experiment with various settings and what-if scenarios in order to understand the consequences of their actions, sensitivity to initial conditions, and interpretability of the outcomes. All in all, they wanted it to be fun, engaging, and relevant. At the same time, we felt that both the class and the laboratory needed to be structured enough to include a broad range of well-defined experiments, verified data inputs, predictable/repeatable outcomes, and open questions to be explored.

We changed the course format to its current incarnation in the Fall 2011 semester. The dependency on math and calculus was eliminated and the list of topics was changed to include social sciences, humanities, and arts in addition to the natural sciences. No textbook is required. For each topic, we designed or found existing presentation materials and experiment/tool that addresses a recognized problem of significant interest relevant to today's students. The purpose of the current eScience course is to convince students that science is interesting, important, relevant to their

[7] www.moodle.com

[8] http://www.wolfram.com/mathematica/

[9] www.vensim.com

everyday lives, and therefore at least worth studying, if not majoring in it. The course is divided into knowledge units. Each knowledge unit exemplifies key concepts that are associated with the scientific method, including Problem definition, Hypothesis generation, Experiment design and implementation, Results analysis, Model design, and Model validation and verification.

The knowledge units address issues of everyday interest to the general population. Knowledge units have included: movement of ants, economics, spread of epidemics, climate change and global warming, cancer, predator-prey relationships, cooperation and collaboration, computer games, arts and music, fractals, and metabolism of lactose (lac operon). In addition, students are exposed to tools, methods, theories, and paradigms that allow them to consider patterns that transcend application domains and problems. These methods and tools include the science of complexity, the science of networks, fractals, chaos theory, problem solving techniques, and game theory.

Because of the diversity in the majors of students who take this course (Business, Computing, Engineering, Liberal Arts, etc.) and the diversity of topics that are covered, some students find this course challenging while others feel it is less so. Again, our goal is to make the course relevant, interesting, and applicable to current issues.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
CN	Fundamentals	Models as abstractions of situations	3
CN	Modeling and Simulation	Purpose of modeling and simulation including optimization; supporting decision making, forecasting, safety considerations; for training and education. Important application areas including health care and diagnostics, economics and finance, city and urban planning, science, and engineering. .	3
CN	Modeling and Simulation	Model building: use of mathematical formula or equation, graphs, constraints; methodologies and techniques; use of time stepping for dynamic systems. .	15
CN	Modeling and Simulation	Formal models and modeling techniques: mathematical descriptions involving simplifying assumptions and avoiding detail. The descriptions use fundamental mathematical concepts such as set and function. Random numbers.	3
CN	Modeling and Simulation	Assessing and evaluating models and simulations in a variety of contexts; verification and validation of models and simulations.	18
IS	Agents	Multi-agent systems Collaborating agents Agent teams Competitive agents (e.g., auctions, voting) Swarm systems and biologically inspired models	15
		Other KA's are covered in other courses	n/a

Additional topics

We begin with an Introduction to eScience, Scientific Method, and Models. Thereafter, we have weekly topics including Spread of Epidemics, Spread of Fire, Movement of Ants and Problem Solving, Predator-prey relationships, Altruism/Collaboration/Competition, Economics, Art and Music, Climate Change, E. coli metabolism of lactose, Cancer and Tumors, Games, Complex Systems and Chaos, Networks, and Fractals. Both theory and practice of computational simulation and modeling techniques are examined as tools to support the scientific method. (33 hours)

Other comments

The number of topics taught each semester varies, new topics are added and some topics are dropped.

COSC/MATH 201: Modeling and Simulation for the Sciences, Wofford College

Angela B. Shiflet
http://www.wofford.edu/ecs/
(Description below based on the Fall 2011 and 2012 offerings)

Knowledge Areas with topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Computational Science (CN)	35.5
Intelligent Systems (IS)	3
Software Development Fundamentals (SDF)	2
Software Engineering (SE)	1
Graphics and Visualization (GV)	0.5

Where does the course fit in your curriculum?

Modeling and Simulation for the Sciences (COSC/MATH 201) has a pre-requisite of Calculus I. However, because the course does not require derivative or integral formulas but only an understanding of the concept of "rate of change," students with no calculus background have taken the course successfully. The course has been offered since the spring of 2001. Dual-listed as a computer science and a mathematics course and primarily targeted at second-year science majors, the course is required for Wofford College's Emphasis in Computer Science (see "Other comments" below). Moreover, Modeling and Simulation meets options for the computer science, mathematics, and environmental studies majors and counts for both computer science and mathematics minors.

Wofford College has a thirteen-week semester with an additional week for final exams. Modeling and Simulation for the Sciences has 3-semester-hours credit and meets 3 contact hours per week.

What is covered in the course?

- The modeling process
- Two system dynamics tool tutorials
- System dynamics problems with rate proportional to amount: unconstrained growth and decay, constrained growth, drug dosage
- System dynamics models with interactions: competition, predator-prey models, spread of disease models
- Computational error
- Simulation techniques: Euler's method, Runge-Kutta 2 method
- Additional system dynamics projects throughout, such as modeling falling and skydiving, enzyme kinetics, the carbon cycle, economics and fishing
- Six computational toolbox tutorials
- Empirical models
- Introduction to Monte Carlo simulations
- Cellular automaton random walk simulations
- Cellular automaton diffusion simulations: spreading of fire, formation of biofilms

- High-performance computing: concurrent processing, parallel algorithms
- Additional cellular automaton simulations throughout such as simulating polymer formation, solidification, foraging, pit vipers, mushroom fairy rings, clouds

What is the format of the course?

Usually, students are assigned reading of the material before consideration in class. Then, after questions are discussed, students often are given a short quiz taken directly from the quick review questions. Answers to these questions are available at the end of each module. After the quiz, usually the class develops together an extension of a model in the textbook. Class time is allotted for the first system dynamics tutorial and the first computational toolbox tutorial. Students work on the remaining tutorials and open-ended projects, often in pairs, primarily outside of class and occasionally in class.

How are students assessed?

Students complete two system dynamics tutorials and six computational toolbox tutorials with at least one of each type of tutorial in a lab situation. The students have approximately one project assignment per week during a thirteen-week semester. Most assignments are completed in teams of two or three students. Generally, a submission includes a completed model, results, and discussion. Students present their models at least twice during the semester. Daily quizzes occur on the quick review questions, and tests comprise a midterm and a final.

Course textbooks and materials

Textbook: *Introduction to Computational Science: Modeling and Simulation* by Angela B. Shiflet and George W. Shiflet, Princeton University Press, with online materials available at the above website.

A second edition of the textbook is nearing completion and will include new chapters on agent-based modeling and modeling with matrices along with ten additional project-based modules and more material on high performance computing.

The first half of the semester on system dynamics uses STELLA or Vensim; and the second half of the semester on empirical modeling and cellular automaton simulations employs Mathematica or MATLAB. (Tutorials and files are available on the above website in these tools and also in Python, R, Berkeley Madonna, and Excel for system dynamics models and in Python, R, Maple, NetLogo, and Excel for the material for the second half of the semester.)

Why do you teach the course this way?

The course has evolved since its initial offering in 2001, and the vast majority students, who have a variety of majors in the sciences, mathematics, and computer science, are successful in completing the course with good grades. Moreover, many of the students have used what they have learned in summer internships involving computation in the sciences.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
CN	Introduction to Modeling and Simulation	Models as abstractions of situations Simulations as dynamic modeling Simulation techniques and tools, such as physical simulations and human-in-the-loop guided simulations. Foundational approaches to validating models	3
CN	Modeling and Simulation	Purpose of modeling and simulation including optimization; supporting decision making, forecasting, safety considerations; for training and education. Tradeoffs including performance, accuracy, validity, and complexity. The simulation process; identification of key characteristics or	29

		behaviors, simplifying assumptions; validation of outcomes. Model building: use of mathematical formula or equation, graphs, constraints; methodologies and techniques; use of time stepping for dynamic systems. Formal models and modeling techniques: mathematical descriptions involving simplifying assumptions and avoiding detail. The descriptions use fundamental mathematical concepts such as set and function. Random numbers. Examples of techniques including: Monte Carlo methods Stochastic processes Graph structures such as directed graphs, trees, networks Differential equations: ODE Non-linear techniques State spaces and transitions Assessing and evaluating models and simulations in a variety of contexts; verification and validation of models and simulations. Important application areas including health care and diagnostics, economics and finance, city and urban planning, science, and engineering. Software in support of simulation and modeling; packages, languages.	
CN	Processing	Fundamental programming concepts, including: The process of converting an algorithm to machine-executable code; Software processes including lifecycle models, requirements, design, implementation, verification and maintenance; Machine representation of data computer arithmetic, and numerical methods, specifically sequential and parallel architectures and computations; The basic properties of bandwidth, latency, scalability and granularity; The levels of parallelism including task, data, and event parallelism.	3
CN	Interactive Visualization	Image processing techniques, including the use of standard APIs and tools to create visual displays of data	0.5
GV	Fundamental Concepts	Applications of computer graphics: including visualization	0.5
SDF	Development Methods	Program comprehension Program correctness Types or errors (syntax, logic, run-time) The role and the use of contracts, including pre- and post-conditions Unit testing Simple refactoring Debugging strategies Documentation and program style	2
IS	Agents	Definitions of agents Agent architectures (e.g., reactive, layered, cognitive, etc.) Agent theory Biologically inspired models	Possibly 3
SE	Software Design	The use of components in design: component selection, design, adaptation and assembly of components, components, components.	1

Additional topics

Successful course participants will:

- Understand the modeling process
- Be able to develop and analyze systems dynamics models and Monte Carlo simulations with a team
- Understand the concept of rate of change
- Understand basic system dynamics models, such as ones for unconstrained and constrained growth, competition, predator-prey, SIR, enzyme kinetics
- Be able to perform error computations
- Be able to use Euler's and Runge-Kutta 2 Methods
- Be able to develop an empirical model from data
- Understand basic cellular automaton simulations, such as ones for random walks, diffusion, and reaction-diffusion
- Be able to verify and validate models
- Understand basic hardware and programming issues of high performance computing
- Be able to use a system dynamics tool, such as Vensim, STELLA, or Berkeley Madonna
- Be able to use a computational tool, such as MATLB, Mathematica, or Maple.

Other comments

Wofford College's Emphasis in Computational Science (ECS), administered by the Computer Science Department, is available to students pursuing a B.S. in a laboratory science, mathematics, or computer science. The Emphasis requires five courses—Modeling and Simulation for the Sciences (this course), CS1, CS2, Calculus I, and Data and Visualization (optionally in 2013, Bioinformatics or High Performance Computing)—and a summer internship involving computation in the sciences. Computer science majors obtaining the ECS must also complete 8 additional semester hours of a laboratory science at the 200+ level. Note: Data and Visualization covers creation of Web-accessible scientific databases, a dynamic programming technique of genomic sequence alignment, and scientific visualization programming in C with OpenGL.

MAT 267: Discrete Mathematics, Union County College

Cranford, NJ
Dr. Cynthia Roemer, Department Chair
roemer@ucc.edu
www.ucc.edu

Per College policy, all course materials are password-protected. Instructional resources are available upon email request.

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Discrete Structures (DS)	42 hours

Where does the course fit in your curriculum?
Union County College offers this course both Fall and Spring semesters. Computer Science majors typically complete the required Discrete Mathematics course as sophomores. Students are eligible to enroll in this course after passing pre-calculus (MAT 143) with a grade of C or better, or scoring well enough on the College Level Mathematics Test to place directly into it. CS majors are also required to complete Calculus I (MAT 171).

What is covered in the course?
This course will develop advanced mathematics skills appropriate for students pursuing STEM studies such as Engineering, Science, Computer Science, and Mathematics. Topics include sets, numbers, algorithms, logic, computer arithmetic, applied modern algebra, combinations, recursion principles, graph theory, trees, discrete probability, and digraphs.

What is the format of the course?
This course earns 3 credit hours and consists of 3 lecture hours per week for 14 weeks. Discrete Mathematics offered at Union County College currently meets twice per week for 80 minutes each.

How are students assessed?
Students are assessed on a combination of homework, quizzes/tests, group activities, discussion, projects, and a comprehensive final exam. Students are expected to complete homework assignments/projects on a weekly basis. For a typical student, each assignment will require at least 3 hours to complete.

Course textbooks and materials
Text: Discrete Mathematics by Sherwood Washburn, Thomas Marlowe, & Charles T. Ryan (Addison-Wesley)

A graphing calculator (e.g. TI-89) and a computer algebra system (e.g. MAPLE) are required for completing certain homework exercises and projects.

Union County College has a Mathematics Success Center that is available for tutoring assistance for all mathematics courses.

Why do you teach the course this way?
Discrete Mathematics is a transfer-oriented course designed to meet the requirements of Computer Science, Engineering and Mathematics degree programs. Many of the Computer Science majors at Union County College

matriculate to New Jersey Institute of Technology. Furthermore, this course is designed to meet the following program objectives. (Also see Other Comments below). Upon successful completion of this course, students will be able to:

- Demonstrate critical thinking, analytical reasoning, and problem solving skills
- Apply appropriate mathematical and statistical concepts and operations to interpret data and to solve problems
- Identify a problem and analyze it in terms of its significant parts and the information needed to solve it
- Formulate and evaluate possible solutions to problems, and select and defend the chosen solutions
- Construct graphs and charts, interpret them, and draw appropriate conclusions

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
DS	Sets, Relations, Functions	all topics	6
DS	Basic Logic	all topics	9
DS	Proof Techniques	all topics	9
DS	Basics of Counting	all topics	7
DS	Graphs and Trees	all topics except Graph Isomorphism (core tier-2)	6
DS	Discrete Probability	all topics except Conditional Independence (core tier-2)	5

Other comments

Correlation of Program Objectives, Student Learning Outcomes, and Assessment Methods

Program Objectives	Student Learning Outcomes	Assessment Methods
Demonstrate critical thinking, analytical reasoning, and problem solving skills	Recognize, identify, and solve problems using set theory, elementary number theory, and discrete probability Recognize, identify, and apply the concepts of functions and relations and graph theory in problem solving Apply proof techniques in logic	**Written:** Homework assignments, examinations in class, and projects to be completed at home **Verbal:** Classroom exercises and discussion
Apply appropriate mathematical and statistical concepts and operations to interpret data and to solve problems	Recognize, identify, and solve problems using set theory, elementary number theory, and discrete probability Recognize, identify, and apply the concepts of functions and relations and graph theory in problem solving	**Written:** Homework assignments, examinations in class, and projects to be completed at home **Verbal:** Classroom exercises and discussion

Identify a problem and analyze it in terms of its significant parts and the information needed to solve it	Recognize, identify, and solve problems using set theory, elementary number theory, and discrete probability Recognize, identify, and apply the concepts of functions and relations and graph theory in problem solving Apply proof techniques in logic	**Written:** Homework assignments, examinations in class, and projects to be completed at home **Verbal:** Classroom exercises and discussion
Formulate and evaluate possible solutions to problems, and select and defend the chosen solutions	Recognize, identify, and solve problems using set theory , elementary number theory, and discrete probability Recognize, identify, and apply the concepts of functions and relations and graph theory in problem solving Apply proof techniques in logic	**Written:** Homework assignments, examinations in class, and projects to be completed at home **Verbal:** Classroom exercises and discussion
Construct graphs and charts, interpret them, and draw appropriate conclusions	Recognize, identify, and apply the concepts of functions and relations and graph theory in problem solving	**Written:** Homework assignments, examinations in class, and projects to be completed at home **Verbal:** Classroom exercises and discussion

CS103: Mathematical Foundations of Computer Science, Stanford University

and

CS109: Probability Theory for Computer Scientists, Stanford University

Stanford, CA, USA
Keith Schwarz and Mehran Sahami
{htiek, sahami}@cs.stanford.edu
Course URLs:
cs103.stanford.edu
cs109.stanford.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Discrete Structures (DS)	30
Algorithms and Complexity (AL)	6
Intelligent Systems (IS)	2

Where does the course fit in your curriculum?
CS103 and CS109 make up the first two courses in the required introductory CS theory core at Stanford. The prerequisites for CS103 are CS2 and mathematical maturity (e.g., comfortable with algebra, but calculus is not a requirement). The prerequisites for CS109 are CS2, CS103, and calculus. However, calculus is only used for topics beyond the CS2013 Discrete Structures guidelines, such as working with continuous probability density functions. Approximately 400 students take each course each year. The majority of students taking the courses are sophomores, although students at all levels (from freshman to graduate students) enroll in these courses.

What is covered in the course?
CS103 covers:

- Sets
- Functions and Relations
- Proof techniques (including direct, contradiction, diagonalization and induction)
- Graphs
- Logic (proposition and predicate)
- Finite Automata (DFAs, NFAs, PDAs)
- Regular and Context-Free Languages
- Turing Machines
- Complexity Classes (P, NP, Exp)
- NP-Completeness

CS109 covers:

- Counting
- Combinations and Permutations
- Probability (including conditional probability, independence, and conditional independence)
- Expectation and Variance
- Covariance and Correlation
- Discrete distributions (including Binomial, Negative Binomial, Poisson, and Hypergeometric)
- Continuous distributions (including Uniform, Normal, Exponential, and Beta)
- Limit/Concentration results (including Central Limit Theorem, Markov/Chebyshev bounds)
- Parameter estimation (including maximum likelihood and Bayesian estimation)
- Classification (including Naive Bayes Classifier and Logistic Regression)
- Simulation

What is the format of the course?

Both CS103 and CS109 use a lecture format, but also include interactive class demonstrations. Each course meets three times per week for 75 minutes per class meeting. CS103 also offers an optional 75 minute discussion session. The courses each run for 10 weeks (Stanford is on the quarter system).

How are students assessed?

CS103 currently requires nine problem sets (approximately one every week), with an expectation that students spend roughly 10 hours per week on the assignments. The problem sets are comprised of rigorous exercises (e.g., proofs, constructions, etc.) that cover the material from class during the just completed week.

CS109 currently requires five problem sets and one programming assignment (one assignment due every 1.5 weeks), with an expectation that students spend roughly 10 hours per week on the assignments. The problem sets present problems in probability (both applied and theoretical) with a bent toward applications in computer science. The programming assignment requires students to implement various probabilistic classification techniques, apply them to real data, and analyze the results.

Course textbooks and materials

CS103 uses two texts (in addition to a number of instructor-written course notes):

1. Chapter One of Discrete Mathematics and Its Applications, by Kenneth Rosen. This chapter (not the whole text) covers mathematical logic.
2. Introduction to the Theory of Computation by Michael Sipser.

CS109 uses the text A First Course in Probability Theory by Sheldon Ross for the first two-thirds of the course. The last third of the course relies on an instructor-written set of notes/slides that cover parameter estimation and provide an introduction to machine learning. Those slides are available here:
http://ai.stanford.edu/users/sahami/cs109/

Why do you teach the course this way?

As the result of a department-wide curriculum revision, we created this two course sequence to capture the foundations we expected students to have in discrete math and probability with more advanced topics, such as automata, complexity, and machine learning. This obviated the need for later full course requirements in automata/complexity and an introduction to AI (from which search-based SAT solving and machine learning were thought to be the most critical aspects). Students do generally find these courses to be challenging.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
DS	Proof Techniques	All	7
DS	Basic Logic	All	6
DS	Discrete Probability	All	6
AL	Basic Automata, Computability and Complexity	All	6
DS	Basics of Counting	All	5
DS	Sets, Relations, Functions	All	4
DS	Graphs and Trees	All Core-Tier1	2
IS	Basic Machine Learning	All	2

Additional topics

CS103 covers some elective material from:

AL/Advanced Computational Complexity
AL/Advanced Automata Theory and Computability

CS109 provides expanded coverage of probability, including:

Continuous distributions (including Uniform, Normal, Exponential, and Beta)
Covariance and Correlation
Limit/Concentration results (including Central Limit Theorem, Markov/Chebyshev bounds)
Parameter estimation (including maximum likelihood and Bayesian estimation)
Simulation of probability distributions by computer

CS109 also includes some elective material from:

IS/Reasoning Under Uncertainty
IS/Advanced Machine Learning

Other comments

Both these courses lectures move quite rapidly. As a result, we often cover the full set of topics in one of the CS2013 Knowledge Units in less time than proscribed in the guidelines. The "Hours" column in the Body of Knowledge coverage table reflects the number of hours we spend in lecture covering those topics, not the number suggested in CS2013 (which is always greater than or equal to the number we report).

CS 250 - Discrete Structures I, Portland Community College

12000 SW 49th Ave, Portland, OR 97219
Doug Jones
cdjones@pcc.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Discrete Structures (DS)	26
Algorithms and Complexity (AL)	4

Where does the course fit in your curriculum?

CS 250 is the first course in a two-term required sequence in discrete mathematics for Computer Science transfer students. Students typically complete the sequence in their second year.

College algebra and 1 term of programming are pre-requisites for CS 250. The second course in the sequence (CS 251) requires CS 250 as a pre-requisite.

Approximately 80 students per year complete the discrete mathematics sequence (CS 250 and CS 251).

What is covered in the course?

- Introduction to the Peano Axioms and construction of the natural numbers, integer numbers, rational numbers, and real numbers.
- Construction and basic properties of monoids, groups, rings, fields, and vector spaces.
- Introduction to transfinite ordinals and transfinite cardinals, and Cantor's diagonalization methods
- Representation of large finite natural numbers using Knuth's "arrow notation"
- Introduction to first order propositional logic, logical equivalence, valid and invalid arguments
- Introduction to digital circuits
- Introduction to first order monadic predicate logic, universal and existential quantification, and predicate arguments
- Elementary number theory, prime factors, Euclid's algorithm
- Finite arithmetic, Galois Fields, and RSA encryption
- Proof techniques, including direct and indirect proofs, proving universal statements, proving existential statements, proof forms, common errors in proofs
- Sequences, definite and indefinite series, recursive sequences and series
- Developing and validating closed-form solutions for series
- Well ordering and mathematical induction
- Introduction to proving algorithm correctness
- Second order linear homogeneous recurrence relations with constant coefficients
- General recursive definitions and structural induction
- Introduction to classical (Cantor) set theory, Russell's Paradox, introduction to axiomatic set theory (Zermelo-Fraenkel with Axiom of Choice).
- Set-theoretic proofs
- Boolean algebras
- Halting Problem

What is the format of the course?

CS 250 is a 4 credit course with 30 lecture hours and 30 lab hours. Classes typically meet twice per week for lecture, with lab sessions completed in tutoring labs outside of lecture.

Course material is available online, but this is not a distance learning class and attendance at lectures is required.

How are students assessed?

Students are assessed using in-class exams and homework. There are 5 in-class exams that count for 40% of the student's course grade, and 5 homework assignments that account for 60% of the student's course grade. In-class exams are individual work only, while group work is permitted on the homework assignments.

It is expected that students will spend 10 to 15 hours per week outside of class time completing their homework assignments. Surveys indicate a great deal of variability in this - some students report spending 6 hours per week to complete assignments, other report 20 or more hours per week.

Course textbooks and materials

The core text is *Discrete Mathematics with Applications* by Susanna S. Epp (Brooks-Cole/Cengage Learning). The text is supplemented with instructor-developed material to address topics not covered in the core text.

Students are encouraged to use computer programs to assist in routine calculations. Many students write their own programs, some use products such as Maple or Mathematica. Most calculators are unable to perform the calculations needed for this course. No specific tools are required.

Why do you teach the course this way?

This is a transfer course designed to meet the lower-division requirements of Computer Science and Engineering transfer programs in the Oregon University System with respect to discrete mathematics. As such, it serves many masters - there is no consistent set of requirements across all OSU institutions.

The majority of Portland Community College (PCC) transfer students matriculate to Portland State University, Oregon Institute of Technology, or Oregon State University, and these institutions have the greatest influence on this course. PCC changes the course content as needed to maintain compatibility with these institutions.

The most recent major course revision occurred approximately 24 months ago, although minor changes tend to occur every Fall term. Portland State University is reviewing all of their lower-division Computer Science offerings, and when they complete their process PCC expects a major revision of CS 250 and CS 251 will be required.

Students generally consider the discrete mathematics sequence to be difficult. Most students have studied some real number algebra, analysis, and calculus, but often have very limited exposure to discrete mathematics prior to this sequence.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Differences among best, expected, and worst case behaviors Big-O, Big-Omega, Big-Theta definitions Complexity classes Note: Remainder of Basic Analysis topics covered in CS 251	4
DS	Basic Logic	Propositional logic, connectives, truth tables, normal forms, validity, inference, predicate logical, quantification, limitations	10

DS	Proof Techniques	Implications, equivalences, converse, inverse, contrapositive, negation, contradiction, structure, direct proofs, disproofs, natural number induction, structural induction, weak/string induction, recursion, well orderings	10
DS	Basics of Counting	Basic modular arithmetic Other counting topics in CS 251	2
DS	Sets, Relations, Functions	Sets only: Venn diagrams, union, intersection, complement, product, power sets, cardinality, proof techniques. Relations and functions covered in CS 261	4

Additional topics

Elementary number theory, Peano Axioms, Zermelo-Fraenkel Axioms, Knuth arrow notation, simple digital circuits, simple encryption/decryption

CS 251 - Discrete Structures II, Portland Community College

12000 SW 49th Ave, Portland, OR 97219
Doug Jones
cdjones@pcc.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Discrete Structures (DS)	22
Algorithms and Complexity (AL)	8

Where does the course fit in your curriculum?

CS 251 is the second course in a two-term required sequence in discrete mathematics for Computer Science transfer students. Students typically complete the sequence in their second year.

College algebra (PCC's MTH 111 course) and 1 term of programming (PCC's CS 161 course) are pre-requisites for CS 250. The second course in the sequence (CS 251) requires CS 250 as a pre-requisite.

Approximately 80 students per year complete the discrete mathematics sequence (CS 250 and CS 251).

What is covered in the course?

- Set-based theory of functions, Boolean functions
- Injection, surjection, bijection
- Function composition
- Function cardinality and computability
- General set relations
- Equivalence relations
- Total and partial orderings
- Basic counting techniques: multiplication rule, addition rule, Dirichlet's Box Principle
- Combinations and permutations
- Pascal's Formula and the Binomial Theorem
- Kolmogorov Axioms and expected value
- Markov processes
- Conditional probability and Bayes' Theorem
- Classical graph theory: Euler and Hamilton circuits
- Introduction to spectral graph theory, isomorphisms
- Trees, weighted graphs, spanning trees
- Algorithm analysis
- Formal languages
- Regular expressions
- Finite-state automata

What is the format of the course?

CS 251 is a 4 credit course with 30 lecture hours and 30 lab hours. Classes typically meet twice per week for lecture, with lab sessions completed in tutoring labs outside of lecture.

Course material is available online, but this is not a distance learning class and attendance at lectures is required.

How are students assessed?

Students are assessed using in-class exams and homework. There are 5 in-class exams that count for 40% of the student's course grade, and 5 homework assignments that account for 60% of the student's course grade. In-class exams are individual work only, while group work is permitted on the homework assignments.

It is expected that students will spend 10 to 15 hours per week outside of class time completing their homework assignments. Surveys indicate a great deal of variability in this - some students report spending 6 hours per week to complete assignments, other report 20 or more hours per week.

Course textbooks and materials

The core text is *Discrete Mathematics with Applications* by Susanna S. Epp (Brooks-Cole/Cengage Learning). The text is supplemented with instructor-developed material to address topics not covered in the core text.

Students are encouraged to use computer programs to assist in routine calculations. Many students write their own programs, some use products such as Maple or Mathematica. Most calculators are unable to perform the calculations needed for this course. No specific tools are required.

Why do you teach the course this way?

This is a transfer course designed to meet the lower-division requirements of Computer Science and Engineering transfer programs in the Oregon University System with respect to discrete mathematics. As such, it serves many masters - there is no consistent set of requirements across all OSU institutions.

The majority of Portland Community College (PCC) transfer students matriculate to Portland State University, Oregon Institute of Technology, or Oregon State University, and these institutions have the greatest influence on this course. PCC changes the course content as needed to maintain compatibility with these institutions.

The most recent major course revision occurred approximately 24 months ago, although minor changes tend to occur every Fall term. Portland State University is reviewing all of their lower-division Computer Science offerings, and when they complete their process PCC expects a major revision of CS 250 and CS 251 will be required.

Students generally consider the discrete mathematics sequence to be difficult. Most students have studied some real number algebra, analysis, and calculus, but often have very limited exposure to discrete mathematics prior to this sequence.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Empirical measurement and performance Time and space trade-offs in algorithms Recurrence relations Analysis of iterative and recursive algorithms	4
DS	Sets, Relations, and Functions	Reflexivity, symmetry, transitivity Equivalence relations Partial orders Surjection, injection, bijection, inverse, composition of functions	4
DS	Basics of Counting	Counting arguments: cardinality, sum and product rule, IE principle, arithmetic and geometric progressions, pigeonhole principle, permutations, combinations, Pascal's identity, recurrence relations	10

DS	Graphs and Trees	Tree, tree traversal, undirected graphs, directed graphs, weighted graphs, isomorphisms, spanning trees	4
DS	Discrete Probability	Finite probability space, events, axioms and measures, conditional probability, Bayes' Theorem, independence, Bernoulli and binomial variables, expectation, variance, conditional independence	4
AL	Basic Automata Computability and Complexity	Finite state machines, regular expressions, Halting problem	4

Additional topics
Basic linear algebra, graph spectra, Markov processes

CS 175 Computer Graphics, Harvard University

Cambridge, MA
Dr. Steven Gortler
http://www.courses.fas.harvard.edu/~lib175
(Description below based on the Fall 2011 offering)

Knowledge Areas with topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Graphics and Visualization (GV)	19
Software Engineering (SE)	7
Architecture and Organization (AR)	4
Software Development Fundamentals (SDF)	2

Where does the course fit in your curriculum?

This is an elective course taken by students mostly in their third year. It requires C programming experience and familiarity with rudimentary linear algebra. Courses are on a semester system: 12 weeks long with 2 weekly 1.5-hour lectures. This course covers fundamental graphics techniques for the computational synthesis of digital images from 3D scenes. This course is not required but counts towards a breadth in computer science requirement in our program.

What is covered in the course?

- Shader-based OpenGL programming
- Coordinate systems and transformations
- Quaternions and the Arcball interface
- Camera modeling and projection
- OpenGL fixed functionality including rasterization
- Material simulation
- Basic and advanced use of textures including shadow mapping
- Image sampling including alpha matting
- Image resampling including mip-maps
- Human color perception
- Geometric representations
- Physical simulation in animation
- Ray tracing

What is the format of the course?

This course teaches the use and techniques behind modern shader-based computer graphics using OpenGL. It begins by outlining the basic shader-based programming paradigm. Then it covers coordinates systems and transformations. Special care is taken to develop a systematic way to reason about these ideas. These ideas are extended using quaternions as well as developing a scene graph data structure. The students then learn how to implement a key-frame animation system using splines. The course then covers cameras as well as some of the key fixed-function steps such as rasterization with perspective-correct interpolation.
Next, we cover the basics of shader-based material simulation and the various uses of texture mapping (including environment and shadow mapping). Then, we cover the basics of image sampling and alpha blending. We also cover image reconstruction as well as texture resampling using Mip-Maps.

The course gives an overview to a variety of geometric representations, including details about subdivision surfaces. We also give an overview of techniques in animation and physical simulation. Additional topics include human color perception and ray tracing.

How are students assessed?

Students implement a set of 10 to 12 programming and writing assignments.

Course textbooks and materials

In 12 weeks, students complete 10 programming projects in C++, and a final project. Students use *Foundations of 3D Computer Graphics* by S. J. Gortler as their primary textbook.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
GV	Fundamental Concepts	Basics of Human visual perception (HCI Foundations). Image representations, vector vs. raster, color models, meshes. Forward and backward rendering (i.e., ray-casting and rasterization). Applications of computer graphics: including game engines, cad, visualization, virtual reality. Polygonal representation. Basic radiometry, similar triangles, and projection model. Use of standard graphics APIs (see HCI GUI construction). Compressed image representation and the relationship to information theory. Immediate and retained mode. Double buffering.	3
GV	Basic Rendering	Rendering in nature, i.e., the emission and scattering of light and its relation to numerical integration. Affine and coordinate system transformations. Ray tracing. Visibility and occlusion, including solutions to this problem such as depth buffering, Painter's algorithm, and ray tracing. The forward and backward rendering equation. Simple triangle rasterization. Rendering with a shader-based API. Texture mapping, including minification and magnification (e.g., trilinear MIP-mapping). Application of spatial data structures to rendering. Sampling and anti-aliasing. Scene graphs and the graphics pipeline.	10
GV	Geometric Modeling	Basic geometric operations such as intersection calculation and proximity tests Parametric polynomial curves and surfaces. Implicit representation of curves and surfaces. Approximation techniques such as polynomial curves, Bezier curves, spline curves and surfaces, and non-uniform rational basis (NURB) spines, and level set method. Surface representation techniques including tessellation, mesh representation, mesh fairing, and mesh generation techniques such as Delaunay triangulation, marching cubes.	6

SDF	Development Methods	Program correctness The concept of a specification Unit testing Modern programming environments, Programming using library components and their APIs Debugging strategies Documentation and program style	2
AR	Performance enhancements	Superscalar architecture Branch prediction, Speculative execution, Out-of-order execution Prefetching Vector processors and GPUs Hardware support for Multithreading Scalability	3
CN	Modeling and Simulation	Formal models and modeling techniques: mathematical descriptions involving simplifying assumptions and avoiding detail. The descriptions use fundamental mathematical concepts such as set and function.	2
SE	Tools and Environments	Software configuration management and version control; release management Requirements analysis and design modeling tools Programming environments that automate parts of program construction processes	3
SE	Software Design	The use of components in design: component selection, design, adaptation and assembly of components, components and patterns, components and objects, (for example, build a GUI using a standard widget set).	4

CS371: Computer Graphics, Williams College

Dr. Morgan McGuire
http://www.cs.williams.edu/cs371.html
(Description below based on the Fall 2010 & 2012 offerings)

Knowledge Areas with topics and learning outcomes covered in the course:

Knowledge Area	Total Hours of Coverage
Graphics and Visualization (GV)	19
Software Engineering (SE)	7
Architecture and Organization (AR)	4
Software Development Fundamentals (SDF)	2

Where does the course fit in your curriculum?

This is an elective course taken by students mostly in their third year, following at least CS1, CS2, and a computer organization course. Courses are on a semester system: 12 weeks long with 3 weekly 1-hour lectures and a weekly four-hour laboratory session with the instructor. This course covers fundamental graphics techniques for the computational synthesis of digital images from 3D scenes. In the computer science major, this course fulfills the project course requirement and the quantitative reasoning requirement.

What is covered in the course?

- Computer graphics and its place in computer science
- Surface modeling
- Light modeling
- The Rendering Equation
- Ray casting
- Surface scattering (BSDFs)
- Spatial data structures
- Photon mapping
- Refraction
- Texture Mapping
- Transformations
- Rasterization
- The graphics pipeline
- GPU architecture
- Film production and effects
- Deferred shading
- Collision detection
- Shadow maps

What is the format of the course?

PhotoShop, medical MRIs, video games, and movie special effects all programmatically create and manipulate digital images. This course teaches the fundamental techniques behind these applications. We begin by building a mathematical model of the interaction of light with surfaces, lenses, and an imager. We then study the data structures and processor architectures that allow us to efficiently evaluate that physical model. Students will complete a series of programming assignments for both photorealistic image creation and real-time 3D rendering using C++, OpenGL, and GLSL as well as tools like SVN and debuggers and profilers. These assignments

cumulate in a multi-week final project. Topics covered in the course include: projective geometry, ray tracing, bidirectional surface scattering functions, binary space partition trees, matting and compositing, shadow maps, cache management, and parallel processing on GPUs. The cumulative laboratory exercises bring students through the entire software research and development pipeline: domain-expert feature set, formal specification, mathematical and computational solutions, team software implementation, testing, documentation, and presentation.

How are students assessed?

In 13 weeks, students complete 9 programming projects, two of which are multi-week team projects.

Course textbooks and materials

Students use the iOS app *The Graphics Codex* as their primary textbook and individually choose one of the following for assigned supplemental readings, based on their interest: *Fundamentals of Computer Graphics, 3rd Edition*, A K Peters*; Computer Graphics: Principles and Practice, 3rd Edition*, Addison Wesley; or *Real-Time Rendering, 3rd Edition*, A K Peters.

Why do you teach the course this way?

In this course, students work from first principles of physics and mathematics, and a body of knowledge from art. That is, I seek to lead with science and then support it with engineering. Many other CS courses--such as networking, data structures, architecture, compilers, and operating systems--develop the ability to solve problems that arise within computer science and computers themselves. In contrast, graphics is about working with problems that arise in other disciplines, specifically physics and art. The challenge here is not just solving a computer science problem but also framing the problem in computer science terms in the first place. This is a critical step of the computational and scientific approach to thinking, and the field of graphics presents a natural opportunity to revisit it in depth for upper-level students. Graphics in this case is a motivator, but the skills are intentionally presented as ones that can be applied to other disciplines, for example, biology, medicine, geoscience, nuclear engineering, and finance. The rise of GPU computing in HPC is a great example of numerical methods and engineering originating in computer graphics being generalized in just this way.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
GV	Fundamental Concepts	Basics of Human visual perception (HCI Foundations). Image representations, vector vs. raster, color models, meshes. Forward and backward rendering (i.e., ray-casting and rasterization). Applications of computer graphics: including game engines, cad, visualization, virtual reality. Polygonal representation. Basic radiometry, similar triangles, and projection model. Use of standard graphics APIs (see HCI GUI construction). Compressed image representation and the relationship to information theory. Immediate and retained mode. Double buffering.	3
GV	Basic Rendering	Rendering in nature, i.e., the emission and scattering of light and its relation to numerical integration. Affine and coordinate system transformations. Ray tracing. Visibility and occlusion, including solutions to this problem such as depth buffering, Painter's algorithm, and ray tracing. The forward and backward rendering equation. Simple triangle rasterization. Rendering with a shader-based API.	10

		Texture mapping, including minification and magnification (e.g., trilinear MIP-mapping). Application of spatial data structures to rendering. Sampling and anti-aliasing. Scene graphs and the graphics pipeline.	
GV	Geometric Modeling	Basic geometric operations such as intersection calculation and proximity tests. Parametric polynomial curves and surfaces. Implicit representation of curves and surfaces. Approximation techniques such as polynomial curves, Bezier curves, spline curves and surfaces, and non-uniform rational basis (NURB) spines, and level set method. Surface representation techniques including tessellation, mesh representation, mesh fairing, and mesh generation techniques such as Delaunay triangulation, marching cubes.	6
SDF	Development Methods	Program correctness The concept of a specification Unit testing Modern programming environments, Programming using library components and their APIs. Debugging strategies. Documentation and program style.	2
AR	Performance enhancements	Superscalar architecture. Branch prediction, Speculative execution, Out-of-order execution. Prefetching. Vector processors and GPUs. Hardware support for Multithreading. Scalability.	3
CN	Modeling and Simulation	Formal models and modeling techniques: mathematical descriptions involving simplifying assumptions and avoiding detail. The descriptions use fundamental mathematical concepts such as set and function.	2
SE	Tools and Environments	Software configuration management and version control; release management Requirements analysis and design modeling tools Programming environments that automate parts of program construction processes	3
SE	Software Design	The use of components in design: component selection, design, adaptation and assembly of components, components and patterns, components and objects (for example, build a GUI using a standard widget set).	4

Other comments

http://graphics.cs.williams.edu/courses/cs371/f12/files/welcome.pdf is a carefully-crafted introduction to computer graphics and this specific style of course that may be useful to other instructors.

Human Aspects of Computer Science, University of York

Department of Computer Science
Paul Cairns
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	18

Brief description of the course's format and place in the undergraduate curriculum
Students take this course in the first term of Stage 1 (first year) of the undergraduate degree programs in single honors Computer Science subjects e.g., BSc in Computer Science, MEng in Computer Systems Software Engineering. It represents 1/6 of the 120 credits required in Stage 1.There are no pre-reqs for obvious reasons and there are no modules that require it as a pre-requisite. There are usually around 100 students each year.

What is covered in the course?
The course is centered on Human-Computer Interaction. The topics covered are:

- Experimental design and data representation
- Inferential statistics
- Writing up experiments
- User-Centered Design
- Developing requirements through personas and scenarios
- Conceptual design, interface design
- Prototyping: lo-fi and paper
- Visual Design
- Evaluation techniques: heuristics, cognitive walkthrough, experiments

What is the format of the course?
It is face-to-face. Students attend 2 one-hour lectures, 1 two-hour practical and a one-hour reading seminar each week for 9 weeks of the autumn term. Lectures are a mix of traditional lecturing, small group exercises and class discussion. Practicals are primarily individual work or group work related to assessments. Reading seminars are presentations on research papers and class discussions on the papers.

How are students assessed?
There are three assessments. There are two open assessments for which students work in groups of (ideally) four. The first is to design and conduct an experiment in HCI having been giving a basic experimental hypothesis to investigate. The second is to do a user-centered design project though there is not time for iteration or formal evaluation. The third assessment is a closed exam in which students critique a research paper in order to answer short questions on the paper. Students are expected to do 100 hours of work in total on the assessments roughly split 40:40:20 for the three assessments.

Course textbooks and materials
Preece, J., Rogers, Y. and Sharp, H. (2011) *Interaction Design, 3rd edn*, Wiley and Sons. (selected chapters)
Harris, P. (2008) *Designing and Reporting Experiments in Psychology, 3rd edn,* OUP
Cairns P. and Cox A. eds, (2008) *Research Methods for HCI*, Cambridge. (Chaps 1, 6 and 10).

Other materials are:
R and RStudio are used as the statistics package for analyzing experimental data.

Why do you teach the course this way?

The course was partly designed to fill a need in the recently revised undergraduate curriculum. The two core content areas were experimental design and HCI. I put these together and produced a research oriented course to show how experiments are done in HCI. It still has a feel of a course of two halves but the idea of considering a common subject area helps and the reading seminars are intended to bind the two halves together by showing the students how research methods lead to advances in HCI that can be used in design.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
HCI	Foundations	All	4
HCI	Designing Interaction	Visual design, paper prototyping, UI standards	2
HCI	Programming Interactive Systems	Choosing interaction styles, designing for resource constrained devices	2
HCI	UCD and testing	All	4
HCI	Statistical methods for HCI	Experiment design, EDA, presenting statistical data, using statistical data, non-parametric testing	6

FIT3063 Human Computer Interaction, Monash University

Australia
Judy Sheard
Judy.sheard@monash.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	16

Where does the course fit in your curriculum?

3rd year of Business Information Systems, Computer Science and Information Technology Systems undergraduate degrees.
It is compulsory in the Information Technology Systems degree for the following majors: Applications development, Enterprise information management, Systems development.
The prerequisites are Systems development, Systems design and implementation.
Approx 100 students take the course in 1st and 2nd semester.

What is covered in the course?

This unit provides a detailed understanding of the underpinning theories, principles and practices of interface design for computer-based systems. It examines issues in the design of system interfaces from a number of perspectives: user, programmer, designer. It explores the application of the relevant theories in practice. The unit will cover topics such as methods and tools for developing effective user interfaces, evaluation methods such as the conduct of usability and heuristic evaluations, design of appropriate interface elements including the design of menus and other interaction styles. The unit also focuses on designing for a diverse range of users and environments.

Topics covered:

- Background and motivation for HCI
- Human factors
- Theoretical foundations: theories, models, principles, standards, guidelines
- Interface design elements
- Interface design: methods and principles
- Interface design: data gathering and task analysis
- Interaction styles
- Usability
- Accessibility
- Interaction devices
- Future of HCI

What is the format of the course?

Face-to-face, 48 contact hours (24 hours lectures and 24hours tutorials). Students are expected to put in an additional 96 hours out of class

How are students assessed?

1. Discussion forum
   - Contributions to a discussion forum during the semester. Each student is expected to contribute 2 postings and comment on one other posting (5%)
2. Class Test (held in week 6 tutorial class (5%)
   - in-class exercise – evaluation of a form according to Shneiderman's principles

3. Assignment (20% + 10%) Due in weeks 10 and 12.
    - Stage 1: design of an interface. This will be done in groups.
    - Stage 2: heuristic evaluation of the website using Nielsen's usability principles. This will include a description of the process used to conduct the evaluation, the evaluation results and recommendations for changes with supporting evidence. Each group evaluates the design of one other group.
4. Exam (60%)

Course textbooks and materials

Sharp, H., Rogers, Y. & Preece, J. *Interaction design: beyond human-computer interaction*.

Recommended readings from:

Shneiderman & Plaisant *Designing the user interface: Strategies for Effective Human-Computer Interaction*

Why do you teach the course this way?

The course is an amalgam of two HCI courses taught in different degrees in the Faculty. One focused on theory, design and evaluation and the other on design, application and development. The current course focuses on theory, design, application and evaluation.

The aim of the course is to give students knowledge and understanding of:

- the underpinning theories relevant to HCI;
- the principles and practices of HCI in designing user interfaces;
- the importance and role of usability and evaluation in systems design;
- the issues relating to user diversity, different types of systems, interaction styles, devices and environments.

Comments from the students at the start of semester is that the course is easy but by the end they think that it is hard.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
HCI	Foundations	Contexts for HCI Processes for user-centered development different measures for evaluation Physical capabilities that inform interaction design: color, perception Cognitive models that inform interaction design: attention, perception, recognition, memory, gulf of expectation and execution. Accessibility	4
HCI	Designing Interaction	Principles of graphical user interfaces Elements of visual design (layout color, fonts, labelling) Task analysis Paper prototyping Keystroke –level evaluation Help and documentation User interface standards	4
HCI	User-Centered Design & Testing	Approaches to and characteristics of the design process Usability Techniques for data gathering Prototyping techniques Evaluation without users Evaluation with users Internationalization	4

HCI	New Interactive Technologies	Choosing interaction styles & interaction techniques, Representing information to users (navigation, representation, manipulation) Approaches to design: touch and multi-touch interfaces, speech recognition, natural language processing, ubiquitous.	2
HCI	Mixed, Augmented and Virtual Reality	Sound, haptic devices, augmented virtual reality	2

CO328: Human Computer Interaction, University of Kent

United Kingdom
Sally Fincher; Michael Kölling
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	12

Where does the course fit in your curriculum?

This is a compulsory first year course, taught in the second semester. It represents one-eighth of student effort for the year.

What is covered in the course?

This module provides an introduction to human-computer interaction. Fundamental aspects of human physiology and psychology are introduced and key features of interaction and common interaction styles delineated. A variety of analysis and design methods are introduced (e.g., GOMS, heuristic evaluation, user-centred and contextual design techniques). Throughout the course, the quality of design and the need for a professional, integrated and user-centered approach to interface development is emphasized. Rapid and low-fidelity prototyping feature as one aspect of this.

Course topics

- Evaluating interfaces: heuristic evaluation, GOMS
- Evaluation Data & Empirical Data
- Lo-fi Prototyping
- Color, Vision & Perception
- Some Features of Human Memory
- Errors
- Controls, widgets, icons & symbols
- Elements of visual design
- Documentation

What is the format of the course?

The course is taught exclusively face-to-face. There are two lecture slots and one small-group, hands-on class slot per week, although we don't always use the lecture slots to deliver lectures.

How are students assessed?

There are 3 assignments:

1. A group assignment to go "out into the world" and observe real behavior. This takes place over three weeks: the first week to do the observation work, the second to present findings to the class, the third to write a report – incorporating any insights gained from the presentation. Total expected time: 10 hours for the observation and presentation; and additional 5 hours for the report.
2. An individual assignment to undertake analysis of an existing interface. This is presented as a 1,500-2,000 word report. Total expected time: 10 hours over three weeks.
3. A group design task using lo-fi prototyping. This is structured with staged deliverables to walk the group through a design process that includes requirements, brainstorming, ideation, sketching, selection and prototyping. The total expected time includes scheduled class time: 50 hours, over five weeks.

Together these are worth 50% of the total grade. The remaining 50% is a formal exam.

Course textbooks and materials

There is no required textbook for this course, although we recommend Dan Saffer's *Designing for Interaction* (New Riders, 2009) if students ask. The following readings are required:

- Donald A. Norman, Chapter 1 (from *The Design of Everyday Things,* MIT Press, 1998)
- Bruce "Tog" Tognazzini, *First Principles of Interaction Design*
- Marc Rettig and Aradhana Goel, *Designing for Experience: Frameworks and Project Stories*
- Marc Rettig, *Prototyping for Tiny Fingers*
- William Horton, *Top Ten Blunders by Visual Designers*
- George Miller, *The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information*
- Thomas Kelley, "The Perfect Brainstorm" (from *The Art of Innovation*, Profile Books, 2002)
- Bill Buxton, "The Anatomy of Sketching" (from *Sketching User Experiences*, Morgan Kaufmann, 2007)

Why do you teach the course this way?

This course used to be an elective course available to second and third year students. In the recent curriculum review (2011) it was moved into the first year. It is likely that we will be tweaking this over the next couple of years as we deliver it to a new cohort. We teach HCI as a full-on, hands-on experience, believing the best way to teach design is by doing it. Some students (typically the less technical) like it very much; some students (typically the more technical) find it troubling and "irrelevant". Both sorts can find it challenging.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
HCI	Foundations	All	4
HCI	Designing Interaction	All	4
HCI	User-centered design & testing	All	4

Human Computer Interaction, University of Cambridge

Alan Blackwell
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http://www.cl.cam.ac.uk/Teaching/current/HCI/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	8

Brief description of the course's format and place in the undergraduate curriculum
This course is offered to CS majors only, taught in the first four weeks of their third year (a half term). Formal teaching is 8 lecture hours, supplemented by 2 optional informal tutorial involving student exercises as proposed by individual tutors. At least one guest lecture is given by a user experience practitioner, young researcher or start-up founder.

Course description and goals
The goal is to present HCI as a discipline that is concerned with technical advance, and that must integrate different disciplinary perspectives. Fundamental theoretical issues deal with principles of human perception, visual representation and purposeful action, discussed in the context of novel interactive technologies. Building on a first year course in professional software design, the course ends with an overview of systematic approaches to the design and analysis of user interfaces.

On completing the course, students should be able to

- propose design approaches that are suitable to different classes of user and application;
- identify appropriate techniques for analysis and critique of user interfaces;
- be able to design and undertake quantitative and qualitative studies in order to improve the design of interactive systems;
- understand the history and purpose of the features of contemporary user interfaces.

Course topics

- The scope and challenges of HCI and Interaction Design.
- Visual representation
- Text and gesture interaction
- Inference-based approaches
- Augmented reality and tangible user interfaces
- Usability of programming languages
- User-centered design research
- Usability evaluation methods

Course textbooks, materials, and assignments

- *Interaction Design: Beyond human-computer interaction* by Helen Sharp, Yvonne Rogers & Jenny Preece (multiple editions)
- *HCI Models, Theories and Frameworks: Toward a multidisciplinary science* edited by John Carroll (2003*)*
- *Research methods for human-computer interaction* edited by Paul Cairns and Anna Cox (2008)
- *Interaction-Design.org entry on Visual Representation* by Alan Blackwell (2011) http://www.interaction-design.org/encyclopedia/visual_representation.html

Suggested assignments (set and assessed by independent tutors) may include empirical comparison of features in two simple applications, analytic evaluation of a novel interface, or an observational study in a software use context.

Final grade is determined in a traditional written examination. However, students are also encouraged to use HCI methods to inform design and evaluation of their final year (capstone) project and dissertation.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
HCI	Foundations	all	1
HCI	Designing Interactions	all	2
HCI	User-Centered Design and Testing	all	2
HCI	New Interactive Technologies	Selection of technologies	2
HCI	Design-Oriented HCI	HCI as design discipline	1

Additional topics

Usability of programming languages and other structured notations, in terms of the Cognitive Dimensions of Notations framework.

Other comments

Although this is the course named HCI, students are exposed to HCI issues in a first year course "Software and Interaction Design".

Human-Computer Interaction, Stanford University

Offered Coursera.org
Scott Klemmer
srk@cs.stanford.edu
hci-class.org

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	7

Where does the course fit in your curriculum?

This course is a free, public, online class based on Stanford's introductory HCI course. There are no prerequisites. Enrollment numbers from the last three offerings of the class: 54,270 students, 87,725 students, 33,825 students.

What is covered in the course?

Short-form description: Helping you build human-centered design skills, so that you have the principles and methods to create excellent interfaces with any technology.

Long-form description: In this course, you will learn how to design technologies that bring people joy, rather than frustration. You'll learn several techniques for rapidly prototyping and evaluating multiple interface alternatives -- and why rapid prototyping and comparative evaluation are essential to excellent interaction design. You'll learn how to conduct fieldwork with people to help you get design ideas. How to make paper prototypes and low-fidelity mockups that are interactive -- and how to use these designs to get feedback from other stakeholders like your teammates, clients, and users. You'll learn principles of visual design so that you can effectively organize and present information with your interfaces. You'll learn principles of perception and cognition that inform effective interaction design. And you'll learn how to perform and analyze controlled experiments online. In many cases, we'll use Web design as the anchoring domain. A lot of the examples will come from the Web, and we'll talk just a bit about Web technologies in particular. When we do so, it will be to support the main goal of this course, which is helping you build human-centered design skills, so that you have the principles and methods to create excellent interfaces with any technology.

What is the format of the course?

The class is online, spanning 9 weeks. For the first 7 weeks there is approximately 1 hour of recorded lecture content to view. In the last offering, we experimented with online studios, in which students with similar project topics shared and gave feedback to each other on a weekly basis via Google Hangouts. We also had weekly lecture screenings, in which the teaching staff would screen that week's lectures on Google Hangouts and invite students who were interested in joining and watching simultaneously. We also encouraged students to form their own online and in-person study groups.

How are students assessed?

There are three "tracks" for this course:

Apprentice track:
Four quizzes (100%). Students who achieve a reasonable fraction of this (80% or higher) will receive a statement of accomplishment from us, certifying that you successfully completed the apprentice track. To complete the apprentice track, we suggest committing 4-5 hours a week.

Studio track:
Six assignments (culminating in design project) (worth 67%) and quizzes (worth 33%). Students who achieve a reasonable fraction of this (80% or higher) will receive a statement of accomplishment from us, certifying that you successfully completed the studio track. To complete the studio track, we suggest committing 10 hours per week.

Studio practicum track:
Six assignments (culminating in design project) (worth 100%). This practicum is designed for students seeking to continue developing their design skills through an additional iteration of assignments. Students who achieve a reasonable fraction of this (80% or higher) will receive a statement of accomplishment from us, certifying that you successfully completed the studio practicum. To complete the studio practicum track, we suggest committing 5-6 hours per week. The 6 assignments and 2 of the quizzes use peer assessment to determine scores.

Course textbooks and materials
No textbooks are used, but additional reading on certain topics are referenced in lecture videos and linked to on an additional resources page. We recommend students use Balsamiq as their low-fidelity prototyping tool and Axure or Justinmind as their high-fidelity prototyping tool.

Why do you teach the course this way?
This course was first offered in June 2012, following by a second offering in September 2012 and finally in April 2013. The content is based on Stanford's introductory HCI course (CS 147). The primary difference lies in the level of programming needed: In the online class, interactive prototypes are created using a prototyping tool, whereas the Stanford version functionally implements the prototypes. In Fall 2012, CS 147 used the recorded lecture videos from the online class. In addition, a new class was created at Stanford that would mirror the online assignments (thus requiring no programming prerequisite). Feedback suggests that the online course is considered challenging, particularly in terms of its pace.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
HCI	Foundations	The birth of HCI, the power of prototyping, evaluating designs, needfinding, design heuristics, direct manipulation, mental models, representation, distributing cognition, designing studies	4
HCI	Designing Interaction	Task analysis, visual design, information design, rapid prototyping	2
HCI	User-centered design & testing	Needfinding, rapid prototyping, heuristic evaluation, designing experiments	2.5
HCI	Statistical Methods for HCI	In-person and web experimental design, within v. between subjects design, assigning participants to conditions, chisquared test	1

Human Information Processing (HIP), Open University Netherlands

Gerrit van der Veer
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http://www.opener2.ou.nl/opener/hip/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	6

Where does the course fit in your curriculum?

It is a free (Creative Commons License, and Open Source) course.
It is no fixed part of any curriculum, though recommended for students taking courses like "Web culture", "Design of human-computer interaction" or "Context of Computer science" (I regret to mention: all of these are in Dutch. HIP, though, is often taken by students outside of these courses, e.g., Students of Psychology. HIP is in English.)

What is covered in the course?

- Senses: Short term sensory memory – receptors – stimuli;
- Perception;
- Attention;
- Memory: Long-term memory – working memory;
- Mental models;
- Intention: Decision making and response selection;
- Action: Response execution (motion or behavior) – responses

What is the format of the course?

Fully online:

- short lectures as series of slides inside chapters,
- lab sessions and demos (try it),
- media (printing chapter or slides),
- pointers to further resources (find out more),
- a progress facility (learner-activated indication "Ĭ completed this slide" with resulting overview of progress)
- student managed navigation (free order of chapters and sub-chapters; previous and next slide)
- a (student created) login is needed in order to support the individual student's progress.

How are students assessed?

There are no assignments (because the course is not an official part of any curriculum or course). If relevant, the "try it yourself" sections have self-assessment and choice of trying again.

Course textbooks and materials

None

Why do you teach the course this way?

The Open University Netherlands is a University for distance education. Our students are adults (25-75 years of age) mostly professionals. Students are self-motivated
This course is a free facility, developed for free by personal initiative of me and my PhD students, to support adult learning in the field of human-computer interaction, interaction design and related domains.

We offer several of these courses, independent of the University curriculum, and the University provides the server space and uses our courses to advertise.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
CN	Interactive Visualization	visualization	1
GV	Fundamental Concepts	human perception	1
HCI	Foundations	all	4

Software and Interface Design, University of Cambridge

Alan Blackwell
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http://www.cl.cam.ac.uk/Teaching/current/SWIDesign/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Human-Computer Interaction (HCI)	3
Other areas	8

Brief description of the course's format and place in the undergraduate curriculum

This course is offered to CS majors only, taught over four weeks at the end of their first year (a half term). Formal teaching is 11 lecture hours, supplemented by 2 optional informal tutorials involving student exercises as proposed by individual tutors. The course is a prerequisite for a compulsory group design project in the second year of the degree.

Course description and goals

This course introduces principles and methods for the design of software systems in professional contexts. The whole of the software development lifecycle is considered, but with special emphasis on user-centered design, including approaches to capture and analysis of user requirements, iterative prototyping and testing of interactive systems.

The goal is to present HCI as a discipline that is concerned with technical advance, and that must integrate different disciplinary perspectives. Fundamental theoretical issues deal with principles of human perception, visual representation and purposeful action, discussed in the context of novel interactive technologies. Building on a first year course in professional software design, the course ends with an overview of systematic approaches to the design and analysis of user interfaces.

On completing the course, students should be able to

- undertake system design in a methodical manner
- proceed from a general system or product requirement to a design that addresses user needs
- develop design models and prototypes in an iterative manner recognizing managerial risks
- evaluate interactive systems, including identification and correction of faults.

Course topics

- Mental models, leading to gulfs of execution and evaluation.
- Observing and describing the needs of users in context
- Methods for iterative modelling and prototyping
- Observational and experimental methods for usability evaluation

Course textbooks, materials, and assignments

- *Interaction Design: Beyond human-computer interaction* by Helen Sharp, Yvonne Rogers & Jenny Preece (multiple editions)
- *Software Engineering* by Pressman (multiple editions)

Suggested assignments (set and assessed by independent tutors) involve carrying out initial phases of a system design, using as a practice example one of the design briefs that has recently been implemented and exhibited in a public show by second year students.

Final grade is determined in a traditional written examination, which usually presents a simple interactive system design problem, and asks students to demonstrate their understanding of design process by reference to that problem.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
HCI	Foundations	all	1
HCI	Designing Interactions	all	1
HCI	User-Centered Design and Testing	all	1

Computer Systems Security (CS-475), Lewis-Clark State College

Lewiston, Idaho, U.S.A.
Daniel Conte de Leon
dcontedeleon@acm.org

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage (38)
Information Assurance and Security (IAS)	28
Human-Computer Interaction (HCI)	3
Networking and Communication (NC)	2
Social Issues and Professional Practice (SP)	2
Architecture and Organization (AR)	1
Operating Systems (OS)	1
Programming Languages (PL)	1

Where does the course fit in your curriculum?

Context within the Program

This course is usually taken within the last year of an undergraduate degree program in Computer Science. Students from all four emphasis areas within our Computer Science program are required to take this course. The emphasis areas are: Computer Science and Mathematics, Information Technology, Information Systems, and Web Development.

Prerequisites

Students should have finished the introductory CS sequence, a data structures course, a discrete mathematics course and Calculus, a computer architecture course, and have familiarity with multiple computing languages such as C, HTML, Python, and SQL. In addition, basic knowledge of computer networks and familiarity with Linux systems and the shell and command line tools are needed.

What is covered in the course?

Short Description

This course covers the fundamental concepts and practical applications of computing systems security with a holistic view and an applied approach. Topics include: security concepts and services, physical, operational, and organizational security, the role of people in systems security, introduction to cryptography and public key infrastructure, computing systems hardening, secure code, and secure applications development.
The course emphasis is on developing, deploying, and maintaining a secure computing infrastructure with a hands-on approach.

List of Topics

Topics in this course broadly match topics listed within this CS2013 guidelines and their coverage is detailed in the *Body of Knowledge coverage* section below. One additional topic is listed in the *Additional topics* section.

What is the format of the course?

Schedule and Meetings

Lewis-Clark State College is on a semester-based schedule. Semesters are 16 weeks long including a final exams week. This course meets face-to-face in a computer laboratory twice a week for a combined lecture and laboratory session. Each session is 2 hours 30 minutes long, including a 15 minute break. The adjusted number of contact hours is approximately 68. The number of lecture equivalent contact hours is 38.

Instructional Approach
This course is taught using an interactive and hands-on approach. Students are required to read the textbook before coming to class session and short quizzes are given almost every week. A hybrid lecture and question and answer session is given almost every session. Students then move to the computers and network gear to carry out laboratory tasks in a collaborative class environment. Laboratory and homework reports must be prepared individually. All posting and submission of coursework is on-line.

Coursework and Submissions
Students are expected to write a laboratory report for each laboratory that is typically due at midnight on the immediately following Sunday. Similar to the quizzes, there is an average of one laboratory report per week. In addition to the weekly quizzes and laboratory reports, students must complete about five homework assignments, a project, a midterm test, and the final exam. The homework assignments vary in content from ethics reports to reviewing and reporting on relevant publications (e.g., NIST guidelines and ACM and IEEE codes of ethics). The projects are usually comprised of a hands-on detailed investigation of a security topic of interest to the student and a subsequent live and hands-on presentation to the class and associated report submission. The final exam is comprised of 2 parts: a hands-on in-lab 2 hour 30 minute exam and a term report on a given topic.

How are students assessed?
Students receive points relative to the adequate and correct completion of coursework as described above plus points obtained during the question and answer sessions. The total grade is weighted using a variation of the following scheme: 1) laboratories, homework, and project 40%, 2) quizzes 25%, 3) mid-term tests 10%, 4) final exams 20%, and 5) participation 5%. Students are expected to work outside of class sessions an average of 8-10 hours per week.

Course textbooks and materials
The textbook selected for the latest section of this course is: *Analyzing Computer Security: A Threat/Vulnerability/Countermeasure Approach* by Charles P. Pfleeger and Shari Lawrence Pfleeger. The textbook used in the previous section of this course was: *Principles of Information Security* by Michael E. Whitman and Herbert J. Mattord. In addition, the following laboratory manual is being used: "Hands-On Information Security Lab Manual" by Michael E. Whitman and Herbert J. Mattord. On-line accessible materials are also used to complement the course content and laboratories. For example, the secure coding standards published by CERT and the Software Engineering Institute, OWASP, and NIST resources.

Systems and Tools
We use a computer laboratory connected to an isolated VLAN. The laboratory has a dedicated switch, multiple hardware and software configurations including modern and older versions of OSs and applications running on either virtual or real hardware. During the laboratory sessions students learn to use a variety of (command line and GUI) network and host scanning, vulnerability analysis, and system hardening tools such as: Wireshark, Metasploit, Nmap, Nessus or OpenVAS, Bastille, Firewalls, Mutillidae, Gcc and secure libraries. The objective is for students to learn the limitations of computer-based systems and networks with respect to information assurance and how to harden, maintain, and create more secure systems.

Why do you teach the course this way?
Course Goals and Rationale
The goal of this course is to introduce students to the challenges, approaches, and techniques for implementing, deploying, and maintaining secure computing systems and networks. The rationale behind this course is to meet the need for information assurance content within the CS curriculum at the same time as tailoring to the diversity of potential career paths in the program's student population.

Course History and Student Perceptions
This course was developed in 2010 and was included as part of an update to the computer science curriculum which began implementation in the year 2011. This course is usually not viewed as challenging by students, however it is perceived as content and laboratory intensive.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AR	Machine-level representation of data	Review of representation of programs as data, and numeric, and non-numeric data and arrays. These and the rest of topics within this KU are covered within our Computer Architecture course.	1
HCI	Human Factors and Security	All [Elective].	3
IAS	Foundational Concepts in Security	All [1 Core-Tier1 hour].	2
IAS	Principles of Secure Design	All Core-Tier1 topics plus prevention, detection, and deterrence, and usable security from Core-Tier2 topics [1 Core-Tier1 hour, 1 Core-Tier2 hour].	3
IAS	Defensive Programming	All topics in Core-Tier1 except security implications of parallel programming plus the security updates topic in Core-Tier2. Also, OS and compiler support from the Elective topics. [1 Core-Tier1 hour, 1 Core-Tier2 hour].	5
IAS	Threats and Attacks	All topics in Core-Tier2 [1 Core-Tier2 hour].	2
IAS	Network Security	All topics in Core-Tier2 [1 Core-Tier2 hour].	6
IAS	Cryptography	All topics in Core-Tier2 [1 Core-Tier2 hour]. Plus Cryptographic primitives, and symmetric and public key cryptography from the Elective topics.	4
IAS	Web Security	Most topics and all learning outcomes [Elective].	4
IAS	Security Policy and Governance	All topics [Elective].	2
NC	Introduction	Review of physical pieces of a network and roles of the different layers. These and the rest of the topics in this KU are covered in our Computer Networks course.	0.5
NC	Networked Applications	Review of naming and addressing schemes and systems. These and the rest of the topics in this KU are covered in our Computer Networks course.	1
NC	Local Area Networks	Review of Ethernet and switching. These and the rest of the topics in this KU are covered in our Computer Networks course.	0.5
OS	Security and Protection	All topics in Core-Tier2, except security mechanisms and protection, which are covered in our Operating Systems course.	1
PL	Language Translation and Execution	Review of run-time stack in the context of buffer overflows. Some of the other topics in this KU such as memory management are covered within our OO Design and Implementation course which uses C++.	1
SP	Security Policies, Laws, and Computer Crimes	All topics except crime prevention strategies [Elective].	2

Additional topics

Computer systems hardening.

Other comments

None.

CS430: Database Systems, Colorado State University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Information Management (IM)	52.5
Information Assurance and Security (IAS)	3.5

Where does the course fit in your curriculum?
This course is an elective for senior undergraduates and first year graduate students offered twice a year in the spring (on-campus) and summer semesters (both on-campus and online). Typically about 45-55 students take this course during each offering period. The prerequisite for this course is the third year Software Development Methods course – CS 314.

Course topics:
- Introduction to DBMS concepts
- Data modeling and database design
- Relational database design
- Query languages
- Storage and indexing
- Query processing
- Transaction processing
- Recovery

What is the format of the course?
Colorado State University uses a semester system: this course is 15 weeks long with 2 one and a half hour of lectures per week and laboratory session for a total of 4 hours per week on an average. Some of the topics in this course are covered via projects during the lab sessions. There is a 16th week for final exams. In the past, this course has been only on campus, but starting in Summer 2011 we are providing it also as a concurrent on-campus and online course.

How are students assessed?
Students are assessed based on written homeworks, programming projects, and midterm and final exams. The projects involve a large-scale relational database design using a commercial DBMS such as PostgreSQL, designing different index structures, query processing and transaction processing, and require written project reports to be submitted. Students work on the projects individually. Class participation typically contributes around 10% towards the final grade and wrap up the assessment. We expect students to spend approximately 6-8 hours each week outside of the classroom on the course.

Course textbooks and materials
The required textbook for this course is *Database Management Systems* by Ramakrishnan and Gehrke, 3rd edition, McGraw-Hill 2003. Two textbooks are recommended: (i) *Database Systems Concepts* by Silberschatz, Korth and Sudarshan, 6th edition, McGraw-Hill, 2010 and (ii) *Database Systems* – The Complete Book by Garcia-Molina,

Ullman and Widom, 2nd edition, Prentice-Hall, 2008. Instructor's slides and different webpages supplement the textbook and are distributed via the course home page.

Why do you teach the course this way?

This course is an elective and students do consider it to be challenging but incredibly beneficial to their job prospects. Many students discuss their knowledge in database administration, database design, database tuning, query optimization, and knowledge of commercial DBMS and the projects developed in this course with potential employers.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
IM	Information Management Concepts	Information storage and retrieval (CT-1) Information capture and representation (CT-1) Searching and retrieving (CT-1) Analysis and indexing (CT-2) Reliability, security, scalability, efficiency (CT-2)	1.5
IM	Database Systems	File systems vs. DBMS Approaches to and evolution of DBMS (CT-2) Database architecture and data independence (CT-2) Core DBMS functions and system components (CT-2) DBMS user, designer, application developer, administrator (CT-1)	1.5
IM	Data Modeling	Conceptual modeling – ER model (CT-2) Logical database design – Relational model, object-relational model (CT-2)	6
IM	Relational Databases	Relational database design, schema design, mapping conceptual schema to relational schema, functional dependencies, superkeys and candidate keys, foreign keys, schema decomposition and refinement, loss-less join and dependency preservation, normal forms – 1NF, 2NF, 3NF, BCNF, multi-valued dependency and 4NF – entity and referential integrity	9
IM	Query Languages	Relational algebra Relational calculus SQL SQL queries, constraints and triggers ODBC, JDBC Query processing strategies Query evaluation Query processing costs	12
IM	Indexing	Basic structure Indexes with SQL	1.5
IM	Physical Database Design	Memory hierarchy, file organization (heap files, clustered files, sorted files), tree-based indexing (B-tree, B+tree), hash-based indexing, I/O cost models for indexing, comparison of indexing techniques, indexes and performance tuning	15

IM	Transaction Processing	ACID properties, failure and recovery, concurrency control, serializability, two phase locking protocols, deadlocks, logs and logging protocol	6
IAS	Foundational Concepts	Database security, access control via database views, integrity, audit	2
IAS	Security Policy and Governance	Backup and recovery	1.5

Additional topics: None

Other comments: None

Technology, Ethics, and Global Society (CSE 262), Miami University

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Public research university
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Social Issues and Professional Practice (SP)	20
Human Computer Interaction (HCI)	10
Graphics and Visualization (GV)	5
Intelligent Systems (IS)	elective

Where does the course fit in your curriculum?
Open to students of any major, but required for all computer science and/or software engineering majors. The only pre-requisite is one semester of college writing/composition. Traditional humanities-style course based primarily on reading and reflecting before class, discussing during class, formal writing after class. Meets three hours per week for 15 weeks.

What is covered in the course?
Students that successfully complete the course will be able to:

1. Formulate and defend a position on an ethical question related to technology.
2. Describe the main ethical challenges currently posed by technology.
3. Describe the results of group discussion on ethical issues as a consensus position or mutually acceptable differences of opinion.
4. Analyze a proposed course of action in the context of various cultures, communities, and countries.
5. Demonstrate effective oral and written communication methods to explain a position on the social responsibilities of software developers and IT workers.

Course topics (Coverage is in lecture hours, out of a total of 45 lecture hours.)
All of the following (27 hours):

1. Moral theories and reasoning. Includes applying utilitarianism, deontological ethics, and virtue ethics. Discussion of relativism and religious ethics. 3 hours.
2. Professional ethics. Includes definitions of "profession," codes of ethics, and ACM-IEEE Software Engineering Code of Ethics and Professional Practice. 3 hours.
3. Privacy. Definitions of privacy, the role of computing in contemporary privacy dilemmas. 6 hours.
4. Intellectual and intangible property. Definitions of copyright, trademark, and patent, especially as they apply to computer applications and products. Fair use and other limitations to the rights of creators. Intangible property that is not "creative" in nature. 6 hours.
5. Trust, safety, and reliability. Causes of computer failure, case studies (including Therac-25). 3 hours.
6. Review and exams. 3 hours.
7. Public presentations of independent research projects. 3 hours.

Selection from the following, at instructor discretion (18 hours):

1. Effects of computing on society and personal identity. Social network analysis, Marshall McLuhan, bullying and trolling, crowd-sourced knowledge, cybernetics. 6 hours.
2. Democracy, freedom of speech, and computing. The First Amendment, protection of children, state censorship, corporate censorship, case studies. 6 hours.
3. Computing and vulnerable groups. Case studies of effects of computing on prisoners, the elderly, the young, racial and ethnic minorities, religious minorities, people with disabilities, people with chronic diseases, developing countries, and so on. 6 hours.
4. Autonomous and pervasive technologies. Cases related to data surveillance, moral responsibility for autonomous systems, robots, and systems that function with little human oversight. 6 hours.

What is the format of the course?

Face-to-face, primarily based on discussion. 45 contact hours, 90 hours of out-of-class work. Students read the textbook outside of class, and in-class time is spent on applying ideas from the textbook to cases or problems.

How are students assessed?

30% based on 4 formal papers, 20% for essay-based exams (one midterm and a final), 35% for class participation and informal writing assignments, 15% for a public presentation (usually in Pecha Kucha format).

Course textbooks and materials

Readings selected from Brinkman and Sanders, Ethics in a Computing Culture, from Cengage Learning, 2012. Supplementary readings, videos, and so on selected from the "recommended readings" listings in the book.

Why do you teach the course this way?

Many of the topics of this course are incredibly complicated, and do not have clear right or wrong answers. The course is designed to encourage students to reflect on the course material, develop their ideas through engagement with each other, and then document their thinking.

Many schools are successful with distributing SP topics throughout the curriculum, but we found that this made it very difficult to assess whether or not the material was actually delivered and mastered. By creating a required course, we ensure that every student gets the material. Opening the course to non-computing majors has significantly increased the diversity of the course's audience. This benefits the students of the course, because it allows the instructor to demonstrate and highlight ethical clashes that arise when people from different academic disciplines try to work together.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Social Context	All	Worked throughout course
SP	Analytical Tools	All	3
SP	Professional Ethics	All except for "role of professional in public policy" and "ergonomics and healthy computing environments"	3
SP	Intellectual Property	All except for "foundations of the open source movement"	6
SP	Privacy and Civil Liberties	All, though "Freedom of expression and its limitations" is at instructor discretion	6-7

SP	Professional Communication	These topics covered across the curriculum, particular in our required software engineering course and capstone experience	0
SP	Sustainability	All topics in elective material of course. Covered in about ¾ of offerings of the course.	0-2
SP	History	Not covered. This material is covered in an introductory course.	0
SP	Economies of Computing	Not covered, except for "effect of skilled labor supply and demand on the quality of computing products," "the phenomenon of outsourcing and off-shoring; impacts on employment and on economics," and "differences in access to computing resources and the possible effects thereof." These are elective topics, covered in about ¾ of offerings of the course.	0-2
SP	Security Policies, Laws and Computer Crimes	These topics are covered in our computer security course.	0
HCI	Human Factors and Security	Vulnerable groups and computing	5
HCI	Collaboration and Communication	Psychology and social psychology of computing	5
GV	Fundamental Concepts	Media theory and computing	5

Additional topics
Autonomous computing and its dangers – elective topic in the Intelligent Systems KA

CS 662; Artificial Intelligence Programming, University of San Francisco

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Intelligent Systems (IS)	60

Where does the course fit in your curriculum?
The course is taken as a senior-level elective, and as a required course for first-year Master's students.

What is covered in the course?
An overview of AI, including search, knowledge representation, probabilistic reasoning and decision making under uncertainty, machine learning, and topics from NLP, information retrieval, knowledge engineering and multi-agent systems.

What is the format of the course?
Face-to-face. 4 hours lecture per week (either 3x65 or 2x105).

How are students assessed?
Two midterms and a final. Also, heavy emphasis on programming and implementation of techniques. Students complete 7-9 assignments (see website for examples). Expectation is 3 hours outside of class for every hour of lecture.

Course textbooks and materials
Russell and Norvig's *Artificial Intelligence: A Modern Approach* is the primary text. I prepare lots of summary material (see website) and provide students with harness code for their assignments in Python. I also make use of pre-existing packages and tools such as NLTK, Protégé and WordNet when possible.

Why do you teach the course this way?
My goals are:

- Illustrate the ways in which AI techniques can be used to solve real-world problems. I pick a specific domain (such as Wikipedia or a map of San Francisco) and have the students apply a variety of techniques to problems in this domain. For example, as the assumptions change, the same SF map problem can be used for search, constraints, MDPs, planning, or learning.
- Provide students with experience implementing these algorithms. Almost all of our students go into industry, and need skill in building systems.
- Illustrate connections between techniques. For example, I discuss decision trees and rule learning in conjunction with forward and backward chaining to show how, once you've decided on a representation, you can either construct rules using human expertise, or else learn them (or both).

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
IS	Fundamental Issues		*2*
IS	Basic Search Strategies	A*, BFS, DFS, IDA*, problem spaces, constraints	8
IS	Basic Knowledge Rep.	Predicate logic, forward chaining, backward chaining, resolution,	8
IS	Basic Machine Learning	Decision trees, rule learning, Naïve Bayes, precision and accuracy, cross-fold validation	6
IS	Adv. KR	FOL, inference, ontologies, planning	6
IS	Advanced Search	Genetic algorithms, simulated annealing	3
IS	Reasoning Under Uncertainty	Probability, Bayes nets, MDPs, decision theory	8
IS	NLP	Parsing, chunking, n-grams, information retrieval	4

Other comments

I also integrate reflection and pre-post questions – before starting an assignment, students must answer questions (online) about the material and the challenges they expect to see. I ask similar questions afterward, both for assessment and to encourage the students to reflect on design decisions.

Intelligenza Artificiale (Artificial Intelligence), Politecnico di Milano

Milano, Italy
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area/Knowledge Unit	Total Hours of Coverage
Intelligent Systems/Fundamental Issues	8
Intelligent Systems/Basic Search Strategies	18
Intelligent Systems/Basic Knowledge Representation and Reasoning	12
Intelligent Systems/Advanced Search	6
Intelligent Systems/Advanced Representation and Reasoning	6

Where does the course fit in your curriculum?
Students usually take the course in the first year of the MSc program in computer engineering.
Usually around 100 students take the course each year. The course is not compulsory. There are no formal prerequisites. However, some familiarity with logics and computer science is strongly suggested.

What is covered in the course?
- INTRODUCTION TO AI. Historical outline of the discipline. Fundamental concepts. Main research areas and application fields.
- PROBLEM SOLVING AND SEARCH. State spaces and search methods. Non-informed and informed search strategies. Constraint satisfaction problems. Games and adversarial search.
- LOGIC AND REASONING. The use of propositional and first order logic for the representation of knowledge. Knowledge-based reasoning as logical deduction. Inference procedures (forward chaining, backward chaining, resolution).
- PLANNING. Plan formation and execution. The STRIPS model. Search in plan spaces.
- FOUNDATIONS OF AI. Some critical concepts and philosophical problems of AI.

What is the format of the course?
The course is face-to-face and covers 50 hours, which are organized in 30 hours with instructor and 20 hours with teaching assistants for exercise practice.

How are students assessed?
Students are assessed by a single final exam. This is in line with most of the courses in Italian universities. The estimated effort for preparing the final exam is about 100 hours.

Course textbooks and materials
Stuart Russell, Peter Norvig, *Artificial Intelligence: A Modern Approach*, Prentice Hall, 2010.

Why do you teach the course this way?
The course aims at fostering the students' ability to apply Artificial Intelligence (AI) models and techniques to the development of software applications. The students consider the course interesting and medium-challenging.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours

IS	IS/Fundamental Issues	• Overview of AI problems, Examples of successful recent AI applications
		• What is intelligent behavior?
		  o The Turing test
		  o Rational versus non-rational reasoning
		• Nature of environments
		  o Fully versus partially observable
		  o Single versus multi-agent
		  o Deterministic versus stochastic
		  o Static versus dynamic
		  o Discrete versus continuous
		• Nature of agents
		  o Autonomous versus semi-autonomous
		  o Reflexive, goal-based, and utility-based
		  o The importance of perception and environmental interactions
		• Philosophical and ethical issues
			8

IS	IS/Basic Search Strategies	• Problem spaces (states, goals and operators), problem solving by search • Factored representation (factoring state into variables) • Uninformed search (breadth-first, depth-first, depth-first with iterative deepening) • Heuristics and informed search (hill-climbing, generic best-first, A*) • Space and time efficiency of search • Constraint satisfaction (backtracking methods)	18
IS	IS/Basic Knowledge Representation and Reasoning	• Review of propositional and predicate logic • Resolution and theorem proving (propositional logic only) • Forward chaining, backward chaining	12
IS	IS/Advanced Search	• Minimax Search, Alpha-beta pruning	6
IS	IS/Advanced Representation and Reasoning	• Planning: o Partial and totally ordered planning	6

Additional topics
None.

CMSC 471, Introduction to Artificial Intelligence, U. of Maryland, Baltimore County

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http://www.csee.umbc.edu/courses/undergraduate/471/fall11/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Intelligent Systems (IS)	38
Programming Languages (PL)	1

Where does the course fit in your curriculum?
Most students take CMSC 471 in their senior year, but some take it as a junior. It is a "core elective" in our curriculum (students have to take two of the 11 core courses, which also include areas such as databases, networking, and graphics). Students in the Game track (5-10% of CS majors) must take CMSC 471 as one of their core electives. The prerequisite course is CMSC 341 (Data Structures, which itself has a Discrete Structures prerequisite). CMSC 471 is offered once a year, capped at 40 students, and is always full with a waiting list.

What is covered in the course?
Course description: "This course will serve as an introduction to artificial intelligence concepts and techniques. We will use the Lisp programming language as a computational vehicle for exploring the techniques and their application. Specific topics we will cover include the history and philosophy of AI, Lisp and functional programming, the agent paradigm in AI systems, search, game playing, knowledge representation and reasoning, logical reasoning, uncertain reasoning and Bayes nets, planning, and machine learning. If time permits, we may also briefly touch on multi-agent systems, robotics, perception, and/or natural language processing."

What is the format of the course?
The course is face-to-face, two 75-minute sessions per week (three credit hours). The primary format is lecture but there are many active learning and problem solving activities integrated into the lecture sessions.

How are students assessed?
There are typically six homework assignments (with a mix of programming and paper-and-pencil exercises), a semester project that can be completed in small groups, and midterm and final exams. Students typically spend anywhere from 5-20 hours per week outside of class completing the required readings and homeworks.

Course textbooks and materials
The primary textbook is Russell and Norvig's "Artificial Intelligence: A Modern Approach." Students are expected to learn and use the Lisp programming language (CLISP implementation), and Paul Graham's "ANSI Common Lisp" is also assigned.

Why do you teach the course this way?
My intention is to give students a broad introduction to the foundational principles of artificial intelligence, with enough understanding of algorithms and methods to be able to implement and analyze them. Students who have completed the course should be able to continue into a graduate program of study in AI and be able to successfully apply what they have learned in this class to solve new problems. I also believe that the foundational concepts of

search, probabilistic reasoning, logical reasoning, and knowledge representation are extremely useful in other areas even if students don't continue in the field of AI. Using Lisp exposes them to a functional programming language and increases their ability to learn a new language and a different way of thinking. Most students describe the course as one of the most difficult of their undergraduate career, but it also receives very high ratings in terms of interest and quality.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
IS	Fundamental Issues	Intelligence, agents, environments, philosophical issues	4
IS	Basic Search Strategies	Problem spaces, uninformed/informed/local search, minimax, constraint satisfaction	4
IS	Basic Knowledge Representation and Reasoning	Propositional and first-order logic, resolution theorem proving	5.5
IS	Basic Machine Learning	Learning tasks, inductive learning, naive Bayes, decision trees	1.5
IS	Advanced Search	A* search, genetic algorithms, alpha-beta pruning, expectiminimax	6
IS	Advanced Representation and Reasoning	Ontologies, nonmonotonic reasoning, situation calculus, STRIPS and partial-order planning, GraphPlan	3.5
IS	Reasoning Under Uncertainty	Probability theory, independence, Bayesian networks, exact inference, decision theory	6
IS	Agents	Game theory, multi-agent systems	4.5
IS	Advanced Machine Learning	Nearest-neighbor methods, SVMs, K-means clustering, learning Bayes nets, reinforcement learning	3
PL	Functional Programming	Lisp programming	1

Additional topics

N/A

Other comments

Note: Additional electives are offered in Robotics, Machine Learning, Autonomous Agents and Multi-Agent Systems, and Natural Language Processing.

Introduction to Artificial Intelligence, Case Western Reserve University

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Course offered Spring 2012: http://engr.case.edu/ray_soumya/ai_course_exemplar/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Intelligent Systems (IS)	30

Where does the course fit in your curriculum?
Students take the course typically in either their junior or senior years. It is required for the BS/CS degree and an elective for the BA/CS degree. The minimum required prerequisite for this course is an introductory programming in Java course. A background in data structures and algorithms is strongly recommended but not required. Usually around 40 students take the course each year. This course is required for graduate level artificial intelligence and machine learning courses.

What is covered in the course?
- Problem solving with search: uninformed, informed search, search for optimization (hill climbing, simulated annealing, genetic algorithms), adversarial search (minimax, game trees)
- Logic and Planning: Propositional Logic, syntactic and model-based inference, first order logic (FOL), FOL inference complexity, unification and resolution, planning as FOL inference, STRIPS encoding, state space and plan space planning, partial order planning.
- Probability and Machine Learning: Axioms of probability, basic statistics (expectation and variance), inference by enumeration, Bayesian networks, inference through variable elimination and Monte Carlo, intro to supervised machine learning, probabilistic classification with naive Bayes, parameter estimation with maximum likelihood, Perceptrons, parameter estimation with gradient descent, evaluating algorithms with cross validation, confusion matrices and hypothesis testing.
- Decision making under uncertainty: Intro to sequential decision making, Markov decision processes, Bellman equation/optimality, value and policy iteration, model-based and model free reinforcement learning, temporal difference methods, Q learning, Function approximation.
- I also have one lecture on natural language processing with a very brief introduction to language models, information retrieval and question answering (Watson), but students are not evaluated on this material.

What is the format of the course?
2 Classroom lectures 75 minutes each per week. 3 Office hours per week (1.5 instructor/1.5 TA).

How are students assessed?
The course is divided into 4 parts as outlined above. Each part has two written homework assignments except the last part which has one (7 total). Each written homework is followed by a quiz (closed book) that tests the material on that homework (7 total). Written homeworks typically consists of numerical problems and proofs.

There are five programming assignments: 2 on search (1 A*, 1 game trees), 1 on planning, 1 on probabilistic inference and 1 on Q-learning.

The theoretical part (homeworks + best 6 quizzes) is worth 60%. The programming part is worth 40%.

Students are expected to spend about 6 hours per week on the homework and programming assignments.
All assignments (not quizzes) can be done in pairs (optional).

Course textbooks and materials

Textbook*: Artificial Intelligence: A Modern Approach, 3rd edition*, Russell and Norvig, supplemented by notes for the machine learning part

Programs are in Java. Programming assignments are implemented in the SEPIA environment. SEPIA (Strategy Engine for Programming Intelligent Agents) is a strategy game similar to an RTS (e.g., Warcraft, Age of Empires etc) that my students and I have built.

Why do you teach the course this way?

I reviewed and restructured this course in 2011.

The course is intended to be a broad coverage of AI subfields. Unfortunately AI is too broad to cover everything, but I try to hit many of the key points. It also mostly follows the textbook, which I have found is less confusing for students (some do not like jumping around a book). I try to balance exposure to the theoretical aspects with fun/interesting implementation.

For the quizzes and homework, having many short ones gives more frequent feedback to students about how well they understand the material, as well as distributes the risk of them losing too many points in any one assignment because they were having a bad day. I evaluate students in a quiz immediately after a homework because they have the material fresh in their minds at that point. Doing assignments in pairs builds teamwork and community, reduces the pressure of assignments and should be more fun.

From the student evaluations, the course is not viewed as "challenging" as such, but work-intensive.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
IS	Fundamental Issues	Overview of AI problems, Examples of successful recent AI applications What is intelligent behavior? The Turing test Rational versus non-rational reasoning Nature of environments Fully versus partially observable Single versus multi-agent Deterministic versus stochastic Static versus dynamic Discrete versus continuous Nature of agents Autonomous versus semi-autonomous Reflexive, goal-based, and utility-based The importance of perception and environmental interactions	1.0
IS	Basic Search Strategies	Problem spaces (states, goals and operators), problem solving by search Uninformed search (breadth-first, depth-first, depth-first with iterative deepening) Heuristics and informed search (hill-climbing, generic best-first, A*) Space and time efficiency of search Two-player games (Introduction to minimax search)	4.5

IS	Basic Knowledge Representation and Reasoning	Review of propositional and predicate logic (cross-reference DS/Basic Logic) Resolution and theorem proving (propositional logic only) DPLL, GSAT/WalkSAT First Order Logic resolution Review of probabilistic reasoning, Bayes theorem, inference by enumeration Review of basic probability (cross-reference DS/Discrete Probability) Random variables and probability distributions Axioms of probability Probabilistic inference Bayes' Rule	7.5
IS	Basic Machine Learning	Definition and examples of broad variety of machine learning tasks, including classification Inductive learning Statistical learning with Naive Bayes and Perceptrons Maximum likelihood and gradient descent parameter estimation Cross validation Measuring classifier accuracy, Confusion Matrices	6.0
IS	Advanced Search	Constructing search trees Stochastic search Simulated annealing Genetic algorithms Implementation of A* search, Beam search Minimax Search, Alpha-beta pruning Expectimax search and chance nodes	2.25
IS	Advanced Representation and Reasoning	Totally-ordered and partially-ordered Planning	1.75
IS	Reasoning Under Uncertainty	Conditional Independence Bayesian networks Exact inference (Variable elimination) Approximate Inference (basic Monte Carlo)	2.0
IS	Agents	Markov Decision Processes, Bellman Equation/Optimality, Value and Policy Iteration	1.25
IS	Natural Language Processing	Language models, n-grams, vector space models, bag of words, text classification, information retrieval, pagerank, information extraction, question-answering (Watson). [Overview, students are not evaluated on NLP]	1.25
IS	Advanced Machine Learning	Model based and model free reinforcement learning, temporal difference learning, Q learning, function approximation	2.5

CS188: Artificial Intelligence, University of California Berkeley

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Intelligent Systems (IS)	27
Human-Computer Interaction (HCI)	1

Brief description of the course's format and place in the undergraduate curriculum
The pre-requisites of this course are:

- **CS 61A or 61B:** Prior computer programming experience is expected (see below); most students will have taken both these courses.
- **CS 70 or Math 55:** Facility with basic concepts of propositional logic and probability are expected (see below); CS 70 is the better choice for this course.

This course has substantial elements of both programming and mathematics, because these elements are central to modern AI. Students must be prepared to review basic probability on their own. Students should also be very comfortable programming on the level of CS 61B even though it is not strictly required.

Course description and goals
This course will introduce the basic ideas and techniques underlying the design of intelligent computer systems. A specific emphasis will be on the statistical and decision-theoretic modeling paradigm. By the end of this course, you will have built autonomous agents that efficiently make decisions in fully informed, partially observable and adversarial settings. Your agents will draw inferences in uncertain environments and optimize actions for arbitrary reward structures. Your machine learning algorithms will classify handwritten digits and photographs. The techniques you learn in this course apply to a wide variety of artificial intelligence problems and will serve as the foundation for further study in any application area you choose to pursue.

Course topics

- Introduction to AI
- Search
- Constraint Satisfaction
- Game Playing
- Markov Decision Processes
- Reinforcement Learning
- Bayes Nets
- Hidden Markov Modeling
- Speech
- Neural Nets
- Robotics
- Computer Vision

Course textbooks, materials, and assignments
The textbook is Russell and Norvig, *Artificial Intelligence: A Modern Approach*, Third Edition.
All the projects in this course will be in Python. The projects will be on the following topics:

1. Search
2. Multi-Agent Pacman
3. Reinforcement Learning
4. Bayes Net
5. Classification

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
IS	Fundamental Issues	All	1
IS	Basic Search Strategies	All	2.5
IS	Basic Knowledge Representation and Reasoning	Probability, Bayes Theorem	2.5
IS	Basic Machine Learning	All	1
IS	Advanced Search	Except Genetic Algorithms	3
IS	Reasoning Under Uncertainty		6
IS	Agents		0.5
IS	Natural Language Processing		0.5
IS	Advanced Machine Learning		4
IS	Robotics		1
IS	Perception and Computer Vision		0.5
HCI	Design for non-mouse interfaces		1

Additional topics

- Neural Networks – 2 hours
- DBNs, Particle Filtering, VPI – 0.5 hours

Other comments

None

Introduction to Artificial Intelligence, University of Hartford

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Intelligent Systems (IS)	24
Programming Languages (PL)	3

Where does the course fit in your curriculum?
The course is typically taken in the junior or senior year as an upper level elective. It is taken mostly by Computer Science and Computer Engineering students. The Data Structures course is the prerequisite. There is no required course that has this course as a prerequisite. Instructors may offer independent study courses that require this course as a prerequisite. Student enrollment range is 10-24 per offering.

What is covered in the course?
The AI topics below follow the topic coverage in Russell & Norvig's *Artificial Intelligence: A Modern Approach*.

- Introduction to Lisp
- Fundamental Issues
  What is AI? Foundations of AI, History of AI.
- Intelligent Agents
  Agents and Environments, Structure of Agents.
- Problem Solving by Searching
  Problem Solving Agents, Searching for Solutions, Uninformed Search Strategies: Breadth-First Search, Depth-First Search, Depth-limited Search, Iterative Deepening Depth-first Search, Comparison of Uninformed Search Strategies.
- Informed Search and Exploration
  Informed (Heuristic) Search Strategies: Greedy Best-first Search, A* Search, Heuristic Functions, Local Search Algorithms, Optimization Problems.
- Constraint Satisfaction Problems
  Backtracking Search for CSPs, Local Search for CSPs.
- Adversarial Search
  Games, Minimax Algorithm, Alpha-Beta Pruning.
- Reasoning and Knowledge Representation
  Introduction to Reasoning and Knowledge Representation, Propositional Logic, First Order Logic, Semantic Nets, Other Knowledge Representation Schemes.
- Reasoning with Uncertainty & Probabilistic Reasoning
  Acting Under Uncertainty, Bayes' Rule, Representing Knowledge in an Uncertain Domain, Bayesian Networks.
- Machine Learning
  Forms of Learning, Decision Trees and the ID3 Algorithm, Nearest Neighbor, Statistical Learning.

What is the format of the course?

The course is a face-to-face course with 2.5 contact hours per week. It is approximately 50% lecture/discussion and 50% lab sessions.

How are students assessed?

Two exams and a final exam are given that constitute 45% of the grade. Assignments include programming and non- programming type problems. Students are given 1-1.5 weeks to complete. A term-long project with 4-5 deliverables is assigned. The project involves the development of a machine learning system. More information on our approach is included in Section VI.

Grading Policy

Exams 1, 2	30%
Final Exam	15%
Assignments	15%
Term Project	30%
Class Presentation	10%

Course textbooks and materials

Book: *Artificial Intelligence: A Modern Approach* by Russell and Norvig
Software: Allegro Common Lisp

Why do you teach the course this way?

Our approach to teaching introductory artificial intelligence unifies its diverse core topics through a theme of machine learning, through a set of hands-on term long projects, and emphasizes how AI relates more broadly with computer science. Machine learning is inherently connected with the AI core topics and provides methodology and technology to enhance real-world applications within many of these topics. Using machine learning as a unifying theme is an effective way to tie together the various AI concepts while at the same time emphasizing AI's strong tie to computer science. In addition, a machine learning application can be rapidly prototyped, allowing learning to be grounded in engaging experience without limiting the important breadth of an introductory course. Our work involves the development, implementation, and testing of a suite of projects that can be closely integrated into a one-term AI course.

With funding from NSF, our multi-institutional project, Machine Learning Experiences in Artificial Intelligence (MLeXAI), involved the development and implementation of a suite of 26 adaptable machine learning projects that can be closely integrated into a one-term AI course. Our approach would allow for varying levels of mathematical sophistication, with implementation of concepts being central to the learning process. The projects have been implemented and tested at over twenty institutions nationwide. Associated curricular modules for each project have also been developed. Each project involves the design and implementation of a learning system which enhances a particular commonly-deployed AI application. In addition, the projects provide students with an opportunity to address not only core AI topics, but also many of the issues central to computer science, including algorithmic complexity and scalability problems. The rich set of applications that students can choose from spans several areas including network security, recommender systems, game playing, intelligent agents, computational chemistry, robotics, conversational systems, cryptography, web document classification, computer vision, data integration in databases, bioinformatics, pattern recognition, and data mining.

Additional information on MLeXAI, the machine learning projects, and the participating faculty and institutions is available at the project web page at: http://uhaweb.hartford.edu/compsci/ccli.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hrs
PL	Lisp	A Brief Introduction	3
IS	Fundamental Issues	AI problems, Agents and Environments, Structure of Agents, Problem Solving Agents	3
IS	Basic Search Strategies	Problem Spaces, Uninformed Search (Breadth-First, Depth-First Search, Depth-first with Iterative Deepening), Heuristic Search (Hill Climbing, Generic Best-First, A*), Constraint Satisfaction (Backtracking, Local Search)	5
IS	Advanced Search	Constructing Search Trees, Stochastic Search, A* Search Implementation, Minimax Search, Alpha-Beta Pruning	3
IS	Basic Knowledge Representation and Reasoning	Propositional Logic, First-Order Logic, Forward Chaining and Backward Chaining, Introduction to Probabilistic Reasoning, Bayes Theorem	3
IS	Advanced Knowledge Representation and Reasoning	Knowledge Representation Issues, Non-monotonic Reasoning, Other Knowledge Representation Schemes.	3
IS	Reasoning Under Uncertainty	Basic probability, Acting Under Uncertainty, Bayes' Rule, Representing Knowledge in an Uncertain Domain, Bayesian Networks	3
IS	Basic Machine Learning	Forms of Learning, Decision Trees, Nearest Neighbor Algorithm, Statistical-Based Learning such as Naïve Bayesian Classifier.	4

Additional topics:

A brief introduction to 1-2 additional AI sub-fields. (2 hours)

Additional Comments

The machine learning algorithms covered vary based on the machine learning project selected for the course.

Acknowledgement: This work is funded in part by the National Science Foundation DUE-040949 and DUE-0716338.

References:

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- Russell, I., Markov, Z. 2009. Project MLeXAI Home Page, http://uhaweb.hartford.edu/compsci/ccli/.

- Russell, S. and Norvig, P. 2010. *Artificial Intelligence: A Modern Approach*, Upper Saddle River, NJ: Prentice-Hall.

Computer Networks I, Case Western Reserve University

Cleveland, OH
Prof. Vincenzo Liberatore
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Networking and Communication (NC)	39

Where does the course fit in your curriculum?

The course is taken in the senior year and it is required for Computer Science majors. The pre-requisite are junior standing and the sophomore course on data structures (or consent of instructor). Java programming experience is also required, and familiarity with a scripting language (awk, python, etc.) is helpful. Certain maturity level in mathematics, algorithms, and statistics is helpful. It has no required following course. It is a pre-requisite for Communications Networks II and for the Internet Applications courses (non-required). The most recent offering had an enrollment of 39 students.

What is covered in the course?

The course covers various aspects of computer networking, including (1) application layer protocols such as HTTP and SMTP, (2) transport layer (TCP/UDP) and congestion control, (3) routing and IP, and (4) link layer access protocols including Ethernet and 802.11.
Typical schedule:

Week 1: Network architecture, layering, and protocols.
Week 2: Principles of application-layer, application-layer protocols: FTP, SMTP, DNS.
Week 3: HTTP, Web Caching and content delivery networks. Peer-to-peer applications.
Week 4: Socket programming, introduction to transport layer protocols.
Week 5: Principles of reliable transfer, TCP reliable transfer implementation.
Week 6: TCP reliable transfer cont'd, RTT and timer, flow control, TCP connection management, state transition. Principles of congestion control.
Week 7: TCP congestion control. TCP performance: response time. TCP throughput
Week 8: Introduction to network layer. Inside a router.
Week 9: IPv4 and IP Addressing. IPv6 and ICMP. Routing algorithms.
Week 10: Internet routing architecture and protocols. Multicast routing.
Week 11: Introduction to link layer. Multiple access protocols.
Week 12: Aloha protocol, CSMA. Efficiency of CSMA/CD. Ethernet.
Week 13: LAN addressing and ARP. ATM networks.
Week 14: Wireless and mobile networks.

What is the format of the course?

Face-to-face lectures, for 3 contact hours/week.

How are students assessed?

6 written homework assignments; 2 course projects (each project takes about one month); midterm exam (about 1 ¼ hour); final exam (3 hours).

Course textbooks and materials

Required textbook: *Computer Networking, A Top-Down Approach Featuring the Internet*, by James F. Kurose and Keith W. Ross, 6th edition. Pearson, 2012.

Why do you teach the course this way?
The goal of the course is to teach the fundamental concepts and principles in today's networks. The course has been offered for 15+ years, and was made a requirement about 5 years ago. Students consider this course to be of the same difficulty as other senior-level courses.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
NC	Introduction		3
NC	Network Applications		7
NC	Reliable Data Delivery		7.5
NC	Routing and Forwarding		6
NC	Local Area Networks		9
NC	Resource Allocation	Congestion control, CDN (other topics in this KU are covered in Computer Networks II, technical elective in Computer Science curriculum)	3.5
NC	Mobility	Wireless and mobile networks (e.g., 802.11). Mobile-IP not covered in curriculum.	3

CS144: Introduction to Computer Networking, Stanford University

Stanford, CA, USA
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Course URLs:
cs144.stanford.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Networking and Communication (NC)	15
Architecture and Organization (AR)	3
Systems Fundamentals (SF)	7

Where does the course fit in your curriculum?

Seniors dominate the undergraduate enrollment in the course, although some juniors also take the course. It satisfies a requirement in the *Systems* track, or counts as a CS elective course for students not in the *Systems* track. The course is offered once a year. Generally, 120-160 students take the course. Its prerequisite is a course called Principles of Computer Systems, where students learn the elements of systems and also become proficient C programmers.

What is covered in the course?

CS144 is an introductory course on computer networking, specifically the Internet. The course explains how the Internet works, ranging from how bits are modulated on wireless networks to application-level protocols like BitTorrent and HTTP. It also explains the principles of network design, such as layering, packet switching, and the end-to-end argument. Students implement a handful of low-level protocols and services, including reliable transport, IP forwarding, and a Network Address Translation device. Students gain experience reading and understanding RFCs (Internet Protocol specifications) as statements of what a system should do. The course grounds many of the concepts in current practice and recent developments, such as net neutrality and DNS security.

What is the format of the course?

It uses a flipped classroom. Students view ~150 minutes of video instructional material each week, combined with automatically graded online quizzes. Class time is split between in-class exercises, guest lectures from industry and academia, and optional discussion sections led by the instructors. There is 100 minutes/week of required in-class time (exercises and lectures) and 50 minutes/week of optional in-class time (section).

How are students assessed?

Student grades are based on a combination of two exams, four programming assignments, two problem sets, a technical writing assignment, and online quizzes embedded in the class videos.

Course textbooks and materials

Students read Kurose and Ross's "Computer Networking" (most recent edition) and Internet standards (RFCs). They program in C, using open-source software tools developed at Stanford to emulate computer networks (Mininet).

Why do you teach the course this way?
The course is a mixture of principles and practice. We teach principles so that what the students learn will be applicable not just now, but hopefully far into the future. Examples of principles are layering, the end-to-end argument, and packet switching. We also teach practice so that students can see and experience how these principles can be instantiated in a real working system as large and complex as the Internet. We teach using a flipped classroom because much of the practice is factual material that is best presented in a reference form: students can review and re-watch videos. We use in-class time to ground these concepts and facts through interactive, real-time exploration of the Internet using software tools. For example, when the students learn about layers and packet encapsulation we have them use the Wireshark tool to see what happens when browser requests a web page, and how the layers come together in individual data packets.

The course dedicates a significant amount of time to packet switching and queuing within the network. The purpose of this focus is to give students a deep understanding of how the network works and how to explain its behavior. All of the variability in network behavior is due to queueing and packet switching. While students find some of the mathematical formulations a bit challenging at first, we spend enough time on the material that they can become comfortable with them and complete the course understanding not just the edges, but also the inner workings, of the Internet.

Students consider the course to be challenging, but not the most challenging course in the department. It's considered to be in the top 25% in terms of difficulty and workload, in part because debugging networking code is a very new and difficult to learn skill. It's the first time most students have ever dealt with distributed programs.

We revise the course every year to keep up to date with how the Internet evolves. The course has been offered six times (2013 will be the seventh). It was changed to be a flipped classroom in its sixth offering (2012).

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
NC	Introduction	All	1
NC	Networked Applications	All	2
NC	Reliable Data Delivery	All	4
NC	Routing and Forwarding	All	4
NC	Local Area Networks	All	2
NC	Resource Allocation	All	1
NC	Mobility	All	1
AR	Interfacing and Communication	Introduction to networks: communications networks as another layer of remote access	3
SF	Cross-Layer Communications	Reliability	1
SF	State and State Machines	Digital vs. Analog/Discrete vs. Continuous Systems Clocks, State, Sequencing Computers and Network Protocols as examples of State Machines	2

SF	Evaluation	Performance figures of merit; Amdahl's law	1
SF	Resource Allocation and Scheduling	Advantages of fair scheduling, preemptive scheduling	1
SF	Reliability through Redundancy	Redundancy through check and retry Redundancy through redundant encoding (error correcting codes, CRC, FEC) How errors increase the longer the distance between the communicating entities; the end-to-end principle as it applies to systems and networks	2

Computer Networks, Williams College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Architecture and Organization (AR)	1
Computational Science (CN)	1
Discrete Structures (DS)	1
Information Assurance and Security (IAS)	1
Networking and Communication (NC)	6
Operating Systems (OS)	0.2
Systems Fundamentals (SF)	1.8
See note in "Format of the Course" on number of contact hours	

Where does the course fit in your curriculum?
This course is not required in our curriculum. Majors are required to complete two elective courses. This course fulfils that requirement, but they have many other choices. Data Structures and Computer Organization are prerequisites. The course is limited to 10 students. Typical enrollment falls between 6 and 10.

What is covered in the course?
The description found in the course catalog says: This course explores the principles underlying the design of computer networks. We will examine techniques for transmitting information efficiently and reliably over a variety of communication media. We will look at the addressing and routing problems that must be solved to ensure that transmitted data gets to the desired destination. We will come to understand the impact that the distributed nature of all network problems has on their difficulty. We will examine the ways in which these issues are addressed by current networking protocols such as TCP/IP and Ethernet. Students will meet weekly with the instructor in pairs to present solutions to problem sets and reports evaluating the technical merit of current solutions to various networking problems.

What is the format of the course?
The course is offered in a format that is somewhat peculiar to our institution. The format is called a tutorial. In a tutorial course, the primary form of student faculty contact is weekly meetings in which pairs of students registered for the course meet with the instructor to discuss their work on an assignment they received a week earlier. In this course, assignments typically require readings from the text and one or more papers from the literature. The students are then asked to solve a series of exercises and or answer questions related to the readings. During the meetings, the students present and discuss their answers to the exercises.

As a result of this format, there are actually only 12 hours of direct student/faculty contact. The hours shown for various areas in the "Body of Knowledge" section below are therefore out of 10 hours rather than the 36 or so hours available in a typical lecture-based course.

How are students assessed?

Students complete weekly written assignments, one significant programming project, and take two open-book take-home examinations.

Course textbooks and materials

The course uses Peterson and Davie, *Computer Networks: A Systems Approach* as a text. Other readings can be found on the course web site.

Why do you teach the course this way?

The course was developed shortly after our institution initiated the tutorial format. The motivation for the format was to strengthen each student's ability to learn independently and to engage in an intellectual discussion effectively. As a result, the course design places relatively little emphasis on programming projects and much more emphasis on analytical problems. This also shifted the topics covered and the emphasis placed on various topics. In particular, areas that are well suited to mathematical analysis (contention-resolution protocols, error-correcting codes, etc.) receive more attention than they might if the course were offered in a more traditional lecture/lab format.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AR	Interfacing and Communication	Compare common network organizations	1
CN	Fundamentals	Modelling and abstraction, simulation as dynamic modelling, create a formal mathematical model and use for simulation	1
DS	Discrete Probability	Finite probability space, events Axioms of probability and probability measures independence	1
IAS	Network Security	Network specific threats and attack types (e.g., denial of service, spoofing, sniffing and traffic redirection, man-in-the-middle, message integrity attacks, routing attacks, and traffic analysis); Use of cryptography for data and network security; Security for wireless	0.5
IAS	Cryptography	The Basic Cryptography Terminology covers notions pertaining to the different (communication) partners, secure/unsecure channel, attackers and their capabilities, encryption, decryption, keys and their characteristics, signatures, etc.; Overview of Mathematical Preliminaries where essential for Cryptography; includes topics in linear algebra, number theory, probability theory, and statistics.; Public Key Infrastructure support for digital signature and encryption and its challenges.	0.5

NC	Introduction	All	1.5
NC	Networked Applications	Naming and address schemes (DNS, IP addresses, Uniform Resource Identifiers, etc.); HTTP as an application layer protocol; Multiplexing with TCP and UDP;	0.5
NC	Data Delivery	Error control (retransmission techniques, timers); Flow control (acknowledgements, sliding window); TCP	1
NC	Routing and Forwarding	Routing versus forwarding; Static routing; Internet Protocol (IP); Scalability issues (hierarchical addressing)	1
NC	Local Area Networks	Multiple Access Problem; Common approaches to multiple access (exponential-backoff, time division multiplexing, etc.); Local Area Networks; Ethernet; Switching	0.5
NC	Resource Allocation	Need for resource allocation; Fixed allocation (TDM, FDM, WDM) versus dynamic allocation; End-to-end versus network assisted approaches; Fairness; Principles of congestion control; Approaches to Congestion (Content Distribution Networks, etc.)	1
NC	Mobility	802.11 networks	0.5
OS	Overview of Operating Systems	Mechanisms to support client-server models	0.2
SF	State-State Transition-State Machines	Computers and Network Protocols as examples of State Machines	0.2
SF	Parallelism	Request parallelism (e.g., web services) vs. Task parallelism (map-reduce processing); Client-Server/Web Services, Thread (Fork-Join), Pipelining	0.3
SF	Resource Allocation and Scheduling	Kinds of scheduling: first-come, priority; advantages of fair scheduling, pre-emptive scheduling	0.3

SF	Reliability through Redundancy	How errors increase the longer the distance between the communicating entities; the end-to-end principle as it applies to systems and networks; Redundancy through check and retry; Redundancy through redundant encoding (error correcting codes, CRC, FEC)	1

CSCI 432 Operating Systems, Williams College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Operating Systems (OS)	30
Systems Fundamentals (SF)	(Overlap with OS hours)
Networking and Communication (NC)	2
Parallel and Distributed Computing (PD)	(Overlap with OS hours)

Where does the course fit in your curriculum?

Operating Systems is typically taken by juniors and seniors. It is not compulsory, although it does satisfy our "project course" requirement, and students are required to take at least one project course to complete the major. The prerequisites are Computer Organization and either Algorithms or Programming Languages. The latter requirement is mostly used to ensure a certain level of maturity rather than specific skills or knowledge. Average class size is 15-20 students.

What is covered in the course?

This course explores the design and implementation of computer operating systems. Topics include historical aspects of operating systems development, systems programming, process scheduling, synchronization of concurrent processes, virtual machines, memory management and virtual memory, I/O and file systems, system security, OS/architecture interaction, and distributed operating systems. The concepts in this course are not limited to any particular operating system or hardware platform. We discuss examples that are drawn from historically significant and modern operating systems including Unix, Windows, Mach, and the various generations of Mac OS.

The objective of this course is threefold: to demystify the interactions between the software written in other courses and hardware, to familiarize students with the issues involved in the design and implementation of modern operating systems, and to explain the more general systems principles that are used in the design of all computer systems.

What is the format of the course?
The course format is primarily lectures with some interactive discussion. There are no officially scheduled lab sessions, but a few lectures are held in the lab to help with project setup.

How are students assessed?
Student evaluation is largely based on 4 implementation projects that include significant programming, as well as 2-3 written homework assignments, 6-8 research paper evaluations, and a midterm exam. Projects typically span 2-3 weeks and require 20-30 hours of work each. Written homework assignments and paper evaluations require 3-10 hours of work each.

Course textbooks and materials
Textbook: *Modern Operating Systems,* 3rd ed., by Andrew Tanenbaum
Other assigned reading material: 6-8 research papers

Programming Project One: Inverted Index in C++ (warm-up project)
Programming Project Two: Threads and Monitors in C++
Programming Project Three: Virtual Memory Manager in C++
Programming Project Four: Smash the Stack in C++

Why do you teach the course this way?
The course combines classical OS concepts with more modern technologies. The combination of textbook readings as well as select research papers gives students a breadth of knowledge about current and recent OS topics. The programming projects are challenging, but most students are able to successfully finish all of them in the allotted time.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
OS	Overview of Operating Systems	Role and purpose of OS, key design issues, influences of security and networking	2
OS	Operating System Principles	Structuring methods, abstractions, processes, interrupts, dual-mode (kernel vs. user mode) operation	3
OS/PD/ SF	Concurrency (OS)/Communication and Coordination (PD)/Parallelism (SF)	Structures, atomic access to OS objects, synchronization primitives, spin-locks	5
OS/PD/ SF	Scheduling and Dispatch (OS)/System Performance Evaluation (OS)/Parallel Performance (PD)/Resource Allocation and Scheduling (SF)	Preemptive and non-preemptive scheduling, evaluating scheduling policies, processes and threads	4
OS	Memory Management	Virtual memory, paging, caching, thrashing	4

OS	Security and Protection	Access control, buffer overflow exploits, OS mechanisms for providing security and controlling access to resources	4
OS/SF	Virtual Machines (OS)/Cross-Layer Communications (SF)/Virtualization and Isolation (SF)	Types of virtualization, design of different hypervisors, virtualization trade-offs	3
OS	Device Management	Briefly discuss device drivers, briefly discuss mechanisms used in interfacing a range of devices	1
OS	File Systems	File system design and implementation, files, directories, naming, partitioning	3
OS	Fault Tolerance	Discuss and define relevance of fault tolerance, reliability, and availability in OS design	1
NC	Reliable Data Delivery	OS role in reliable data delivery	0.5
NC	Networked Applications/Introduction	Role of OS in network naming schemes, role of layering	1
NC	Routing and Forwarding	Role of OS in routing and forwarding	0.5
OS	Real Time and Embedded Systems		0

Additional topics

Other comments

I have often contemplated replacing Project Four with one that focused on File Systems rather than Security. However, the students really enjoy the Stack Smashing project, and we do not offer another course that focuses on Security in our curriculum.

CS 420, Operating Systems, Embry-Riddle Aeronautical University

Prof. Nick Brixius
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Operating Systems (OS)	24
Parallel and Distributed Computing (PD)	5
Systems Fundamentals (SF)	4

Brief description of the course's format and place in the undergraduate curriculum
Third or fourth year course – prerequisite is CS225, Computer Science II and third year standing – 3 semester credits – 3 hours lecture per week.

Course description and goals
The course will study the basic concepts, design and implementation of operating systems. Topics to be covered include an overview of basic computing hardware components, operating system structures, process management, memory management, file systems, input/output systems, protection and security. The Windows and UNIX/Linux operating systems will be reviewed as implementation examples.

The coursework will include "hands-on" application of reading assignments and lecture material through homework assignments, including several programming projects.

Course topics
1. Overview of an Operating System
2. Computing Hardware Overview
3. Process Management
4. CPU Scheduling
5. Deadlocks and Synchronization
6. Memory Management
7. File systems and storage
8. Distributed Systems

Course textbooks, materials, and assignments
Textbook: Silberschatz, A., Galvin, P.B. and Gagne, G. (2010) *Operating System Concepts with Java.* Addison Wesley Publishing Co., New York. (Eighth Edition) ISBN 978-0-470-50949-4

Java and the Java Virtual Machine are used for programming assignments

Assignment One: Java threads, OS components
Assignment Two: Process states and process management
Assignment Three: Process Scheduling and race conditions
Assignment Four: Concurrency and deadlocks

Assignment Five: Memory management
Assignment Six: File systems and HDD scheduling
Assignment Seven: Network support and distributed systems

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
OS	OS/Overview of Operating Systems	High-level overview of all topics	2
OS	OS/Operating System Principles	Processes, process control, threads.	2
OS	OS/Scheduling and Dispatch	Preemptive, non-preemptive scheduling, schedulers and policies, real-time scheduling	3
SF	SF/Resource Allocation and Scheduling	Kinds of scheduling	2
OS	OS/Concurrency	Exclusion and synchronization; deadlock	3
OS	OS/Memory Management	Memory management, working sets and thrashing; caching	3
OS	OS/File Systems	Files (metadata, operations, organization, etc.); standard implementation techniques; file system partitioning; virtual file systems; memory mapped files, journaling and log structured file systems	2
SF	SF/Virtualization & Isolation	Rationale for protection and predictable performance, levels of indirection, methods for implementing virtual memory and virtual machines	2
OS	OS/Virtual Machines	Paging and virtual memory, virtual file systems, virtual file, portable virtualization, hypervisors	2
OS	OS/Device Management	Characteristics of serial & parallel devices, abstracting device differences, direct memory access, recovery from failures	3
PD	PD/Parallelism Fundamentals	Multiple simultaneous computations; programming constructs for creating parallelism, communicating, and coordinating;	2
PD	PD/Distributed Systems	Distributed message sending; distributed system and service design;	3
OS	OS/Security and Protection	Overview of system security, policy, access control, protection, authentication	2
OS	OS/Real Time and Embedded Systems	Memory/disk management requirements in real-time systems; failures, risks, recovery; special concerns in real-time systems	2

CPSC 3380 Operating Systems, U. of Arkansas at Little Rock

Dr. Peiyi Tang
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Operating Systems (OS)	24
Parallel and Distributed Computing (PD)	5
Systems Fundamentals (SF)	4

Course description and goals

An operating system (OS) defines an abstraction of hardware and manages resource sharing among the computer's users. The OS shares the computational resources such as memory, processors, networks, etc. while preventing individual programs from interfering with one another. After successful completion of the course, students will learn how the programming languages, architectures, and OS interact.

Course topics

After a brief history and evolution of OS, the course will cover the major components of OS. Topics will include process, thread, scheduling, concurrency (exclusion and synchronization), deadlock (prevention, avoidance, and detection), memory management, IO management, file management, virtualization, and OS' role for realizing distributed systems. The course will also cover protection and security with respect to OS.

Course textbooks, materials, and assignments

Textbook: "Operating System Concepts" by A. Silberschatz, P. Galvin and G. Gagne, John Wiley & Sons, 2009, ISBN: 978-0-470-12872-5

Lab System: Nachos 4.3 (in C++).

Assignment One: Program in Execution
Assignment Two: Process and Thread
Assignment Three: Synchronization with Semaphores
Assignment Four: Synchronization with Monitors

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
OS	OS/Overview of Operating Systems	Overview of OS basics	2
OS	OS/Operating System Principles	Processes, process control, threads	2
OS	OS/Scheduling and Dispatch	Preemptive, non-preemptive scheduling, schedulers and policies, real-time scheduling	3
SF	SF/Resource Allocation and Scheduling	Kinds of scheduling	2
OS	OS/Concurrency	Exclusion and synchronization; deadlock	3
OS	OS/Memory Management	Memory management, working sets and thrashing; caching	3
OS	OS/File Systems	Files (metadata, operations, organization, etc.); standard implementation techniques; file system partitioning; virtual file systems; memory mapped files, journaling and log structured file systems	2
SF	SF/Virtualization & Isolation	Rationale for protection and predictable performance, levels of indirection, methods for implementing virtual memory and virtual machines	2
OS	OS/Virtual Machines	Paging and virtual memory, virtual file systems, virtual file, portable virtualization, hypervisors	2
OS	OS/Device Management	Characteristics of serial & parallel devices, abstracting device differences, direct memory access, recovery from failures	3
PD	PD/Parallelism Fundamentals	Multiple simultaneous computations; programming constructs for creating parallelism, communicating, and coordinating	2
PD	PD/Distributed Systems	Distributed message sending; distributed system and service design	3
OS	OS/Security and Protection	Overview of system security, policy, access control, protection, authentication	2
OS	OS/Real Time and Embedded Systems	Memory/disk management requirements in real-time systems; failures, risks, recovery; special concerns in real-time systems	2

582219 Operating Systems, University of Helsinki

Department of Computer Science
Dr. Teemu Kerola
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https://www.cs.helsinki.fi/en/courses/582219

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Operating Systems (OS)	23
Systems Fundamentals (SF)	4
Parallel and Distributed Computing (PD)	3
Architecture and Organization (AR)	2

Brief description of the course's format and place in the undergraduate curriculum

Pre-requisites: Computer Organization I (24h). Course targeted to 2nd year students. Course consists of 18 lectures (2h) and 9 homework practice sessions (2h).
Follow-up courses: Distributed Systems, Mobile Middleware, OS lab project (in planning).

Course description and goals

Understand OS services to applications, concurrency problems and solution methods for them, OS basic structure, principles and methods of OS implementation.

Course topics

OS history, process, threads, multicore, concurrency problems and their solutions, deadlocks and their prevention, memory management, virtual memory, scheduling, I/O management, disk scheduling, file management, embedded systems, distributed systems.

Course textbooks, materials, and assignments

Textbook: "Operating Systems – Internals and Design Principles", 7th ed. by W. Stallings, Pearson Education Ltd, 2012, ISBN 13: 978-0-273-75150-2
Homework 1: Overview, multicore, cache
Homework 2: Processes, threads
Homework 3: Mutual exclusion, scenarios, semaphores, monitors, producer/consumer
Homework 4: Message-passing, readers/writers, deadlocks
Homework 5: Memory management, virtual memory
Homework 6: Scheduling
Homework 7: I/O management
Homework 8: File management, embedded systems
Homework 9: Distributed systems
Exams: 2 (2.5h each)

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
OS	OS/Overview of Operating Systems	Role, functionality, design issues, history, evolution, SMP considerations	2
AR	AR/Memory System Organization	Cache, TLB	2
SF	SF/Computational Paradigms	Processes, threads, process/kernel states	1
SF	SF/Cross-Layer Communication	Layers, interfaces, RPC, abstractions	1
SF	SF/Parallelism	Client/server computing, HW-support for synchronization, multicore architectures	2
OS	OS/Operating System Principles	Process control, OS structuring methods, interrupts, kernel-mode	2
OS	OS/Concurrency	Execution scenarios, critical section, spin-locks, synchronization, semaphores, monitors	4
PD	PD/Communication-Coordination	Message passing, deadlock detection and recovery, deadlock prevention, deadlock avoidance	2
OS	OS/Scheduling and Dispatch	Scheduling types, process/thread scheduling, multiprocessor scheduling	4
OS	OS/Memory Management	Memory management, partitioning, paging, segmentation	2
OS	OS/Security and Protection	-- covered in Introduction to Computer Security --	
OS	OS/Virtual Machines	Hypervisors, virtual machine monitor, virtual machine implementation, virtual memory, virtual file systems	3
OS	OS/Device Management	Serial and parallel devices, I/O organization, buffering, disk scheduling, RAID, disk cache	2
OS	OS/File Systems	File organization, file directories, file sharing, disk management, file system implementation, memory mapped files, journaling and log structured systems	2
OS	OS/Real Time and Embedded Systems	Real time systems, real time OS characteristics, real-time scheduling, embedded systems OS characteristics	2
PD	PD/Parallel Architectures	Multicore, SMP, shared/distributed memory, clusters	1

Other comments

We have special emphasis on concurrency, because more and more applications are executed multithreaded in multicore environments.

RU STY1 Operating Systems, Reykjavik University

Dr. Ymir Vigfusson
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No public website is available

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Operating Systems (OS)	18
Architecture and Organization (AR)	8
Networking and Communication (NC)	4
Systems Fundamentals (SF)	4.5

Brief description of the course's format and place in the undergraduate curriculum

The course is taught in the 4th semester of a 3-year program with the only prerequisite being first semester Computer Architecture. By then the students are familiar with several programming languages, including C++, which prepares them for the low-level C programming used in the course. Lectures are given 2x1.5 hours per week over 12 weeks in an auditorium, plus 1.5 hours of optional recitation sessions in regular classrooms. Online recordings are provided of all lectures and sessions. Two big written homework assignments are solved in pairs, and five major lab 2-week projects. After the Operating Systems course, high-scoring students are invited to a follow-up 3-week computer security course in which low-level assembly, C programming, reverse engineering and exploit writing skills are developed further.

Note that our Operating Systems course covers material traditionally taught in introductory Computer Architecture courses, such as hands-on x86 assembly programming, since we pace down our first-semester Computer Architecture course while students are learning the ropes.

Course description and goals

The operating system abstracts hardware from software through a multitude of interfaces. Operating systems strive to share devices, memory and other computational resources between competing users and programs in a fast, robust and accurate manner. The course will explain what's under the hood of typical operating system abstractions, with special emphasis on the treatment of memory and the CPU, including assembly. At the end of the course students will understand how the OS interacts with hardware, how higher level systems interact with the OS, and be able to program against these lower-level abstractions.

Course topics

The course covers many of the fundamentals of computer architecture and operating systems: x86 assembly, virtual memory, caches, processes, signals, threads, process communication, concurrency and deadlocks, scheduling, dynamic memory management, I/O management, virtual machines and the basics of network programming, file systems, and security.

Course textbooks, materials, and assignments

Computer Systems: A Programmer's Perspective, by Bryant and O'Hallaron, 2nd edition (February 2010). Addison Wesley. ISBN 9780136108047.

Lab System: Shared access to a CentOS 5 Linux shell server.

Programming Language: C

Assignment One: Bit manipulation (datalab)
Assignment Two: Reverse engineering C code in x86 assembly (bomblab)
Assignment Three: Write a shell with job control (shelllab)
Assignment Four: Design and implement a memory allocator (malloclab)
Assignment Five: Design and implement a multi-threaded proxy server (proxylab)
Optional Assignment: Write buffer overflows for C programs (buflab)

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
OS	Overview of Operating Systems	Role, purpose, design issues of modern OSes.	1
OS	Operating System Principles	Processes, process control, threads, interrupts, context-switching	2
AR	Machine-level representation of data	Bits, bytes, words, two-complement representation of numbers, records, arrays	3
AR	Assembly level machine organization	Von Neumann machine, x86 assembly instructions, heap, stack, code, subroutine calls, I/O and interrupts	4
OS & SF	OS/Scheduling and Dispatch & SF/Resource Allocation and Scheduling	CPU scheduling, scheduling policies, deadlines, real-time concerns	2
OS	Concurrency	Basics of exclusion and synchronization, interrupts, deadlocks, progress graphs; pthreads interface	3
OS & SF & AR	OS/Memory Management & SF/Proximity & AR/Memory system org. and arch.	Storage systems, memory management, working sets and thrashing; latencies, caching, locality, cache consistency, virtual memory, fault handling	5
PL	Runtime systems	Dynamic memory management, garbage collection	3
OS	File Systems	Files (metadata, operations, organization, etc.); standard implementation techniques; file system partitioning; virtual file systems; memory mapped files, journaling and log structured file systems	2
SF	SF/Virtualization & Isolation	Rationale for protection and predictable performance, levels of indirection, methods for implementing virtual memory and virtual machines	2
OS	Virtual Machines	Paging and virtual memory, virtual file systems, virtual devices and I/O, hypervisors, sandboxes (specifically the Chrome sandbox), emulators,	3
OS & IAS	OS/Security and Protection & IAS/Defensive Programming	Overview of system security; buffer overflows and exploits, input sanitation, correct handling of exceptions. Policy/protection/authentication handled in a different course.	2

SF	Support For Parallelism	Thread parallelism, event-driven concurrency, client/server web services	1.5
NC	Networked applications	DNS, peer-to-peer systems (Chord, BitTorrent), HTTP, socket APIs, multiplexing with TCP/UDP	4

Additional topics
Reverse engineering, 1 hour

Parallel Programming Principle and Practice, Huazhong U. of Science and Technology

Wuhan, China
Hai Jin
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http://grid.hust.edu.cn/courses/parallel/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Parallel and Distributed Computing (PD)	24
Architecture and Organization (AR)	2

Where does the course fit in your curriculum?

0804021 is an optional course. It is typically taken by third-year undergraduate students and first-year graduate students in either the Professional Masters' degree program or the PhD program. Enrollment ranges from 40 to 70 students.

The students are supposed to know the following:

- 0810011: "C Programming Language"
- 0700183: "Discrete Mathematics"
- 0842151: "Fundamentals of Computer System I"
- 0842161: "Fundamentals of Computer System II"
- 0842191: "Parallel and Sequential Data Structures and Algorithms"
- 0800421: ""Operating System Design and Implementation"

Experience with programming in C and C++ is required in order to carry out the laboratory works.

What is covered in the course?

Part 1: Principle

This section covers the very basics of parallel computing, and is intended for someone who is just becoming acquainted with the subject. It begins with a brief overview, including concepts and terminology associated with parallel computing. The topics of parallel memory architectures and programming models are then explored. These topics are followed by a discussion on a number of issues related to designing parallel programs.

- Why Parallel Programming?
- Parallel Architecture
- Parallel Programming Models
- Parallel Programming Methodology
- Parallel Programming: Performance

Part 2: Typical Issues Solved by Parallel Programming

This section concludes with several examples of how to parallelize simple serial programs. Including: threads and shared memory programming with TBB and OpenMP, SIMD programming model and Cuda & OpenCL, programming using the Message Passing Paradigm, parallel computing with MapReduce.

- Shared Memory Programming and OpenMP: A High Level Introduction
- Case Studies: Threads programming with TBB
- Programming Using the Message Passing Paradigm
- Introduction to GPGPUs and CUDA Programming Model
- Parallel Computing with MapReduce

Part 3: Parallel Programming Case Study and Assignment

Students in this course are required to complete several assignments, which account for 30% of their grade.

What is the format of the course?
0804021 is a 2 credit course with 28 lecture hours and 12 lab hours. Classes typically meet twice per week for lecture, with lab sessions completed in tutoring labs outside of lecture. Course material is available online. The course is taught online and face-to-face. Generally there is a combination of lectures, class discussion, case studies, written term papers, and team research and presentation.

How are students assessed?
Students are assessed on a combination of class attendance, group activities, discussion, projects, participation in parallel programming competition held by enterprises, and a comprehensive final exam.

Course textbooks and materials
- C Lin, L Snyder. *Principles of Parallel Programming*. USA: Addison-Wesley Publishing Company, 2008.
- B Gaster, L Howes, D Kaeli, P Mistry, and D Schaa. *Heterogeneous Computing With Opencl*. Morgan Kaufmann Publishing and Elsevier, 2011.
- A Grama, A Gupra, G Karypis, V Kumar. *Introduction to Parallel Computing (2nd ed.).* Addison Wesley, 2003.
- J Jeffers, J Reinders. *Intel Xeon Phi Coprocessor High-Performance Programming*. Morgan Kaufmann Publishing and Elsevier, 2013.
- T Mattson, B Sanders, B Massingill. *Patterns for Parallel Programming*. Addison-Wesley Professional, 2004.

Why do you teach the course this way?
Being funded by the Project of "Parallel Programming Principle and Practice" from the Ministry of Education (MOE) of the People's Republic of China to design a syllabus for senior undergraduate students on parallel and distributed programming, we serve as the China's first pilot of restructured courses to integrate topics of CS2013/TCPP Curriculum Initiative on PDC requirements into the undergraduate curriculum.

The goal of the course is to provide an introduction to parallel computing including parallel computer architectures, analytical modeling of parallel programs, principles of parallel algorithm design. We will introduce existing mainstream parallel programming environment and present development situation, which will make the students understand the basic knowledge of parallel programming. The labs will guide students to use tools to simulate an optimized parallel program, enable them to master skills to design, code, debug, analysis and optimize some mainstream parallel software.

The course has a good reputation among students. The students that have taken this course won Best MIC performance award at "Asia Student Supercomputer Challenge 2013" (http:// www.asc-events.org/13en/index13en.php). This course has been granted an Early Adopter status by the NSF/TCPP curriculum committee (http://www.cs.gsu.edu/~tcpp/curriculum/?q=list-of-early-adopters-fall-2012.html).

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PD	Parallelism Fundamentals	Overview: Parallel computing, architectural demands and trends, goals of parallelism, communication, coordination	2
PD	Parallel Decomposition	Independence and partitioning, Data and task decomposition, Synchronization	1
PD	Communication and Coordination	Shared Memory, Threads, Message Passing, Consistency	2

PD	Parallel Algorithms, Analysis, and Programming	Shared memory programming and OpenMP, Threads programming with TBB, Programming using the message passing paradigm, Parallel computing with MapReduce, GPGPUs and CUDA programming	12
PD	Parallel Architecture	Pipelining, Superscalar, Out-of-order execution, Vector Processing/SIMD, Multithreading: pThreads, Uniprocessor memory systems, A parallel zoo of architectures, Multicore chips	4
PD	Parallel Performance	Relationship of communication, data locality and architecture, Orchestration for performance: load balancing, Characteristics: speed- up, cost, scalability, isoefficiency	2
PD	Distributed Systems	Distributed computing	1
PD	Formal Models and Semantics	Shared memory model (OpenMP), Threads model (pthread, cilk TBB), MPI, GPGPU programming model (cuda or openCL), Other models (cloud MapReduce, Data Flow Model, Systolic Array Model)	2

Additional topics
Motivating Problems (application case studies),
Steps in creating a parallel program,
Tools for development of parallel programs

Introduction to Parallel Programming, Nizhni Novgorod State University

Nizhni Novgorod, Russia
Victor Gergel
gergel@unn.ru
http://www.hpcc.unn.ru/?doc=98 (In Russian)
http://www.hpcc.unn.ru/?doc=107 (In English)

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Parallel and Distributed Computing (PD)	20

Where does the course fit in your curriculum?
3rd year (5th semester). Compulsory course. Usually has 40-50 students.
The students are supposed to know the following:

- CS101 "Introduction to Programming"
- CS105 "Discrete mathematics"
- CS220 "Computer Architecture"
- CS225 "Operating Systems"
- CS304 "Numerical Methods "

Experience with programming in C is required in order to carry out the laboratory works.

What is covered in the course?

- Introduction to Parallel Programming
- Overview of Parallel System Architectures
- Modeling and Analysis of Parallel Computations
- Communication Complexity Analysis of Parallel Algorithms
- Parallel Programming with MPI
- Parallel Programming with OpenMP
- Principles of Parallel Algorithm Design
- Parallel Algorithms for Solving Time Consuming Problems (Matrix calculation, System of linear equations, Sorting, Graph algorithms, Solving PDE, Optimization)
- Modeling the parallel program executing

What is the format of the course?
In-person lectures. Lectures: 36 contact hours. Labs: 18 hours. Homework: 18 hours.

How are students assessed?
Assignments include reading papers and implementing programming exercises.

Course textbooks and materials

- Gergel V.P. (2007) *Theory and Practice of Parallel Programming*. Moscow, Intuit. (In Russian)
- Gergel V.P. (2010) *High-Performance Computations for Multiprocessor Multicore Systems*. Moscow: Moscow State University. (In Russian)
- Quinn, M. J. (2004). *Parallel Programming in C with MPI and OpenMP*. New York, NY: McGraw-Hill.

- Grama, A., Gupta, A., Kumar V. (2003, 2nd edn.). *Introduction to Parallel Computing*. Harlow, England: Addison-Wesley.
- To develop parallel programs C/C++ is used, MS Visual Studio, Intel Parallel Studio, cluster under MS HPC Server 2008.

Why do you teach the course this way?

The goal of the course is to study the mathematical models, methods and technologies of parallel programming for multiprocessor systems. Learning the course is sufficient for a successful start to practice in the area of parallel programming.

The course has a good reputation among students. The students that are studied this course were the winner in the track "Max Linpack performance" of the Cluster Student Competition at Supercomputing 2011. The course was a part of the proposal that was the winner of the contest "Curriculum Best Practices: Parallelism and Concurrence" of European Association "Informatics Europe" (2011) – see. http://www.informatics-europe.org/services/curriculum-award/105-curriculum-award-2011.html

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PD	Parallelism Fundamentals	Overview: Information dependencies analysis, decomposition, synchronization, message passing	2
PD	Parallel Decomposition	Data and task decomposition, Domain specific (geometric) decomposition	0.5
PD	Communication and Coordination	Basic communication operations, Evaluating communication overhead	2
PD	Parallel Algorithms, Analysis, and Programming	Characteristics of parallel efficiency, Spectrum of parallel algorithms (Matrix calculation, System of linear equations, Sorting, Graph algorithms, Solving PDE, Optimization) OpenMP, MPI, MS VS, Intel Parallel Studio	10
PD	Parallel Architecture	Structure of the MIMD class of Flynn's taxonomy, SMP, Clusters, NUMA	1.5
PD	Parallel Performance	Characteristics of parallel efficiency: speed-up, cost, scalability, isoefficiency. Theoretical prediction of parallel performance and comparing with computational results	2
PD	Formal Models and Semantics	Information dependencies analysis, Evaluating characteristics of parallel efficiency (superlinear and linear speed-up, max possible speed up for a given problem, speed-up of a given parallel algorithm), Equivalent transformation of parallel programs	2

Additional topics

Isoefficiency,
Redundancy of parallel computations,
Classic illustrative parallel problems (readers-writers, dining philosophers, sleeping barbarian, etc.),
Tools for development of parallel programs,
Formal models based on Information dependencies analysis

CS in Parallel (course modules on parallel computing)

Richard Brown, St. Olaf College
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http://csinparallel.org

What is CSinParallel?
CSinParallel is not a single course, but is a project that has produced several modules on parallel computing that are suitable for use in a variety of courses. As such, the description of CSinParallel modules provided here does not match the standard form for course exemplars in CS2013. Rather, we list below the modules available from CSinParallel.org at the time of this writing, and indicate for each module the Knowledge Units from CS2013 that are addressed by that module. The interested reader is encouraged to explore details of each module at the CSinParallel.org web site.

Description of the Project from the CSinParallel.org Website
CSinParallel modules provide conceptual principles of parallelism and hands-on practice with parallel computing, in self-contained 1- to 3-day units that can be inserted in various CS courses in multiple curricular contexts. These modules offer an incremental approach to getting CS undergraduates the exposure to parallelism they will need as they begin their careers.

CSinParallel Modules

#	Module Name	Author(s)
1	Map-reduce Computing for Introductory Students using WebMapReduce	Dick Brown and Libby Shoop
2	Multicore Programming (3 versions)	Dick Brown and Libby Shoop
3	Concurrent Access to Data Structures (2 versions)	Libby Shoop, Dick Brown and Patrick Garrity
4	Parallel Computing Concepts	Dick Brown
5	Parallel Sorting	Libby Shoop
6	Concurrency and Map-Reduce Strategies in Various Programming Languages	Dick Brown
7	Patternlets in Parallel Programming	Joel Adams
8	GPU Programming	Libby Shoop and Yu Zhao
9	Heterogeneous Computing	Libby Shoop
10	Distributed Computing Fundamentals	Libby Shoop
11	Pi Calculus: A Theory of Message Passing	Dick Brown
12	Exemplar: Drug Design	Dick Brown
13	Exemplar: Computing Pi using Numerical Integration	Dick Brown and EAPF
14	An Advanced Introduction to Map-reduce using WebMapReduce	Dick Brown

Body of Knowledge coverage

For each CSinParellel module in the grids below, we indicate with an 'x' if a given module contains coverage of Core (either Tier1 or Tier2) topics from a given Knowledge Unit. This provides an overview of the topical coverage for each CSinParallel module. The interested reader can get detailed information on each module from the CSinParallel.org website. (Knowledge Areas not covered by any CSinParallel module are not listed below.)

		1: Map-reduce for CS1/WMR	2: Multicore Programming	3: Concurrent Data Structures	4: Parallel Computing Concepts	5: Parallel Sorting	6: Parallelism in Prog. Languages	7: Patternlets	8: GPU programming	9: Heterogeneous Computing	10: Distributed Comp. Fundamentals	11: Pi Calculus	12: Drug design	13: Pi/numerical integration	14: Advanced Map-Reduce Intro/WMR
AL	Basic Analysis					x									
	Algorithmic Strategies					x									
	Fund. DS & Alg.														
	Basic Autom. & Comp.														
AR	Digital Logic		x		x				x						
	Machine-level rep. of data	x													x
	Assembly level mach. org.														
	Memory org. and arch.								x						
	Interfacing and comm.														
CN	Fundamentals												x	x	
DS	Sets, Relations, & Functions														
	Basic Logic											x			
	Proof Techniques											x			
	Basics of Counting														
	Graphs & Trees														
	Discrete Probability														

		1: Map-reduce for CS1/WMR	2: Multicore Programming	3: Concurrent Data Structures	4: Parallel Computing Concepts	5: Parallel Sorting	6: Parallelism in Prog. Languages	7: Patternlets	8: GPU programming	9: Heterogeneous Computing	10: Distributed Comp. Fundamentals	11: Pi Calculus	12: Drug design	13: Pi/numerical integration	14: Advanced Map-Reduce Intro/WMR
IM	Info. Management Concepts	x													x
	Database Systems														
	Data Modeling														
OS	Overview of OS														
	Operating Systems Principles														
	Concurrency														
	Scheduling and Dispatch	x	x	x	x										
	Memory Management	x													
	Security and Protection														
PD	Parallelism Fundamentals	x	x	x	x	x	x	x	x	x	x	x	x	x	
	Parallel Decomposition	x	x	x		x			x	x	x	x	x	x	
	Comm. & Coord.	x	x	x				x	x	x	x		x	x	
	Parallel Algorithms	x	x	x	x		x						x	x	x
	Parallel Architecture														x
SDF	Algorithms and Design			x			x	x					x	x	
	Fund. Prog. Concepts	x	x											x	
	Fund. DS	x		x									x	x	
	Development Methods			x									x		

		1: Map-reduce for CS1/WMR	2: Multicore Programming	3: Concurrent Data Structures	4: Parallel Computing Concepts	5: Parallel Sorting	6: Parallelism in Prog. Languages	7: Patternlets	8: GPU programming	9: Heterogeneous Computing	10: Distributed Comp. Fundamentals	11: Pi Calculus	12: Drug design	13: Pi/numerical integration	14: Advanced Map-Reduce Intro/WMR
SE	Software Processes	x	x	x			x	x	x	x	x		x	x	x
	Software Project Manage.														
	Tools and Environments														
	Requirements Engineering														
	Software Design	x	x	x			x	x	x	x	x		x	x	x
	Software Construction	x	x	x		x	x	x	x	x	x		x	x	x
	Software Verif. & Valid.														
	Software Evolution														
	Software Reliability														
SF	Computational Paradigms	x	x	x	x	x		x	x				x	x	x
	Cross-Layer Communications	x	x				x								
	State and State Machines		x									x			
	Parallelism		x	x		x		x	x	x	x		x	x	x
	Evaluation		x		x				x				x	x	
	Resource Alloc. & Sched.	x	x	x									x		x
	Proximity	x							x	x					x
	Virtualization & Isolation														
	Reliab. through Redundancy														x
SP	Social Context	x	x	x	x				x	x			x		x
	Analytical Tools														
	Professional Ethics														
	Intellectual Property														
	Privacy & Civil Liberties														
	Prof. Communication														
	Sustainability														

CS453: Introduction to Compilers, Colorado State University

Fort Collins, CO
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	38
Software Engineering (SE)	8
Algorithms and Complexity (AL)	4

Where does the course fit in your curriculum?

This course is an elective for senior undergraduates and first year graduate students offered once a year in the spring semester. Typically about 20-25 students take this course. The prerequisite for this course is a required third year Software Development Methods course.

What is covered in the course?

CS 453 teaches students how to implement compilers. Although most computer science professionals do not end up implementing a full compiler, alumni of this course are surprised by how often the skills they learn are used within industry and academic settings. The subject of compilers ties together many concepts in computer science: the theoretical concepts of regular expressions and context free grammars; the systems concept of layers including programming languages, compilers, system calls, assembly language, and architecture; the embedded systems concept of an architecture with restricted resources; and the software engineering concepts of revision control, debugging, testing, and the visitor design pattern. Students write a compiler for a subset of Java called MeggyJava. We compile MeggyJava to the assembly language for the ATmega328p microcontroller in the Meggy Jr RGB devices.

Course topics:

- Regular and context free languages including DFAs and NFAs.
- Scanning and parsing
  - Finite state machines and push down automata
  - FIRST and FOLLOW sets
  - Top-down predictive parsing
  - LR parse table generation
- Meggy Jr Simple runtime library
- AVR assembly code including the stack and heap memory model
- Abstract syntax trees
- Visitor design pattern
- Semantic analysis including type checking
- Code generation for method calls and objects
- Data-flow analysis usage in register allocation
- Iterative compiler design and development
- Test-driven development and regression testing
- Revision control and pair programming

What is the format of the course?

Colorado State University uses a semester system: this course is 15 weeks long with 2 one and a half hour of lectures per week and 1 weekly recitation section (4 total contact hours / week, for approximately 60 total hours not counting the final exam). There is a 16th week for final exams. In the past this course has been only on campus, but starting in Spring 2013 we are providing it as a blended on campus and online course.

How are students assessed?

There are 7 programming assignments and 4 written homeworks, which together constitute 50% of the course grade. The programming assignments lead the students through the iterative development of a compiler written in Java that translates a subset of Java to AVR assembly code. The AVR assembly code is then assembled and linked with the avr-gcc tool chain to run on Meggy Jr game devices. The process is iterative in that the first programming assignment that starts building the compiler results in a compiler that can generate the AVR code for the setPixel() call; therefore students can write MeggyJava programs that draw 8x8 pictures on their devices. Later assignments incrementally add features to the MeggyJava language and data structures such as abstract syntax trees to the compiler. We also have a simulator available at http://code.google.com/p/mjsim/ to enable debugging of the generated AVR code and for grading purposes. Students start doing their programming assignments individually, but are then encouraged to work as programming pairs. We expect students to spend approximately 8-12 hours each week outside of the classroom on the course.

Course textbooks and materials

Lecture notes written by the instructor and materials available online largely replace a textbook, though for additional resources, we recommend *Modern Compiler Implementation in Java* (Second Edition) by Andrew Appel, Cambridge, 2002. Additionally we provide the students with a link and reading assignments for a free online book *Basics in Compiler Design* by Torben Mogensen. The lecture notes are available at the webpage provided above.

Why do you teach the course this way?

We view the compiler course as bringing together many theoretical and practical skills from previous courses and enabling the students to use these skills within the context of a full semester project. The key elements of this course are the approach to iterative compiler development, the emphasis on many software development tools such as debuggers, revision control, etc., and mapping a high level programming language, Java, to a popular assembly language for embedded systems. All of these elements are new editions to the compiler course in our department and have been incorporated into the course since 2007. In general the move to targeting an active assembly language AVR that operates on a game device Meggy Jr has been more popular with the students than the previous targets of C and then MIPS.

This course is an elective and students do consider it to be challenging. Many students discuss the compiler developed in this course with potential employers. Additionally graduates report that understanding how a language maps to assembly helps their debugging skills after starting positions in industry after their degree.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Automata Computability and Complexity	Finite state machines, regular expressions, and context free grammars	2
AL	Advanced Automata Computability and Complexity	NFAs, DFAs, their equivalence, and push-down automata.	2
PL	Event Driven and Reactive Programming	Programming the Meggy Jr game device.	3
PL	Program Representation	All	1

PL	Language Translation and Execution	All except tail calls, closures, and garbage collection	6
PL	Syntax Analysis	All	8
PL	Compiler Semantic Analysis	All	5
PL	Code Generation	All	6
PL	Runtime Systems	All	4
PL	Static Analysis	Data-flow analysis for register allocation	3
PL	Language Pragmatics	All except lazy versus eager	2
SE	Software Verification and Validation	Test-driven development and regression testing	4
SE	Software Design	Use of the visitor design pattern	2
SE	Software Processes	All Core 1 and Core 2 topics	2

Additional topics

- Iterative compiler development instead of the monolithic phase based approach (lexer, parser, type checker, code generator).
- Revision control

Other comments: None

Csc 453: Translators and Systems Software, The University of Arizona

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	35

Where does the course fit in your curriculum?
This course is an upper-division elective aimed at third-year and fourth-year students. It is one of a set of courses in the "Computer Systems" elective area, from which students are required to take (at least) one. Pre-requisites are: a third-year course in C and Unix; and a third-year course on data structures; a third-year survey course on programming languages is recommended but not required. Enrollment is typically around 40.

What is covered in the course?
This course covers the design and implementation of translator-oriented systems software, focusing specifically on compilers, with some time spent on related topics such as interpreters and linkers.

Course topics:

- Background. Compilers as translators. Other examples of translators: document-processing tools such as ps2pdf and latex2html; web browsers; graph-drawing tools such as dot; source-to-source translators such as f2c; etc.
- Lexical analysis. Regular expressions; finite-state automata and their implementation. Scanner-generators: flex.
- Parsing. Context-free grammars. Top-down and bottom-up parsing. SLR(1) parsers. Parser-generators: yacc, bison.
- Semantic analysis. Attributes, symbol tables, type checking.
- Run-time environments. Memory organization. Stack-based environments.
- Intermediate representations. Abstract syntax trees, three-address code. Code generation for various language constructs. Survey of machine-independent code optimization.
- Interpreters. Dispatch mechanisms: byte-code, direct-threading, indirect-threading. Expression evaluation: Registers vs. operand stack. Just-in-time compilers. Examples: JVM vs. Dalvik for Java; Spidermonkey for JavaScript; JIT compilation in the context of web browsers.
- Linking. The linking process, linkers and loaders. Dynamic linking.

What is the format of the course?
The University of Arizona uses a semester system. The course lasts 15 weeks and consists of 2.5 hours per week of face-to-face lectures together with a 50-minute discussion class (about 3.5 contact hours per week, for a total of about 52 hours not counting exams). The lectures focus on conceptual topics while the discussion section focuses on the specifics of the programming project.

How are students assessed?
The course has a large programming project (50% of the final score), one or two midterm exams (20%-25% of the final score), and an optional final exam (25%-30% of the final score).

The programming project involves writing a compiler for a significant subset of C. The front end is generated using flex and yacc/bison; the back end produces MIPS assembly code, which is executed on the SPIM simulator.

The project consists of a sequence of four programming assignments with each assignment builds on those before it:

1. html2txt or latex2html: a simple translator from a subset of HTML to ordinary text (html2txt) or from a subset of LaTeX to HTML (latex2html). Objective: learn how to use flex and yacc/bison.
2. Scanner and parser. Use flex and yacc/bison to generate a front-end for a subset of C.
3. Type-checking.
4. Code generation.

Each assignment is about 2-3 weeks long, with a week between assignments for students to fix bugs before the next assignment. Students are expected to work individually, and typically spend about 15-20 hours per week on the project.

Course textbooks and materials

Lecture notes written by the instructor largely replace a textbook. The *book* Introduction to Compiler Design, by T. Mogensen, is suggested as an optional text (a free version is available online as Basics of Compiler Design).

Why do you teach the course this way?

The class lectures have the dual purpose of focusing on compiler-specific topics in depth but also discussing the variety and scope of these translation problems and presenting compilation as an instance of a broader class of translation problems. Translation problems mapping one kind of structured representation to another arise in a lot of areas of computing: compilers are one example of this, but there are many others, including web browsers (Firefox, Chromium), graph drawing tools (dot, VCG), and document formatting tools (LaTeX), to name a few. Understanding the underlying similarities between such tools can be helpful to students in recognizing other examples of such translation problems and providing guidance on how their design and implementation might be approached. It also has the effect of making compiler design concepts relevant to other aspects of their computer science education. I find it helpful to revisit the conceptual analogies between compilers and other translation tools (see above) repeatedly through the course, as different compiler topics are introduced.

The programming project is aimed at giving students a thorough hands-on understanding of the nitty-gritty details of implementing a compiler for a simple language.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Program Representation	All	4
PL	Language Translation and Execution	All	5
PL	Syntax Analysis	All	8
PL	Compiler Semantic Analysis	All	8
PL	Code Generation	All	5
PL	Runtime Systems	The following topics are covered: Target-platform characteristics such as registers, instructions, bytecodes; Data layout for activation records; Just-in-time compilation.	5

Additional topics

- Structure and content of object files
- static vs. dynamic linking
- Position-independent code
- Dynamic linking

CSCI 434T: Compiler Design, Williams College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	33
Architecture and Organization (AR)	3
Software Engineering (SE)	2

Where does the course fit in your curriculum?

Compiler Design is a senior-level course designed for advanced undergraduates who have already taken courses on computer organization, algorithms, and theory of computation. It is an elective for the Computer Science major.

What is covered in the course?

Specific topics covered in this course include:

- Overview of compilation
- Lexical analysis
- Context-free grammars, top-down and bottom-up parsing, error recovery
- Abstract syntax trees, symbol tables
- Lexical scoping, types (primitive, record, arrays, references), type checking
- Object-oriented type systems, subtyping, interfaces, traits
- Three-address code and other intermediate representations
- Code generation, data representation, memory management, object layout
- Code transformation and optimization
- Class hierarchy analysis
- Dataflow analysis
- Register allocation
- Run-time systems, just-in-time compilation, garbage collection

What is the format of the course?

This course is offered as a tutorial, and there are no lectures. Students meet with the instructor in pairs each week for 1-2 hours to discuss the readings and problem set questions. In addition, students work in teams of two or three on a semester-long project to build a compiler for a Java-like language. The target is IA-64 assembly code. Students submit weekly project checkpoints that follow the topics discussed in the tutorial meetings. The last three weeks are spent implementing a compiler extension of their own design. The students also attend a weekly 2-hour lab in which general project issues and ideas are discussed among all the groups.

The project assignment, and some of the related problem set material, is based on a project developed by Radu Rugina and others at Cornell University.

Given the nature of tutorials, it can be difficult to quantify the number of hours spent on a topic. Below, I base the hours dedicated to each unit by assuming roughly 3 hours of contact time with the students during each week of the 12-week semester.

How are students assessed?

Students are assessed via the preparedness and contributions to the weekly discussions, by their written solutions to problem set questions, and by the quality and correctness of their compiler implementations. Students also give presentations on their final projects to the entire class.

Course textbooks and materials

The primary textbook is *Compilers: Principles, Techniques, and Tools* by Aho, Lam, Sethi, and Ullman. Papers from the primary literature are also included when possible. Supplementary material for background reading and for the project is provided on a website.

Why do you teach the course this way?

The tutorial format offers a unique opportunity to tailor material specifically to student interest, and to allow them to explore and learn material on their own. The interactions between tutorial partners in the weekly meetings develops communication skills and thought processes that cannot be as easily fostered in lecture-style courses. The group projects also enable students to develop solid software engineering practices and to appreciate the theoretical foundations of each phase of compilation.

The students all enjoy the tutorial-style and collaborative environment it fosters, and they typically rate this class among the most challenging offered at Williams.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Basic Type Systems	All (mostly review of existing knowledge)	2
PL	Program Representation	All	2
PL	Language Translation and Execution	All	3
PL	Syntax Analysis	All	5
PL	Compiler Semantic Analysis	All	5
PL	Code Generation	All	5
PL	Runtime Systems	All	5
PL	Static Analysis	Relevant program representations, such as basic blocks, control-flow graphs, def-use chains, static single assignment, etc. Undecidability and consequences for program analysis Flow-insensitive analyses: type-checking Flow-sensitive analyses: forward and backward dataflow analyses Tools and frameworks for defining analyses Role of static analysis in program optimization Role of static analysis in (partial) verification and bug-finding	6
SE	Software Design	System design principles Refactoring designs and the use of design patterns.	2

AR	Machine-level representation of data	Bits, bytes, and words Representation of records and arrays (This is mostly review, in the context of IA-64)	1
AR	Assembly level machine organization	Assembly/machine language programming Addressing modes Subroutine call and return mechanisms Heap vs. Static vs. Stack vs. Code segments (This is mostly review, in the context of IA-64)	2

Compilers, Stanford University

Stanford, CA
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Stanford URL of recent offering: http://class2go.stanford.edu/CS143/Spring2013
Coursera self-study course: https://class.coursera.org/compilers-selfservice/class/index

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	22.5

Where does the course fit in your curriculum?
This course is aimed at students in the 2nd or 3rd year of the Computer Science (CS) major, after both our introductory theory and introductory systems classes have been taken. Stanford has a track system for undergraduates to specialize in subareas of CS. Compilers is not required for any track but is one of the options for the systems track and most students in the systems track take the class.

What is covered in the course?
The course covers the design, definition and implementation of programming languages. Students who have been through the class will be able to specify and implement language syntax using regular expressions or context free grammars as appropriate. Students will understand the distinction between no typing, static typing and dynamic typing and be able to implement simple static type systems as well as perform standard syntax analysis for scoping of global, local, and class-visible names. Students will understand the difference between compile time and run time and be able to reason about and make decisions about what should be done at which time. Students will also be introduced to formal semantics as a form of specification of the behavior of a programming language and be able to use formal semantics in the construction of a compiler. Run-time structures such as the stack, activation records and static data such as string constants and dispatch tables are covered. All of the topics up to this point will also be used as part of a large course project to build a simple compiler for a statically typed object oriented language. Additional topics include register allocation, garbage collection, dataflow analysis, and optimization.

What is the format of the course?
Stanford is on the quarter system; each quarter is 10 weeks. The class meets for lecture 19 times for 75 minutes each for a total of 22.5 hours (2.5 contact hours per week). There are extensive office hours in lieu of a discussion or recitation section.

How are students assessed?
Students have 4 written assignments on the theory (one each on lexical analysis, parsing, type checking and runtime organization, and code generation and associated topics such as register allocation and garbage collection). There is also a course project where students implement a compiler for a statically typed object oriented language. I use the COOL compiler project, which allows students to implement the compiler in either Java or C++. Finally there are two exams, a midterm and a final. The written assignments are about 10% of the grade, the project 50%, and the exams 40%.

Course textbooks and materials
I do not teach from a textbook, but instead provide extensive lecture notes and videos and recommend one of several books as a reference if the students wish to learn more.

Why do you teach the course this way?
I teach the course to try to emphasize the combination of theory and systems knowledge needed to design and implement a programming language well. Theory concepts are used directly in the project (e.g., the specification the students are given for the code generation phase is a formal operational semantics of the language). This is considered a challenging class, but one in which students learn a great deal. The compiler project is also often the biggest system that students have built, so there is some emphasis on helping students learn how to think about and organize a large software project.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Object-Oriented Programming	These topics are covered in introductory courses from the programmer's perspective and the emphasis in this class is on implications for language design and implementation. Topics covered: Classes, fields, methods, constructors Subclasses, inheritance, method overriding Dynamic dispatch Subtyping, relationship between subtyping and inheritance Visibility of class members.	1.25
PL	Basic Type Systems	A type as a set of values with a set of operations. Primitive types, user-defined types. Association of types to program constructs. Type safety, static vs. dynamic typing. Parametric polymorphism is not covered in this course but is covered in a masters-level course on programming languages that a significant number of undergraduates take.	1.25
PL	Program Representation and Execution	Abstract syntax trees vs. concrete syntax. Alternative internal representations of programs, such as 3-address code.	1.25
PL	Language Translation and Execution	Interpreters vs. compilers, compiling to different levels of abstraction (intermediate code, assembly code). The distinction between compile-time and run-time actions. Run-time representations of objects and method tables. Run-time organization of memory and implementation of standard constructs (assignment, loops, if-then-else, method call). Automatic memory management, including mark-and-sweep, stop-and-copy, and reference counting; idea of reachable objects over-approximating the set of live objects. Manual memory management is not covered in this class, but is covered in our introductory sequence. The implementation of loops and recursion is covered, but tail-calls and their optimization are not covered.	2.5
PL	Syntax Analysis	Regular languages, deterministic and non-deterministic finite automata; these topics are covered quickly as review of earlier discrete math classes. Lexical analysis. Top down and bottom up parsing, including Recursive descent, LL, and SLR parsing. Semantic actions.	7.5
PL	Compiler Semantic Analysis	Abstract syntax trees, scope and binding, type checking, non-circular attribute grammars, both S- and L-attributed.	1.25

PL	Code Generation	Method dispatch, graph-coloring based register allocation, basic block and peephole optimizations. Rudimentary instruction selection is covered. In most years instruction scheduling is not covered; this is included in a masters-level course on advanced compilation.	1.25
PL	Runtime Systems	Garbage collection (3 kinds, mark-and-sweep, stop-and-copy, reference counting). Activation trees, activation records, elements of and organization of an activation record. Calling sequence (caller side and callee side).	1.25
PL	Static Analysis	Basic blocks, control-flow graphs. Static single assignment (simplified version covering basic blocks only). Dataflow analysis, including an example of forward analysis (constant propagation) and backwards analysis (liveness analysis). Emphasis on the idea that static analyses make global information local, computing facts at specific program points that can be used to make decisions about optimization opportunities and program correctness. The deeper theory of static analysis (limitations on decidability, may vs. must) is covered in a masters-level course on advanced compilation.	2.5
PL	Type Systems	Type checking. Formal type rules, type environments, formal definition of subtyping. Experience writing, reading, and reasoning about type rules. Aliasing and its effect on subtyping rules. Formal type system for the language being implemented in the course, which serves as a specification of the semantic analysis.	1.25
PL	Formal Semantics	Syntax vs. semantics. Operational semantics of the language being implemented in the course project, which serves as a specification of code generation phase. Lambda calculus and other styles of semantics are not covered in this course; these are included in a masters-level course on programming languages.	1.25
PL	Language Pragmatics	Principles of language design, many examples from real languages of good and questionable designs. Orthogonality. Evaluation order, precedence, associativity.	1.25

Additional topics

One lecture is usually devoted to a current research topic or applying the ideas in the course to analyze the design of mainstream language (e.g., Java).

Other comments

None.

Languages and Compilers, Utrecht University

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http://www.cs.uu.nl/wiki/bin/view/TC/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	22
Algorithms and Complexity (AL)	10

Where does the course fit in your curriculum?
This is a second year elective course in the Computer Science program of Utrecht University. It assumes students have taken courses on imperative and functional programming.

What is covered in the course?
The intended learning objectives of this course are:

- To describe structures (i.e., "formulas") using grammars;
- To parse, i.e., to recognize (build) such structures in (from) a sequence of symbols;
- To analyze grammars to see whether or not specific properties hold;
- To compose components such as parsers, analyzers, and code generators;
- To apply these techniques in the construction of all kinds of programs;
- To familiarize oneself with the concept of computability.

Topics:

- Context-free grammars and languages
- Concrete and abstract syntax
- Regular grammars, languages, and expressions
- Pumping lemmas
- Grammar transformations
- Parsing, parser design
- Parser combinators (top-down recursive descent parsing)
- LL parsing
- LR parsing
- Semantics: datatypes, (higher-order) folds and algebras

What is the format of the course?
This course consists of 16 2-hour lectures, and equally many lab sessions, in which students work on both pen-and-paper exercises and programming lab exercises, implementing parsers and components of compilers.

How are students assessed?
Students are assessed by means of a written test halfway (2 hours) and at the end of the course (3 hours), and by means of three programming assignments. Students should spend 32 hours on lectures, another 32 hours on attending lab sessions, 75 hours on reading lecture notes and other material, and 75 hours on the lab exercises.

Course textbooks and materials

We have developed our own set of lecture notes for the course. We use Haskell to explain all concepts in the course, and the students use Haskell to implement the programming assignments. The lecture notes for LR parsing have not been fully developed, and for this we use a chapter from a book from Roland Backhouse.

Why do you teach the course this way?

This course is part of a series of courses, following a course on functional programming, and followed by a course on compiler construction and a course on advanced functional programming. Together these courses deal with programming concepts, languages and implementations. All these courses use Haskell as the main programming language, but several other programming languages or paradigms are used in the examples. For example, in the third lab exercise of this course, the students have to write a small compiler for compiling the imperative core of C# to a stack machine.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Program representation	All	1
PL	Language Translation and Execution	Interpretation vs. compilation, language translation pipeline	2
PL	Syntax analysis	All	8
PL	Compiler Semantic Analysis	Abstract syntax trees, scope and binding resolution, declarative specifications	4
PL	Code Generation	Very introductory	1
PL	Language Pragmatics	Some language design	2
AL	Basic Automata Computability and Complexity	Finite-state machines, regular expressions, context-free grammars.	4
AL	Advanced Automata Theory and Computability	Regular and context-free languages. DFA, NFA, but not PDA. Chomsky hierarchy, pumping lemmas.	6
PL	Functional Programming	Defining higher-order operations	4

Many, but not all, of the topics of the Knowledge Units above not covered appear in our course on Compiler Construction.

COMP 412: Topics in Compiler Construction, Rice University

Houston, TX
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	21
Algorithms and Complexity (AL)	5

Where does the course fit in your curriculum?

COMP 412 is an optional course. It is typically taken by fourth-year undergraduate students and first-year graduate students in either the Professional Masters' degree program or the PhD program. Some advanced third year students also take the course.
Enrollment ranges from 40 to 70 students.

What is covered in the course?

Scanning, parsing, semantic elaboration, intermediate representation, implementation of the procedure as an abstraction, implementation of expressions, assignments, and control-flow constructs, brief overview of optimization, instruction selection, instruction scheduling, register allocation. (Full syllabus is posted on the website, listed above.)

What is the format of the course?

The course operates as a face-to-face lecture course, with three contact hours per week. The course includes three significant programming assignments (a local register allocator, an LL(1) parser generator, and a local instruction scheduler). The course relies on an online discussion forum (Piazza) to provide assistance on the programming assignments.

How are students assessed?

Students are assessed on their performance on three exams, spaced roughly five weeks apart, and on the code that they submit for the programming assignments. Exams count for 50% of the grade, with the other 50% derived from the programming assignments.

The programming assignments take students two to three weeks to complete.

Course textbooks and materials

The course uses the textbook *Engineering a Compiler* by Cooper and Torczon. (The textbook was written from the course.) Full lecture notes are available online (see course web site).
Students may use any programming language, except Perl, in their programming assignments. Assignments are evaluated based on a combination of the written report and examination of the code.

Why do you teach the course this way?

This course has evolved, in its topics, coverage, and programming exercises, over the last twenty years. Students generally consider the course to be challenging—both in terms of the number and breadth of the concepts presented and in terms of the issues raised in the programming assignments. We ask students to approximate the

solutions to truly hard problems, such as instruction scheduling; the problems are designed to have a high ratio of thought to programming.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Automata Computability and Complexity	Finite state machines, regular expressions, and context-free grammars	2
AL	Advanced Automata Theory and Computability	DFA & NFAs (Thompson's construction, the subset construction, Hopcroft's DFA minimization algorithm, Brzozowski's DFA minimization algorithm), regular expressions, context-free grammars (designing CFGs and parsing them — recursive descent, LL(1), and LR(1) techniques	3
PL	Program Representation	Syntax trees, abstract syntax trees, linear forms (3 address code), plus lexically scoped symbol tables	2
PL	Language Translation & Execution	Interpretation, compilation, representations of procedures, methods, and objects, memory layout (stack, heap, static), Automatic collection versus manual deallocation	4
PL	Syntax Analysis	Scanner construction Parsing: top-down recursive descent parsers, LL(1) parsers and parser generators, LR(1) parsers and parser generators	6
PL	Compiler Semantic Analysis	Construction of intermediate representations, simple type checking, lexical scoping, binding, name resolutions; attribute grammar terms, evaluation techniques, and strengths and weaknesses	3
PL	Code Generation	How to implement specific programming language constructs, as well as algorithms for instruction selection (both tree pattern matching and peephole-based schemes), Instruction scheduling, register allocation	6

Other comments

The undergraduate compiler course provides an important opportunity to address three of the expected characteristics of Computer Science graduates:

Appreciation of the Interplay Between Theory and Practice: The automation of scanners and parsers is one of the best examples of theory put into practical application. Ideas developed in the 1960s became commonplace tools in the 1970s. The same basic ideas and tools are (still) in widespread use in the 2010's.

At the same time, compilers routinely compute and use approximate solutions to intractable problems, such as instruction scheduling and register allocation which are NP-complete in almost any realistic formulation, or constant propagation which runs into computability issues in its more general forms. In theory classes, students learn to discern the difference between the tractable and the intractable; in a good compiler class, they learn to approximate the solution to these problems and to use the results of such approximations.

System-level Perspective: The compiler course enhances the students' understanding of systems in two quite different ways. As part of learning to implement procedure calls, students come to understand how an agreement on system-wide linkage conventions creates the necessary conditions for interoperability between application code and system code and for code written in different languages and compiled with different compilers. In many ways,

separate compilation is the key feature that allows us to build large systems; the compiler course immerses students in the details of how compilation and linking work together to make large systems possible.

The second critical aspect of system design that the course exposes is the sometimes subtle relationship between events that occur at different times. For example, in a compiler, events occur at design time (we pick algorithms and strategies), at compiler build time (the parser generator constructs tables), at compile time (code is parsed, optimized, and new code is emitted), and runtime (activation records are created and destroyed, closures are built and executed, etc.). Experience shows that the distinction between these various times and the ways in which activities occurring at one time either enable or complicate activities at another time is one of the most difficult concepts in the course to convey.

Project experience: In this particular course, the project s are distinguished by their intellectual complexity rather than their implementation complexity. Other courses in our curriculum provide the students with experience in large-scale implementation and project management. In this course, the focus is on courses with a high ratio of thought time to coding time. In particular, the students solve abstracted versions of difficult problems: they write a register allocator for straight-line code; they build a program that parses grammars written in a modified Backus-Naur Form and generates LL(1) parse tables; and they write an instruction scheduler for straight-line code. Students work in their choice of programming language. They typically reuse significant amount of code between the labs.

CSC 131: Principles of Programming Languages, Pomona College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	38
Parallel and Distributed Computing (PD)	4

Where does the course fit in your curriculum?
This course is generally taken by juniors and seniors, and has a prerequisite of Data Structures (CSC 062) and Computability and Logic (CSC 081). It is required for all CS majors.

What is covered in the course?
A thorough examination of issues and features in programming language design and implementation, including language-provided data structuring and data-typing, modularity, scoping, inheritance, and concurrency. Compilation and run-time issues. Introduction to formal semantics. Specific topics include:

- Overview of compilers and Interpreters (including lexing & parsing)
- Lambda calculus
- Functional languages (via Haskell)
- Formal semantics (mainly operational semantics)
- Writing interpreters based on formal semantics
- Static and dynamic type-checking
- Run-time memory management
- Data abstraction & modules
- Object-oriented languages (illustrated via Java and Scala)
- Shared memory parallelism/concurrency (semaphores, monitors, locks, etc.)
- Distributed parallelism/concurrency via message-passing (Concurrent ML, Scala Actors)

What is the format of the course?
The course meets face-to-face in lecture format for 3 hours per week for 14 weeks.

How are students assessed?
There are weekly homework assignments as well as take-home midterm and final exams. Students are expected to spend 6 to 8 hours per week outside of class on course material. Problem sets include both paper-and-pencil as well as programming tasks.

Course textbooks and materials
The course text is "Concepts in Programming Languages", by John Mitchell, supplemented by various readings. Lecture notes are posted, as are links to supplementary material on languages and relevant topics.

Why do you teach the course this way?
This course combines two ways of teaching a programming languages course. On the one hand it provides an overview of the design space of programming languages, focusing on features and evaluating them in terms of how they impact programmers. On the other hand, there is an important stream focusing on the implementation of

programming languages. A major theme of this part of the course is seeing how formal specifications of a language (grammar, type-checking rules, and formal semantics) lead to an implementation of an interpreter for the language. Thus the grammar leads to a recursive descent compiler, type-checking rules lead to the implementation of a type-checker, and the formal semantics leads to the interpretation of abstract syntax trees.

The two weeks on parallelism/concurrency support in programming languages reflects my belief that students need to understand how these features work and the variety of ways of supporting parallelism concurrency – especially as we don't know what approach will be the most successful in the future.

From the syllabus: "Every student passing this course should be able to:

- Quickly learn programming languages and how to apply them to effectively solve programming problems.
- Rigorously specify, analyze, and reason about the behavior of a software system using a formally defined model of the system's behavior.
- Realize a precisely specified model by correctly implementing it as a program, set of program components, or a programming language."

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Object-Oriented Programming	All (with assumed knowledge of OOP from CS1 and CS2 in Java)	5
PL	Functional Programming	All (building on material from earlier course covering functional programming in ML)	5
PL	Event-Driven & Reactive Programming	Previously covered in CS 1 & CS 2	0
PL	Basic Type Systems	All	5
PL	Program Representation	All	2
PL	Language Translation and Execution	All	3
PL	Syntax Analysis	Lexing & top-down parsing (regular expressions and cfg's covered in prerequisite)	2
PL	Compiler Semantic Analysis	AST's, scope, type-checking & type inference	1
PL	Advanced Programming Constructs	Lazy evaluation & infinite streams Control abstractions: Exception Handling, continuations, monads OO abstraction: multiple inheritance, mixins, Traits, multimethods Module systems Language support for checking assertions, invariants, and pre-post-conditions	3
PL	Concurrency and Parallelism	Constructs for thread-shared variables and shared-memory synchronization Actor models Language support for data parallelism	2

PL	Type Systems	Compositional type constructors Type checking Type inference Static overloading	2
PL	Formal Semantics	Syntax vs. semantics Lambda Calculus Approaches to semantics: Operational, Denotational, Axiomatic Formal definitions for type systems	6
PL	Language Pragmatics	Principles of language design such as orthogonality Evaluation order Eager vs. delayed evaluation	2
PD	Parallelism Fundamentals	Multiple simultaneous computations Goals of parallelism vs. concurrency Programming constructs for creating parallelism, communicating, and coordinating Programming errors not found in sequential programming	2
PD	Parallel Decomposition	Need for Communication & Coordination Task-based decomposition: threads Data-parallel decomposition: SIMD, MapReduce, Actors	1
PD	Communication & Coordination	Shared memory Consistency in shared memory Message passing Atomicity: semaphores & monitors Synchronization	1

CSCI 1730: Introduction to Programming Languages, Brown University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	35

Where does the course fit in your curriculum?

The course is designed for third- and fourth-year undergraduates and for PhD students who are either early in their study or outside this research area. Over the years I have shrunk the prerequisites, so it requires only the first year introductory computer science sequence, discrete math, and some theory. The course is not required. However, it consistently has one of the highest enrollments in the department.

What is covered in the course?

The course uses definitional interpreters and related techniques to teach the core of several programming languages.

The course begins with a quick tour of writing definitional interpreters by covering substitution, environments, and higher-order functions. The course then dives into several topics in depth:

- Mutation
- Recursion and cycles
- Objects
- Memory management
- Control operators
- Types
- Contracts
- Alternate evaluation models

What is the format of the course?

Classroom time is a combination of lecture and discussion. We learn by exploration of mistakes.

How are students assessed?

There are about ten programming assignments and three written homeworks. The written ones are open-ended and ask students to explore design alternatives. Advanced students are given a small number of classic papers to read. Students spend over 10 and up to 20 hours per week on the course.

Course textbooks and materials

The course uses *Programming Languages: Application and Interpretation* by Shriram Krishnamurthi. All programming is done in variations of the Racket programming language using the DrRacket programming environment. Some versions of the course task students with writing programs in a variety of other languages such as Haskell and Prolog.

Why do you teach the course this way?

My primary goal in the design of this course is to teach "the other 90%": the population of students who will not go on to become programming language researchers. My goal is to infect them with linguistic thinking: to understand that by embodying properties and invariants in their design, languages can solve problems.

Furthermore, most of them, as working developers, will inevitably build languages of their own; I warn them about classic design mistakes and hope they will learn enough to not make ones of their own.
The course is revised with virtually every offering. Each time we pick one module and try to innovate in the presentation or learning materials.

Independent student feedback suggests the course is one of the most challenging in the department. Nevertheless, it does not prevent high enrollments, since students seem to appreciate the linguistic mindset it engenders.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Object-Oriented Programming	Object representations and encodings, types	3
PL	Functional Programming	All	3
PL	Basic Type Systems	All	9
PL	Language Translation and Execution	Interpretation, representations	3
PL	Runtime Systems	Value layout, garbage collection, manual memory management	3
PL	Advanced Programming Constructs	Almost all (varies by year)	6
PL	Type Systems	All	3
PL	Language Pragmatics	Almost all (varies by year)	3
PL	Logic Programming	Relationship to unification and continuations	2

CSC 2/454: Programming Language Design and Implementation, University of Rochester

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	35

Where does the course fit in your curriculum?
CSC 254 is required of all BS candidates in Computer Science. It is most often taken in the junior year, but sometimes the sophomore or senior. The CS1–CS2 sequence (locally CSC 171–172) is a prerequisite, as is a local course (CSC 173) that covers (among other things) finite and pushdown automata, regular expressions, and recursive descent parsing. The course can be taken for graduate credit (as CSC 454) by first-year MS and PhD students who lack comparable undergraduate background. The course is offered once a year—recently to approximately 40 students.

What is covered in the course?
CSC 2/454 is an introduction to the design and implementation of programming languages. From the design point of view, it covers language features as tools for expressing algorithms. From the implementation point of view, it covers compilers, interpreters, and virtual machines as tools to map those features efficiently onto modern computer hardware. The course touches on a wide variety of languages, both past and present, with an emphasis on modern imperative languages, such as C++ and Java, and, to a lesser extent, on functional languages such as Scheme and Haskell, and dynamic (scripting) languages such as Perl, Python, and Ruby. Rather than dwell on the features of any particular language, it focus on fundamental concepts and on the differences among languages, the reasons for those differences, and the implications those differences have for language implementation.
Specific topics include:

- formal aspects of syntax and semantics
- naming, scoping, and binding
- scanning, parsing, semantic analysis, and code generation
- control flow, subroutines, exception handling, and concurrency
- type systems, data abstraction mechanisms, and polymorphism
- run-time systems, virtual machines, and storage management
- imperative, functional, logic-based, and object-oriented programming paradigms
- programming environments and tools

What is the format of the course?
254 has historically been taught in a fairly traditional formal, with two 75-minute lectures per week. The instructor usually works at the blackboard, however, rather than using prepared slides, and the lectures are highly interactive: student feedback determines the pace and, to a significant extent, the topics that are covered. We are considering the introduction of peer-led team learning "workshops," which have been used with great success in the department's intro-level courses.

How are students assessed?

There are typically six major programming projects, most of which attempt to combine experience with a particular programming paradigm or mechanism (e.g., concurrency, templates, first-class functions, or glue-style scripting) with a language implementation issue (e.g., syntax error handling, semantic analysis, interpretation, or symbol table management).

The first project of the semester asks students to solve a simple combinatorial problem in 5 or 6 different (often unfamiliar to them) languages—e.g., Ada, C#, Haskell, Prolog, and Python.

Each project is expected to take perhaps 10 hours of time, spread over a two-week period. To encourage students to begin thinking about projects as soon as they are assigned, most require a set of simple familiarization questions to be answered (in writing) within the first three days. For the programming itself, students can elect to work alone or in pairs (with no difference in grading).

There is typically a midterm and a final exam. Projects count for approximately half of the course grade, exams for the other half. In some semesters, students have been asked to turn in written answers to the routine review questions in the text, to encourage them to keep up with the reading.

Course textbooks and materials

As text, the course uses the instructor's *Programming Language Pragmatics* (third edition, Morgan Kaufmann, 2009). Reading assignments cover most of chapters 1–4 and 6–10, and about half each of chapters 12–15. Major assignments are typically given in C++ (for templates); Java (for concurrency); Scheme or Haskell; and Perl, Python, or Ruby. Students are provided with access to Linux machines, though many opt to do most of the work on personal Windows or Macintosh machines, and then port it to the Linux environment (where grading occurs).

Why do you teach the course this way?

Like many schools, Rochester once had a "survey of programming languages" course and a separate compiler course. The current course reflects the conviction that language design and language implementation must be studied together, because neither can be fully understood without the other. We have separate, follow-on courses in static and dynamic program analysis, and in language-level tools and software development. The goal is to not to train students to be experts in the use of any particular language, but rather to give them the ability to pick up new languages quickly, to choose wisely among them in various circumstances, and to appreciate what may be going on "under the hood."

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Object-Oriented Programming	All	2
PL	Functional Programming	All	2.5
PL	Basic Type Systems	All	2.5
PL	Program Representation	All	2.5
PL	Language Translation and Execution	All	5
PL	Syntax Analysis	Regular expressions and scanning; context-free grammars; top-down vs. bottom-up parsing; recursive descent & table-driven top-down parsing; syntax error recovery	3.5
PL	Compiler Semantic Analysis	All	4

PL	Runtime Systems	Data layout; storage management; garbage collection; static and dynamic linking; language virtual machines	2.5
PL	Advanced Programming Constructs	Lazy evaluation; exception handling & signals; mixin inheritance; reflection; module systems; string manipulation via pattern matching	4
PL	Concurrency and Parallelism	Thread creation and management; task pools; data races; shared-memory synchronization (language constructs, implementation)	4
PL	Type Systems	Compositional type constructors; type checking and inference; overloading; polymorphism	1
PL	Language Pragmatics	Orthogonality; evaluation order, precedence, associativity; eager vs. delayed evaluation; iterators	1.5

Additional topics: none

Other comments

- Event-driven and Reactive Programming is covered in CSC 210 (Web Programming) and CSC 212 (Human-Computer Interaction).
- Code Generation and Static Analysis are covered in CSC 2/455 (Software Analysis and Improvement).
- Formal Semantics and Logic Programming are covered to a limited degree in CSC 173 (Computation and Formal Systems)

CSE341: Programming Languages, University of Washington

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	32

Where does the course fit in your curriculum?
This course is aimed at second- and third-year students (after CS1 and CS2 but before advanced elective courses). It is no longer required, but it is recommended and the vast majority of students choose to take it.

A version of this course has also been taught as a MOOC on Coursera, first offered in January-March 2013.

What is covered in the course?
Successful course participants will:

- Internalize an accurate understanding of what functional and object-oriented programs mean
- Develop the skills necessary to learn new programming languages quickly
- Master specific language concepts such that they can recognize them in strange guises
- Learn to evaluate the power and elegance of programming languages and their constructs
- Attain reasonable proficiency in the ML, Racket, and Ruby languages and, as a by-product, become more proficient in languages they already know

Course topics:

- Syntax vs. semantics
- Basic ML programming: Pairs, lists, datatypes and pattern-matching, recursion
- Higher-order functions: Lexical scope, function closures, programming idioms
- Benefits of side-effect free programming
- Type inference
- Modules and abstract types
- Parametric polymorphism
- Subtyping
- Dynamically typed functional programming
- Static vs. dynamic typing
- Lazy evaluation: thunks, streams, memoization
- Implementing an interpreter
- Implementing function closures
- Dynamically typed object-oriented programming
- Inheritance and overriding
- Multiple inheritance vs. interfaces vs. mixins
- Object-oriented decomposition vs. procedural/functional decomposition

… a few more minor topics in the same basic space

What is the format of the course?
The University of Washington uses a quarter system: courses are 10 weeks long with 3 weekly lectures and 1 weekly recitation section (4 total contact hours / week, for approximately 36 total not counting exams).

How are students assessed?
Over 10 weeks, there are 7 programming assignments, 3 in Standard ML, 2 in Racket, and 2 in Ruby, each done individually. There is a midterm and a final -- all homeworks and exams are available at the URL above. A majority of students report spending 8-13 hours / week on the course.

Course Textbooks and Materials
Lecture notes (and/or mp4 videos) written by the instructor largely replace a textbook, though for additional resources, we recommend *Elements of ML Programming* by Ullman, the *Racket User's Guide* (available online), and *Programming with Ruby* by Thomas. The lecture notes and videos are available.

Why do you teach the course this way?
This course introduces students to many core programming-language topics and disabuses them of the notion that programming must look like Java, C, or Python. The emphasis on avoiding mutable variables and leveraging the elegance of higher-order functions is particularly important. By not serving as an introductory course, we can rely on students' knowledge of basic programming (conditionals, loops, arrays, objects, recursion, linked structures). Conversely, this is not an advanced course: the focus is on programming and precise definitions, but not theory, and we do not rely on much familiarity with data structures, algorithmic complexity, etc. Finally, we use three real programming languages to get students familiar with seeing similar ideas in various forms. Using more than three languages would require too much treatment of surface-level issues. Using fewer languages would probably be fine, but ML, Racket, and Ruby each serve their purposes very well. Moving the ML portion to OCaml or F# would work without problem. Haskell may also be tempting but the course materials very much assume eager evaluation.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Object-Oriented Programming	All, with some topics re-enforced from CS1/CS2 (hour count is for just this course)	4
PL	Functional Programming	All	10
PL	Basic Type Systems	All	5
PL	Program Representation	All	2
PL	Language Translation and Execution	Only these topics are covered: interpretation vs. compilation, run-time representation of objects and first-class functions, implementation of recursion and tail calls. The other topics are covered in another required course.	2
PL	Advanced Programming Constructs	Only these topics are covered: Lazy evaluation and infinite streams, multiple inheritance, mixins, multimethods, macros, module systems, "eval". Exception handling and invariants, pre/post-conditions are covered in another required course.	6
PL	Type Systems	Only these topics are covered (and at only a very cursory level): Type inference, Static overloading	2
PL	Language Pragmatics	Only this topic is covered: Eager vs. delayed evaluation	1

Additional topics: Pattern-matching over algebraic data types

CSCI 334: Principles of Programming Languages, Williams College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	31
Parallel and Distributed Computing (PD)	5
Information Assurance and Security (IAS)	1

Where does the course fit in your curriculum?

This course is designed for any students who have successfully completed CS1 and CS2. It is required for the Computer Science major.

What is covered in the course?

Specific topics covered in this course include:

- Functional programming concepts in Lisp
- Syntax, semantics, and evaluation strategies
- ML programming, including basic types, datatypes, pattern matching, recursion, and higher order functions
- Types, dynamic/static type checking, type inference, parametric polymorphism
- Run-time implementations: stacks, heaps, closures, garbage collection
- Exception handlers
- Abstract types and modularity
- Object-oriented programming and systems design
- Object-oriented language features: objects, dynamic dispatch, inheritance, subtyping, etc.
- Multiple inheritance vs. interfaces vs. traits
- Scala programming, including most basic language features.
- Language-based security mechanisms and sandboxing
- Models of concurrency: shared memory and actors

What is the format of the course?

Semesters are twelve weeks long. This course meets twice per week for 75 minutes, with most of that time being spent as a lecture, discussing primary literature, or working on interactive programming tasks. (Total lecture hours: 30)

How are students assessed?

Students are assessed via weekly problem sets, a midterm, and a final. The problem sets include pencil-and-paper exercises, as well as programming problems in various languages.

Course textbooks and materials

The primary textbook is “Concepts in Programming Languages”, by John Mitchell. This is augmented with PowerPoint slides and web-based materials on additional topics, as well as some primary literature on the design goals and histories of various programming languages.

Why do you teach the course this way?

This course presents a comprehensive introduction to the principle features and overall design of programming languages. The material should enable successful students to

- recognize how a language's underlying computation model can impact how one writes programs in that language;
- quickly learn new programming languages, and how to apply them to effectively solve programming problems;
- understand how programming language features are implemented;
- reason about the tradeoffs among different languages; and
- use a variety of programming languages with some proficiency. These currently include Lisp, ML, Java, C++, and Scala.

It is also designed to force students to think about expressing algorithms in programming languages beyond C, Java and similar languages, since those are the languages most students have been previously exposed to in our CS1, CS2, and systems courses.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
PL	Object-Oriented Programming	All (with assumed knowledge of OOP from CS1 and CS2 in Java)	4
PL	Functional Programming	All	6
PL	Basic Type Systems	All	5
PL	Program Representation	All	1
PL	Language Translation and Execution	All	3
PL	Advanced Programming Constructs	Lazy evaluation Exception Handling Multiple inheritance, Mixins, Traits Dynamic code evaluation ("eval")	3
PL	Concurrency and Parallelism	Constructs for thread-shared variables and shared-memory synchronization Actor models Language support for data parallelism	3
PL	Type Systems	Type inference Static overloading	2
PL	Formal Semantics	Syntax vs. semantics Lambda Calculus	2

PL	Language Pragmatics	Principles of language design such as orthogonality Evaluation order Eager vs. delayed evaluation	2
IAS	Secure Software Design and Engineering	Secure Design Principles and Patterns (Saltzer and Schroeder, etc.) Secure Coding techniques to minimize vulnerabilities in code Secure Testing is the process of testing that security requirements are met (including Static and Dynamic analysis).	1
PD	Parallelism Fundamentals	All	2
PD	Parallel Decomposition	Need for communication and coordination/synchronization Task-base decomposition Data-parallel decomposition Actors	2
PD	Communication & Coordination	Shared Memory Message Passing Atomicity Mutual Exclusion	1

Programming Languages and Techniques I, University of Pennsylvania

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	24
Software Development Fundamentals (SDF)	13
Algorithms and Complexity (AL)	2
Discrete Structures (DS)	1
Human-Computer Interaction (HCI)	1

Where does the course fit in your curriculum?

Prerequisites: This is a second course though students with prior programming experience or an AP course often do not take the first course (CIS110, which covers fundamentals of computer programming in Java, with emphasis on applications in science and engineering).

Following courses: Discrete Math for CS students (CIS 160), Data structures (CIS 121), Intro to Computer Systems (CIS 240)

Requirements: The course is required for CIS and related majors, but optional for all other students. Enrollment is currently 160 students per term.

Student level: Most students are in their first or second year, but there are some non-CS exceptions

What is covered in the course?

- Programming Design and Testing
- Persistent Data Structures & Functional programming
- Trees & Recursion
- Mutable Data Structures (queues, arrays)
- First-class computation (objects, closures)
- Types, generics, subtyping
- Abstract types and encapsulation
- Functional, OO, and Event-driven programming

What is the format of the course?

Three 50-minute lectures per week + one 50 minute lab section (lead by undergraduate TAs)

How are students assessed?

Two midterm exams, plus a final exam

A large portion of the grade comes from 10 weekly-ish programming projects:
OCaml Finger Exercises
Computing Human Evolution
Modularity & Abstraction
n-Body Simulation
Mutable Collections
GUI implementation
Image Processing
Adventure Game
Spellcheck
Free-form Game

Course textbooks and materials

Programming languages: OCaml and Java (in Eclipse), each for about half the semester
Materials: Lecture slides and instructor-provided course notes (~370 pages)

Why do you teach the course this way?

The goal of CIS 120 is to introduce students (with some programming experience) to computer science by emphasizing *design* -- the process of turning informal specifications into running code. Students taking CIS120 learn how to design programs, including:

- test-driven development
- data types and data representation
- abstraction, interfaces, and modularity
- programming patterns (recursion, iteration, events, call-backs, collections, map-reduce, GUIs, ...)
- functional programming
- how and when to use mutable state
- inheritance and object-oriented programming

Beyond experience with program design, students who take the class should have increased independence of programming, a firm grasp of CS fundamental principles (recursion, abstraction, invariants, etc.), and fluency in core Java by the end of the semester.

The course was last revised Fall 2010 where we introduced OCaml into the first half of the semester.

The OCaml-then-Java approach has a number of benefits over a single-language course:

- It levels the playing field by presenting almost all the students with an unfamiliar language at the beginning.
- Since we use only a small part of OCaml, we can present enough about the language in a few minutes to dive directly into real programming problems in the very first class (instead of having to spend several class sessions at the beginning of the semester reviewing details of a larger language that will be familiar to many but not all of the students).
- OCaml itself is a functional programming language that encourages the use of immutable data structures; moreover its type system offers a rich vocabulary for describing different kinds of data.
- When we do come to reviewing aspects of Java in the second part of the course, the discussion is more interesting (than if we'd started with this at the beginning) because there is a point of comparison.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Fundamental Data Structures and Algorithms	Simple numerical algorithms Sequential and binary search algorithms Binary search trees Common operations on Binary Search Trees	2*
DS	Graphs and Trees	Trees	(with*)
HCI	Programming Interactive Systems	Model-view controller Event management and user interaction Widget classes and libraries	(with**)
PL	Object-Oriented Programming	All Core topics (Tier 1 and Tier 2)	7
PL	Functional Programming	All Core topics (Tier 1 and Tier 2)	7
PL	Event-Driven and Reactive Programming	All Core topics (Tier 1 and Tier 2)	4**
PL	Basic Type Systems	All Core topics except benefits of dynamic typing	3
PL	Language Translation and Execution	Run-time representation of core language constructs such as objects (method tables) and first-class functions (closures) Run-time layout of memory: call-stack, heap, static data	2
PL	Advanced Programming Constructs	Exception Handling	1
SDF	Algorithms and Design	The concept and properties of algorithms (informal comparison of algorithm efficiency) Iterative and Recursive traversal of data structure Fundamental design concepts and principles (abstraction, program decomposition, encapsulation and information hiding, separation of behavior and implementation)	3
SDF	Fundamental Programming Concepts	All Core topics (as a review)	1
SDF	Fundamental Data Structures	All Core topics except priority queues	5
SDF	Development Methods	All Core topics except secure coding and contracts	4

15-312 Principles of Programming Languages, Carnegie Mellon University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Programming Languages (PL)	20
Discrete Structures (DS)	12
Operating Systems (OS)	7
Parallel and Distributed Computing (PD)	5
Algorithms and Complexity (AL)	5

Where does the course fit in your curriculum?
This course fulfills a "Foundations Requirement" in the undergraduate curriculum, which may be met by taking one of three courses. Approximately 60 students take this course per year, typically in their second or third year. The core curriculum, consisting of 15-122 Imperative Programming, 15-150 Functional Programming, and 15-251 Ten Powerful Ideas in Theoretical Computer Science are pre-requisites for this course.

What is covered in the course?
This is a course on the theory of programming languages. Why study these principles? Because they are fundamental to the design, implementation, and application of programming languages.

Programming language design is often regarded as largely, or even entirely, a matter of opinion, with few, if any, organizing principles, and no generally accepted facts. Dozens of languages are in everyday use in research laboratories and in industry, each with its adherents and detractors. The relative merits of languages are debated endlessly, but always, it seems, with an inconclusive outcome. Some would even suggest that all languages are equivalent, the only difference being a matter of personal taste. Yet it is obvious that programming languages do matter!

Yet can we really say that Java is “better” (or “worse”) than C++? Is Scheme “better” than Lisp? Is ML “better” than either of them? Can we hope to give substance to any of these questions? Or should we simply reserve them for late night bull sessions over a glass of beer? While there is certainly an irreducible subjective element in programming language design, there is also a rigorous scientific theory of programming languages that provides a framework for posing, and sometimes answering, such questions. To be sure there are good questions for which current theory offers no solutions, but surprisingly many issues are amenable to a rigorous analysis, providing definite answers to many questions. Programming language theory liberates us from the tar pit of personal opinion, and elevates us to the level of respectable scientific discourse.

Programming language theory is fundamental to the implementation of programming languages, as well as their design. While compiler writers have long drawn on the theory of grammars for parsing and on graph theory for register allocation, the methods used to compile well-known languages such as C do not rely on deep results from programming language theory. For relatively simple languages, relatively simple compilation methods suffice. But as languages become more sophisticated, so must more sophisticated methods be employed to compile them.

For example, some programs can be made substantially more efficient if code generation is deferred until some run-time data is available. A tight inner loop might be ``unrolled" into a linear instruction sequence once the iteration bound is determined. This is one example of partial evaluation, a technique for program specialization that rests on

results from programming language theory. To take another example, modern languages such as ML (and proposed extensions of Java) include what are known as parameterized types to support flexible code re-use. Parameterized types complicate compilers considerably because they must account for situations in which the type of a variable or function argument is not known at compile time. The most effective methods for handling parameterized types rely on typed intermediate languages with quite sophisticated type systems. Here again programming language theory provides the foundation for building such compilers.

Programming language theory has many applications to programming practice. For example, "little languages" arise frequently in software systems -- command languages, scripting languages, configuration files, mark-up languages, and so on. All too often the basic principles of programming languages are neglected in their design, with all too familiar results. After all, the argument goes, these are "just" scripting languages, or "just" mark-up languages, why bother too much about them? One reason is that what starts out as "just" an ad hoc little language often grows into much more than that, to the point that it is, or ought to be, a fully-fledged language in its own right. Programming language theory can serve as a guide to the design and implementation of special purpose, as well as general purpose, languages.

Another application of the theory of programming languages is to provide a rigorous foundation for software engineering. Formal methods for software engineering are grounded in the theory of specification and verification. A specification is a logical formula describing the intended behavior of a program. There are all kinds of specifications, ranging from simple typing conditions ("the result is a floating point number between 0 and 1") to complex invariants governing shared variables in a concurrent program. Verification is the process of checking that the implementation indeed satisfies the specification. Much work has gone into the development of tools for specifying and verifying programs. Programming language theory makes precise the connection between the code and its specification, and provides the basis for constructing tools for program analysis.

The theory of programming languages provides a "reality check" on programming methodology, that part of software engineering concerned with the codification of successful approaches to software development. For example, the merits of object-oriented programming for software development are well known and widely touted. Object-oriented methodology relies heavily on the notions of subtyping and inheritance. In many accounts these two notions are confused, or even conflated into one concept, apparently because both are concerned with the idea of one class being an enrichment of another. But careful analysis reveals that the two concepts are, and must be, distinct: confusing them leads to programs that violate abstraction boundaries or even incur run-time faults.

The purpose of this course is to introduce the basic principles, methods, and results of programming languages to undergraduate students who have completed the introductory sequence in computer science at Carnegie Mellon. I intend for students to develop an appreciation for the benefits (and limitations) of the rigorous analysis of programming concepts.

The development is based on *type theory*, a general theory of computation that encompasses all aspects of programming languages, from the data with which we compute to the means by which we structure programs. Programming language "features" are viewed as manifestations of *type structure*. Basic data structures such as tuples arise as *product types*, trees and graphs arise as *recursive types*, and procedures arise as *monadic function types*. Each language concept is defined by giving its *statics*, which specify how it interacts with other parts of a program, and its *dynamics*, which specifies how it is executed on a computer. *Type safety* is the coherence of the statics with the dynamics; safety is proved as a mathematical theorem governing each language feature. The specific topics vary from one semester to the next, but the course typically covers finite and infinite data structures, higher-order functions, continuations, mutable storage, data abstraction and polymorphism, so-called dynamic typing, parallel computation, laziness, and concurrency, all presented in a single unifying framework.

What is the format of the course?

Two 80 minute lectures per week, one 60 minute recitation, plus office hours with either the teaching assistants or the professor or both.

How are students assessed?

There is one homework assignment every two weeks involving both a theoretical component, in which students are expected to prove theorems about languages, and a practical component, in which students are expected to implement a language concept. The theoretical component develops a new idea or expands on an idea presented in lecture, and the practical component builds on the theory to guide the implementation. There are two examinations, an 80 minute open-book midterm examination, and a 180 minute open-book final examination. Homework accounts for 50% of the grade, the midterm 20%, and the final 30%. Letter grades are assigned relative to overall class performance, with borderline cases influenced by extra credit problems, participation in class and recitation, and effort displayed through attendance at office hours and general quality of work. The assignments take approximately 12 hours to complete.

Course textbooks and materials

Practical Foundations for Programming Languages by Robert Harper, Cambridge University Press, 2013. All programs are written in Standard ML. All written material is typeset in LaTeX. All homework is graded by hand by the teaching assistants.

Why do you teach the course this way?

The course has a reputation for being very challenging, but also very stimulating. The students appreciate greatly the power of types as a scientific theory of programming, and develop great facility with using types and operational semantics to model computational phenomena and to use these models to prove theorems about systems.

This course is not in any way a *taxonomy* of programming languages, nor is it a tour of the zoo of popular languages. Rather it provides a solid grounding in the design, analysis, and implementation of programming languages, which express a rich variety of computational phenomena.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Work, Span, Asymptotics	2
DS	Sets, Relations, Functions	Inductive definitions	1
DS	Logic	Constructive and Classical Logic	1
DS	Proof techniques	Structural induction, rule induction	1
OS	Concurrency	Synchronization, Communication	6
OS	Scheduling	Scheduling parallel computations	1
PD	Parallelism Fundamentals	Deterministic parallelism, fork/join, futures	3
PD	Parallel Decomposition	Fork/Join, Data Parallelism	1
PD	Parallel Algorithms, Analysis, and Programming	Parallelizability, Divide and Conquer, Pipelining	1
PL	Object-oriented Programming	Dynamic Dispatch, Static and Dynamic Classification	3
PL	Functional Programming	Pattern matching, Recursion, Continuations, Parallelism, Laziness	12

PL	Event-driven and Reactive Programming	Streams, Process Calculus	3
PL	Basic type systems	Type systems for all language features	3
PL	Program Representation	Abstract syntax, binding and scope	1
PL	Language Translation and Execution	Concrete and Abstract Syntax; Statics; Dynamics	1
PL	Compiler Semantic Analysis	Type checking, elaboration	3
PL	Advanced Programming Constructs	Laziness, streams, Exceptions, Continuations, Monads, Dynamic Typing, Dynamic Dispatch, Modules	21
PL	Type Systems	Type safety (preservation and progress), Products, Sums, Recursive Types	3
PL	Formal Semantics	Structural Operational Semantics	2

Additional topics

Inductive definitions; abstract syntax with binding and scope; type systems; structural operational semantics; cost semantics; deterministic parallelism; dynamic typing as a degenerate case of static typing; separation of concurrency from parallelism; parametricity as a foundation for data abstraction; modal separation of expressions from commands; distinction between variables (as in mathematics) and assignables (misnamed variables in common languages); process calculus; recursive types; fixed points for functions and type operators.

Other comments

The classifications into areas and units does not fit my syllabus very well. Many of the topics overlap, so that the total hours listed does not add up to the total hours for the course. Every single lecture involves type systems and operational semantics, for example. It is impossible to allocate the time according to the given classifications. Much of the classifications reflect obsolete conceptual analyses of programming languages in particular, and of computer science more broadly, making it nearly impossible to fit my course into the given framework.

15-150: Functional Programming, Carnegie Mellon University

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http://www.cs.cmu.edu/~15150/previous-semesters/2012-spring/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	18
Parallel and Distributed Computing (PD)	9
Algorithms and Complexity (AL)	8
Software Development Fundamentals (SDF)	7
Discrete Structures (DS)	5
Software Engineering (SE)	1

Where does the course fit in your curriculum?

Functional Programming is a required course, and is typically taken in a student's first, second, or third semester. Carnegie Mellon's required introductory CS courses consist of this course on functional programming, a course on imperative programming, a course on discrete math, a course on parallel data structures and algorithms, and a course on computer systems. The only prerequisite for Functional Programming is a basic math course, though students usually have some prior programming experience. Functional Programming is a prerequisite for the parallel data structures and algorithms course. The course typically has an enrollment of 200-250 students per semester. Approximately 1/3 to 1/2 of the students are CS majors, though most of the remaining students are intending to minor or switch to a CS major.

What is covered in the course?

The four key skills that students learn are

- to write parallel functional programs
- to analyze programs' sequential and parallel time complexity
- to write mathematical specifications and verify that programs meet them
- to structure programs using modules and abstract types

One central principle of the course design is that the skills of writing, analyzing, and verifying parallel programs are integrated throughout the semester, rather than separated into units. In the first three weeks of the course, students learn to write basic sequential functional programs on numbers and lists, to analyze their time complexity, and to prove mathematical correctness specifications using induction. Parallelism is introduced in the fourth week: Students learn to write data-parallel functional programs. They learn to analyze not just the usual sequential complexity of programs, but their parallel complexity, and how this influences algorithm and data structure design. An early example is sorting: One might think that mergesort would have logarithmic parallel complexity, because as a sorting problem is repeatedly divided in half, the length of the longest dependency is logarithmic. However, with lists as the data structure, mergesort has a linear parallel complexity, because just the operation of splitting a list into two halves takes linear time, independently of how many processors are available. This motivates studying mergesort on trees, which has a sublinear parallel complexity. Because the parallelism is deterministic, students can reason about the behavior of their programs as if they were sequential, but run them in parallel. These programming, analysis, and verification skills continue to be interwoven throughout the remainder of the course, as students learn more advanced techniques.

Overall, students learn the following aspects of programming, analyzing, and proving:

- The organization of programming languages by types
- Computing by calculation: how programs are evaluated
- Recursive functions and proofs by induction
- Asymptotic analysis and recurrence relations
- Tree parallelism
- Datatypes, pattern-matching, and structural recursion/induction
- Parametric polymorphism
- Higher-order functions
- Continuation-passing style
- Exceptions
- Cost semantics
- Vector parallelism and map-reduce
- Modules and abstract types
- Imperative programming
- Interaction of parallelism and effects
- Laziness and streams

The course is taught in Standard ML. A variety of examples are used to teach these skills, including sequential and parallel sorting, map-reduce algorithms, regular expression matching, n-body simulation, and game-tree search. The assignments integrate parallel programming, analysis, and verification. For example, in one key assignment, students write and prove correct a regular expression matcher, combining an advanced programming technique called continuation-passing-style with sophisticated inductive reasoning. In another, students implement an algorithm for n-body simulation that has good sequential and parallel complexity, using a mix of tree- and vector-parallelism.

What is the format of the course?

The course lasts 14 weeks, and has two 80-minute lectures and one 80-minute lab per week (4 hours total). There are also significant TA tutoring hours, where students may get help from the TAs while working on homework problems.

How are students assessed?

There are 10 homework assignments; 8 are one-week assignments and 2 are longer projects. Most of the assignments include programming, proving, and asymptotic analysis components. Students report spending an average of 10-15 hours per week on the assignments. Students are allowed to collaborate on assignments, but ultimately must recreate any collaborative work on their own. There are also 2 in-class exams (midterm and final), and students are assessed on participation in weekly labs.

Course textbooks and materials

The course uses original lecture notes and assignments that were developed for this class. These are available from the above Web page.

Why do you teach the course this way?

The course was designed in Spring 2011, as part of a revision of Carnegie Mellon's introductory curriculum. It has been taught 8 times over the course of 7 semesters/summers, in Pittsburgh and at CMU Qatar, by 5 different lead instructors. Each instructor has his/her own take on the course, and the content varies a bit, but all versions teach the skills and concepts mentioned above. The course has received excellent reviews, and students find it to be very challenging but also very worthwhile and fun.

The 2013 ACM curriculum states that courses should prepare graduates to succeed in a rapidly changing field, and be innovative and track recent developments in the field. This course contains novel foundational material on parallelism and verification, which is based on current and ongoing research on these topics, and will prepare students to apply these concepts in different settings throughout their careers.

The ACM curriculum gives parallelism special consideration as a design dimension for introductory classes. This course teaches students to "think parallel," with sequential programming as a special case. We accomplish this by

teaching a deterministic approach to parallelism that is based on recent research. By doing so, we are able to teach the essential concepts of parallel programming, in a way that is no more difficult than teaching sequential programming, and that is abstract enough that students will be able to apply these ideas in various settings. Students have already returned from summer internships and reported that the course was helpful for their work.

Much of the verification component of the course has been taught for nearly two decades in a previous sophomore-level course on functional programming, and students have been overwhelmingly positive about the advantages that this way of thinking about programming gives them.

Regarding the design of the course activities, the most important aspect is integrating programming, analysis, and proofs throughout the semester, as mentioned above. This gives students time to improve at all three skills, from their introduction early in the course through various levels of deepening as the course progresses. Another important aspect is a carefully planned series of lectures, labs (where the students work on problems with TA assistance), and homework assignments. Students have responded especially well to the lab sessions, which bridge the gap between listening to ideas in lecture and applying them on the homework assignments.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Big O notation: use, Recurrence relations, Analysis of iterative and recursive algorithms	1
AL	Algorithmic Strategies	Brute-force algorithms, Divide-and-conquer, Recursive backtracking	3
AL	Fundamental Data Structures and Algorithms	Worst case quadratic sorting algorithms (selection, insertion), Worst or average case O(N log N) sorting algorithms (quicksort, heapsort, mergesort), Binary search trees, Pattern matching and string/text algorithms	3
AL	Advanced Data Structures Algorithms and Analysis	Balanced trees (e.g. red-black trees)	1
DS	Basic logic	Propositional logic, Logical connectives, Predicate logic	1
DS	Proof techniques	The structure of mathematical proofs, direct proofs, disproving by counterexample, induction over natural numbers, structural induction, weak and strong induction, recursive mathematical definitions	4
PD	Parallelism Fundamentals	all	1
PD	Parallel Decomposition	Need for communication and coordination/synchronization, Independence and partitioning, Basic knowledge of parallel decomposition concepts, Data-parallel decomposition	3
PD	Parallel Algorithms, Analysis, and Programming	All Core-Tier2	5
PL	Functional Programming	All	6
PL	Basic Type Systems	All Core-Tier1 plus parametric polymorphism	2
PL	Advanced Programming Constructs	Lazy evaluation and infinite streams, Control Abstractions, Module systems	7
PL	Concurrency and Parallelism	Language support for data parallelism	1

PL	Type systems	Compositional type constructors, Informal introduction to type checking/inference	2
SDF	Algorithms and Design	all	1
SDF	Fundamental Programming Concepts	all	2
SDF	Fundamental Data Structures	Records/structs, Abstract data types and their implementation, References and aliasing, Linked lists, Strategies for choosing the appropriate data structure	2
SDF	Development Methods	Program correctness, Simple refactoring, Documentation and program style	2
SE	Software Verification and Validation	Verification and validation concepts, Static approaches and dynamic approaches to verification	1

CIS 133J: Java Programming I, Portland Community College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	26
Programming Languages (PL)	11
Algorithms and Complexity (AL)	3

Where does the course fit in your curriculum?

The prerequisite for this course is the course "Software Design", which covers the basics of software design in a language-independent manner.

This course can be taken in the first or second year. A two-course programming sequence is required for the CIS degree, of which 3 are offered in the languages Java, VB.NET, and C++. This course is the first course in the Java sequence. The second follow-on course is required and a third course in the sequence is optional.

About 290 students take the course each year. While most are working towards a CIS Associate's degree, some students take it for transfer credit at a local institution such as OIT (Oregon Tech), and some take it simply to learn the Java language.

What is covered in the course?

- Object-oriented programming concepts
- Objects, classes
- State, behavior
- Methods, fields, constructors
- Variables, parameters
- Scope, lifetime
- Abstraction, modularization, encapsulation
- Method overloading
- Data types
- Conditional statements, logical expressions
- Loops
- Collection processing
- Using library classes
- UML class diagrams
- Documentation
- Debugging
- Use of an IDE

What is the format of the course?

The course is offered both face-to-face and online. In the face-to-face version, there are 40 classroom hours and at least 20 optional lab hours. This is a quarter course and typically meets twice a week for two hours over 10 weeks, with 2 optional lab hours each week.

All classrooms are equipped with a computer at each desk and the classroom time consists of both lecture and activities on the computers. The lab time is unstructured; students typically work on assignments and ask questions related to assignments or readings.

The online version of the course has pre-recorded videos guiding the students through the basic concepts and some of the more difficult content. There are also in-house written materials that supplement the textbook. Discussion boards provide a forum for questions and class discussions. Assignments and assessment are the same as in the face-to-face course.

How are students assessed?

Assessment varies by instructor, but in all cases the majority of the final grade comes from programming projects (e.g., 70%), and a smaller portion (e.g., 30%) from exams.

There are seven programming projects. In six of the projects, students add functionality to existing code, ranging from adding a single one-line method in the first assignment to adding significant functionality to skeleton code in the last assignment. In one project students write all code from scratch.

Students are expected to spend approximately two hours outside of class studying and working on assignments for each one hour they spend in class.

The midterm and final exams consist of multiple choice and true-false questions, possibly with a portion where students write a small program.

Course textbooks and materials

The textbook is Objects First with BlueJ, and the BlueJ environment is used throughout the course.

Why do you teach the course this way?

This course was previously taught with a more procedural-oriented approach and using a full-fledged IDE. The switch was made to BlueJ and a true objects-first approach in order to concentrate more on the concepts and less on syntactical and practical details needed to get a program running. In addition, there is an emphasis on good program design.

The background and skill level of students in the course varies greatly, and some find it very challenging while others have no trouble with the course.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Fundamental Data Structures and Algorithms	Simple numerical algorithms and sequential search are covered	3
PL	Object-Oriented Programming	Core-tier1 and core-tier2 topics are covered including classes, objects with state and behavior, encapsulation, visibility, collection classes. The topics relating to inheritance, subtyping, and class hierarchies are not covered in this course but are covered in the next course in the sequence.	8

PL	Basic Type Systems	All core-tier1 topics are covered with the exception of discussion of static typing. Of the core-tier2 topics, only generic types are covered, in connection with Java collection classes.	2
PL	Language Translation and Execution	Interpretation vs. compilation is covered, in connection with the Java language model as contrasted with straight compiled languages such as C++.	1
SDF	Algorithms and Design	The role of algorithms, problem-solving strategies (excluding recursion), and fundamental design concepts are covered. The concept and properties of algorithms, including comparison, has been introduced in a prerequisite course.	2
SDF	Fundamental Programming Concepts	All topics except recursion are covered	10
SDF	Fundamental Data Structures	Arrays, records, strings, lists, references and aliasing are covered	12
SDF	Development Methods	All topics are covered, but some of the program correctness subtopics only at the familiarity level	2

Introduction to Computer Science, Harvey Mudd College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	24
Algorithms and Complexity (AL)	9
Architecture and Organization (AR)	7.5
Programming Languages (PL)	3
Parallel and Distributed Computing (PD)	1.5

Where does the course fit in your curriculum?

Every first-semester student at Harvey Mudd College – and about 100 students from sister institutions at the Claremont Colleges – take one of the sections of this course. It has no prerequisites and is offered in three distinct "colors": CS 5 "gold" is for students with no prior experience, CS 5 "black" is for students with some experience, and CS 5 "green" is a version with a biological context to all of the computational content. 275 students were in CS 5 in fall 2012.

What is covered in the course?

This course has five distinct modules of roughly three weeks each:
(1) We begin with conditionals and recursion, practicing a functional problem-solving approach to a variety of homework problems. Python is the language in which students solve all of their assignments in this module.
(2) In the second module students investigate the fundamental ideas of binary representation, combinational circuits, machine architecture, and assembly language; they complete assignments in each of these topics using Python, Logisim, and a custom-built assembly language named Hmmm. This unit culminates with the hand-implementation of a recursive function in assembly, pulling back the curtain on the "magic" that recursion can sometimes seem.
(3) Students return to Python in the third module, building imperative/iterative idioms and skills that build from the previous unit's assembly language jumps. Creating the Mandelbrot set from scratch, Markov text-generation, and John Conway's Game of Life are part of this module's student work.
(4) The fourth module introduces object-oriented skills, again in Python, with students implementing a Date calculator, a Board class that can host a game of Connect Four, and a Player class that implements game-tree search.
(5) The fifth module introduces mathematical and theoretical facets of computer science, including finite-state machines, Turing machines, and uncomputable functions such as Kolmogorov complexity and the halting problem. Small assignments use JFLAP to complement this in-class content, even as students' work centers on a medium-sized Python final project, such as a genetic algorithm, a game using 3d graphics with the VPython library, or a text-analysis web application.

What is the format of the course?

This is a three-credit course with two 75-minute lectures per week. An optional, but incentivized lab attracts 90+% of the students to a two-hour supplemental session each week.

How are students assessed?
Students complete an assignment each week of 2-5 programming or other computational problems. Survey from the past five years show that the average workload has been consistent at about 4 hours/week outside of structured time, though the distribution does range from one hour to over 12. In addition, there is one in-class midterm exam and an in-class final exam.

Course textbooks and materials
The course has a textbook that its instructors wrote for it: CS for Scientists and Engineers by its instructors, C. Alvarado, Z. Dodds, R. Libeskind-Hadas, and G. Kuenning. Beyond that, we use Python, Logisim, JFLAP, and a few other supplemental materials.

Why do you teach the course this way?
Our CS department redesigned its introductory CS offering in 2006 to better highlight the breadth and richness of CS over the previous introductory offering. In addition, the department's redesign sought to encourage more women to pursue CS beyond this required experience. A SIGCSE '08. [1] publication, reported the initial curricular changes and their results, including a significant and sustained increase in the number of women CS majors. Subsequent publications at SIGCSE, ITiCSE, and Inroads. [2,3,4,5] flesh out additional context for this effort and several longer-term assessments of the resulting changes.

References:

[1] Dodds, Z., Libeskind-Hadas, R., Alvarado, C., and Kuenning, G. Evaluating a Breadth-First CS 1 for Scientists. *SIGCSE '08*.

[2] Alvarado, C., and Dodds, Z. Women in CS: An Evaluation of Three Promising Practices. *SIGCSE '10*.

[3] Dodds, Z., Libeskind-Hadas, R., and Bush, E. When CS1 is Biology1: Crossdisciplinary collaboration as CS context. *ITiCSE '10*.

[4] Dodds, Z., Libeskind-Hadas, R., and Bush, E. Bio1 as CS1: evaluating a crossdisciplinary CS context. *ITiCSE '12*.

[5] Alvarado, C., Dodds, Z., and Libeskind-Hadas, R. Broadening Participation in Computing at Harvey Mudd College. *ACM Inroads*, Dec. 2012.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	AL/Algorithmic Strategies	Brute-force, especially as expressed recursively	3
AL	AL/Basic Automata, Computability and Complexity	Precisely those, plus Kolmogorov Complexity	6
AR	AR/Digital logic and digital systems	Combinational logic design, as well as building flip-flops and memory from them	3
AR	AR/Machine level representation of data	Binary, two's complement, other bases	1.5
AR	AR/Assembly level machine organization	Assembly constructs, von Neumann architecture, the use of the stack to support function calls (and recursion in particular)	3

PD	PD/Parallelism Fundamentals	Parallelism vs. concurrency, simultaneous computation, measuring wall-clock speedup	1.5
PL	PL/Object-Oriented Programming	Definition of classes: fields, methods, and constructors; object-oriented design	3
SDF	SDF/Algorithms and Design	The concept and properties of algorithms; abstraction; program decomposition	6
SDF	SDF/Fundamental Programming Concepts	Basic syntax and semantics of a higher-level language; Variables and primitive data types; Expressions and assignments; functions and recursive functions	12
SDF	SDF/Fundamental Data Structures	Arrays/Linked lists; Strings; Maps (dictionaries)	6

CpSc 215: Software Development Foundations, Clemson University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	18
Programming Languages (PL)	12
Software Engineering (SE)	12

Where does the course fit in your curriculum?

CpSc 215 is a required course taken by all students pursuing a B.A. or B.S. in Computer Science, or a B.S. in Computer Information Systems. It is typically taken in the first or second semester of the sophomore year. On average, two sections of 25-30 students each take the course each semester. Students must receive a 'C' or better in CpSc 102 or CpSc 210 prior to taking the course. These courses offer a foundation in basic computational problem solving using the C programming language, with a brief introduction to object-oriented principles in C++. CpSc 215 serves as a pre-requisite for the majority of the upper-level courses in the computing curriculum at Clemson.

What is covered in the course?

Major topics covered, in their approximate order of coverage, include the following:

- Java Basics: Introduction, interpreted versus compiled languages
- Java Basics: Packages, classpaths, the Java compiler
- Java Basics: The Eclipse integrated development environment
- Java Basics: Parameter passing, shallow versus deep copying, value versus reference semantics
- Java Classes: Fields, methods, accessibility modifiers
- Java Classes: Constructors, overloading
- Java Classes: Static fields, methods, initializers
- Design Patterns: Introduction, historical context
- Design Patterns: Singleton, Flyweight
- Java Libraries: java.io.*, java.util.*, java.net.*, java.math.*
- Java Interfaces: Declaring, implementing, using as types
- Abstract Data Structures: Stacks, queues, sets
- Analytical Reasoning: Introduction to interface contracts
- Analytical Reasoning: Review of basic mathematical types (integers, tuples, strings, sets)
- Analytical Reasoning: Formal contract specifications
- Abstract Data Structures: Partial maps (dictionaries), linked-lists
- Analytical Reasoning: Contract-based Testing and Tracing
- Design Patterns: Decorator

- Analytical Reasoning: Assertion-checking wrappers (using Decorator)
- Java Exceptions: Concepts, declaring, throwing, catching
- Java Inheritance: Concepts, type system integration, polymorphism
- Design Patterns: Template Method, Strategy
- Algorithms as Components: Parameterized sorting implementations
- Java Generics: Concepts, syntax, subclassing issues
- Design Patterns: Observer
- Analytical Reasoning: Introduction to verification
- Analytical Reasoning: Software verification with objects
- Java Libraries: javax.swing.*, basic Swing development

What is the format of the course?

The course format includes 3 credit hours of lecture and 2 credit hours of laboratory time each week.

Lecture Hours. All lecture hours are face-to-face and involve a mixture of traditional lectures, interactive programming sessions, and "hands-on" learning activities. The hands-on activities involve pencil and paper exercises, as well as software-assisted activities performed using an interactive development and reasoning environment. (See URLs above.) Programming sessions and hands-on activities are typically group-based.

Laboratory Hours. All laboratory hours are face-to-face and involve small group programming exercises. Students are required to complete one short programming project each week during a 2-hour "closed lab" in one of Clemson's computing laboratories.

How are students assessed?

Course grades are assigned based on assessment across five categories:

- Quizzes (15%)
  Students are required to complete 4-5 in-class quizzes during the semester. The quizzes vary in duration from approximately 15 minutes to 25 minutes. The quizzes are weighted equally.
- Closed Labs (10%)
  Students are required to complete a short, group-based programming project each week during their assigned closed laboratory time. To receive full credit for the day, each group must demonstrate a working solution before the end of the lab session. Partial credit may be assigned for partial solutions. Each lab session is weighted equally.
- Programming Projects (30%)
  Four group-based programming projects are assigned during the semester. The assignments vary in complexity, duration (1-2.5 weeks), and weight. Assignment scores are based both on the functionality of the submitted solution and a detailed review of the source code to ensure compliance with stated requirements and best programming practices.
- Midterm Exam (20%)
  The midterm exam is a traditional pencil and paper exam given midway through the semester. The exam must be completed within one class period. It is closed book, closed notes, closed neighbor.
- Final Exam (25%)
  The final exam is a traditional pencil and paper exam given at the end of the semester. The exam must be completed within 2.5 hours. It is comprehensive.

Course textbooks and materials

The programming components of the course are taught using the Java programming language and the Eclipse Integrated Development Environment. The analytical reasoning components of the course rely on the RESOLVE specification language and its Web-Integrated Development and Reasoning Environment. While there is no official textbook for the course, students are provided with access to online tutorials, problem sets, interactive exercises, and instructional videos. (See URLs above.)

Why do you teach the course this way?

The course integrates three major themes: object-oriented programming in Java, analytical reasoning, and software design patterns. The emphasis on object-oriented programming is motivated by the importance of this paradigm in modern software practice. The emphasis on analytical reasoning is motivated by the supposition that the next generation of software engineers must be able to reason rigorously about the functionality and performance of the software they develop and maintain. Traditional trial-and-error methods of software development are insufficient to build the next generation of high-quality software. The emphasis on software design patterns is motivated by the wide adoption of patterns in modern software practice, both as prescriptive and descriptive aids.

The "hands-on", collaborative nature of the course was originally motivated by the success of peer instruction and other active learning strategies in mathematics and science. Since then, the efficacy of this approach in teaching software development foundations has been evaluated through over five years of course pilots at Clemson and several other adopting institutions. Results suggest that the approach has had a positive impact on students' performance, self-efficacy, and perception of computing as a discipline of study.

Students tend to consider this course one of the more challenging encountered in the first two years of study. Interestingly, however, the challenge appears to stem more from the object-oriented programming and design pattern components of the course, rather than the analytical reasoning components.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SDF	Algorithm Design	Fundamental design concepts and principles	3
SDF	Fundamental Data Structures	Abstract data types and their implementations, References and aliasing, Linked lists, Strategies for choosing the appropriate data structure	9
SDF	Development Methods	Program Correctness, Modern Programming Environments, Debugging Strategies	6
PL	Object-Oriented Programming	Object-oriented design, Definition of classes: fields, methods, and constructors, Subclasses, inheritance, and method overriding, Dynamic dispatch: definition of method-call, Subtyping, Object-oriented idioms for encapsulation, Using collection classes, iterators, and other common library components	9
PL	Basic Type Systems	Type safety and errors caused by using values inconsistently with their intended types, Generic types (parametric polymorphism)	3
SE	Software Design	Design Patterns	7.5
SE	Formal Methods	Role of formal specification and analysis techniques in the software development cycle, Program assertion languages and analysis approaches (including languages for writing and analyzing pre-and post-conditions), Tools in support of formal methods	4.5

Notes: Only lecture hours are listed above. Of the 42 hours listed above, there is some overlap among the hours devoted for SDF, PL, and SE topics; the actual coverage of the topics spans about 39 hours. The course covers a few additional background topics (3 hours) and includes an exam (1.5 hours).

Additional topics

Connections between software development foundations and discrete structures; mathematical modelling and verification of object-oriented programs; use of verification tools.

CS1101: Introduction to Program Design, WPI

Worcester, MA
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http://web.cs.wpi.edu/~cs1101/a12/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	18
Programming Languages (PL)	8
Algorithms and Complexity (AL)	2

Where does the course fit in your curriculum?

This is the first course in our department's sequence for majors in Computer Science, Robotics Engineering, and Interactive Media and Game Development who do not have much prior programming experience (an alternative course exists for students with AP or similar background). Most students pursuing minors also take this course (before Spring 2013, there was no alternative introductory course for novice programmers). It does not have prerequisites. Enrollment has been 300-400 students per year for each of the last 8 years.

Students who take this course and continue in computing go onto one of (1) a course in Object-Oriented Program Design (for majors and most minors), (2) a non-majors course in C-programming (targeted at students majoring in Electrical and Computer Engineering), or (3) a Visual Basic course for students majoring in Management and Information Systems.

What is covered in the course?

Upon completion of this course, the student should be able to:

- Understand when to use and write programs over structures, lists, and trees
- Develop data models for programming problems
- Write recursive and mutually recursive programs using the Racket programming language
- Explain when state is needed in value-oriented programming
- Develop test procedures for simple programs

Course Topics:

- Basic data types (numbers, strings, images, booleans)
- Basic primitive operations (and, or, +, etc.)
- Abstracting over expressions to create functions
- Documenting and commenting functions
- What makes a good test case and a comprehensive test suite
- Conditionals
- Compound data (records or structs)
- Writing and testing programs over lists (of both primitive data and compound data)
- Writing and testing programs over binary trees
- Writing and testing programs over n-ary trees
- Working with higher-order functions (functions as arguments)
- Accumulator-style programs
- Changing contents of data structures
- Mutating variables

What is the format of the course?
The course consists of 4 face-to-face lecture hours and 1 lab hour per week, for each of 7 weeks (other schools teach a superset of the same curriculum on a more standard schedule of 3-hours per week for 14 weeks).

How are students assessed?
Students are expected to spend roughly 15 hours per week outside of lectures and labs on the course. We assign one extended and thematically-related set of programming problems per week (7 in total in the WPI format). Students work on a shorter programming assignment during the one hour lab; lab assignments are not graded, and thus students do not usually work on them beyond the lab hour. There are 3 hour long exams. Most students report spending 12-18 hours per week on the programming assignments.

Course textbooks and materials
Textbook: *How to Design Programs*, by Felleisen, Findler, Flatt, and Krishnamurthi. MIT Press. Available (for free) online at www.htdp.org.

Language/Environment: Racket (a variant of Scheme), through the DrRacket programming environment (www.drracket.org). A web-based environment, WeScheme (www.wescheme.org) is also available. Software is cross-platform and available for free.

Why do you teach the course this way?
WPI adopted this course in 2004. At the time, our programming sequence started in C++ (for two courses), then covered Scheme and Java (across two more courses). After deciding that C++ was too rough an entry point for novice programmers, we redesigned our sequence around program design goals and a smooth language progression. Our current three-course sequence starts with program design, testing, and core data structures in Racket (a variant of Scheme), followed by object-oriented design, more advanced testing, and more data structures in Java, followed by systems-level programming and larger projects in C and C++. Each course in the sequence exposes more linguistic constructs and programmer responsibilities than the course before.

The "How to Design Programs" curriculum emphasizes data-driven and test-driven program design, following a step-by-step methodology. Given a programming problem, students are asked to complete the following steps in order: (1) define the datatypes, (2) write examples of data in each type, (3) write the skeleton of a function that processes each datatype (using a well-defined, step-by-step process that matches object-oriented design patterns), (4) write the contract/type signature for a specific function, (5) write test cases for that function, (6) fill in the skeleton for the main input datatype to complete the function, and (7) run the test cases.

The most useful feature of this methodology is that it helps pinpoint where students are struggling when writing programs. If a student can't write a test case for a program, he likely doesn't understand what the question is asking: writing test cases early force students to understand the question before writing code. If a student doesn't understand the shape of the input data well enough to write down examples of that data, she is unlikely to be able to write a test case for the program. This methodology helps students and instructors identify where students are actually struggling on individual programs (put differently, it gives a way to respond to the open-ended "my code doesn't work" statement from students). It also provides a way for students to get started even if they are not confident writing code: they can go from a blank page to a program in a sequence of steps that translate nicely to worksheets and other aids.

"How to Design Programs" also emphasizes interesting data structures over lots of programming constructs. Racket has a simple syntax with few constructs. In a typical college-pace course for students with no prior programming experience, students start working with lists after about 6 hours of lecture and with trees after roughly 10-12 hours of lecture. The design and programming process scales naturally to tree-shaped data, rather than require students to learn new programming patterns to handle non-linear data. The process thus lets us weave together programming, program design, and data structures starting in the first course.

Finally, the design process from "How to Design Programs" transitions naturally into object-oriented programming in Java. It takes roughly three lecture hours to teach students how to transform any of their "How to Design Programs" code into well-structured Java programs. Our Java/Object-Oriented Design course therefore starts with students able to program effectively with rich, mutually-recursive class hierarchies after under a week of class time. The natural sequence from "How to Design Programs" into Java is one of the salient curricular features of this course.

More information about the philosophy and resources are online at www.htdp.org.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Fundamental Data Structures and Algorithms	Binary Search Trees	2
PL	Functional Programming	Processing structured data via functions for data with cases for each data variant, first-class functions, function calls have no side effects	8
SDF	Algorithms and Design	Problem-solving strategies, abstraction, program decomposition	6
SDF	Fundamental Programming Concepts	All listed except I/O; I/O deferred to subsequent programming courses	6
SDF	Fundamental Data Structures	Records/structs, Linked Lists; remaining data structures covered in CS2/Object-Oriented Design course	2
SDF	Development Methods	Testing fundamentals, test-driven development, documentation and program style	4

Data Abstraction and Data Structures, Miami University

Oxford OH
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http://cs-comm.lib.muohio.edu/collections/show/3

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	12 – core tier 1
Algorithms and Complexity (AL)	2 – core tier 1, 1 – core tier 2
Social Issues and Professional Practice (SP)	1 – core tier 1

Where does the course fit in your curriculum?

The Data Abstraction and Data Structures course is numbered 274 in our program and thus it is expected that students take this course in the second year of the program. Typically, students take this course in the first semester of the Fall semester. The course is required and has two prerequisites (CS 2 and the discrete structures course).

What is covered in the course?

This course is being used as an exemplar of how we incorporate communication outcomes into the core curriculum. As such, the course description looks very much like other courses for data structures and the real difference is in the execution of the course and how the communication skills are integrated into the assignments.

Course Description:

Abstract data types and their implementation as data structures using object-oriented programming. Use of object-oriented principles in the selection and analysis of various ADT implementations. Sequential and linked storage representations: lists, stacks, queues, and tables. Nonlinear data structures: trees and graphs. Recursion, sorting, searching, and algorithm complexity.

- Apply appropriate data structures and abstract data types (ADT) such as bags, lists, stacks, queues, trees, tables, and graphs in problem solving.
- Apply object-oriented principles of polymorphism, inheritance, and generic programming when implementing ADTs for data structures.
- Create alternative representations of ADTs either from implementation or the standard libraries.
- Apply recursion as a problem solving technique.
- Determine appropriate ADTs and data structures for various sorting and searching algorithms.
- Determine time and space requirements of common sorting and searching algorithms.

Communication Assignments:
Examples of communication assignments for this course can be found at this site: http://cs-comm.lib.muohio.edu/collections/show/3. The assignments incorporate the use of workplace scenarios that provide context for a programming assignment. Students are required to exercise communication skills in the reading and writing of technical documentation in support of the technical products including the creation of test case specifications and API documentation.

What is the format of the course?

The course is taught using the flipped / inverted classroom model. In particular, the students view videos online prior to coming to class, and then work on programming assignments in class. For the communication outcomes, many of the learning activities are either performed in class as preparation for programming tasks, or as a

documentation activity that occurs after labs have concluded. The course is 3 credit hours and typically meets twice a week for 75 minutes.

How are students assessed?

Students are assessed using a combination of programming projects, in-lab assignments, problem sets, and exams. Each of the learning activities is accompanied by writing assignment that relates to the programming assignment. For instance, one assignment requires students to write test cases for a data structure. The test case descriptions indicate the setup and tear down of the tests as well as the expected outcomes of the test.

Course textbooks and materials

All lecture materials are provided as videos on YouTube:
Data Structures: http://www.youtube.com/playlist?list=PLE827E1949733EACC
C++: http://www.youtube.com/playlist?list=PL318424B457A98D69
Textbooks are provided online via Safari Tech Books online and vary by instructor.

Why do you teach the course this way?

Communication in this course is taught as an integrated part of the technical content. In particular, communication is taught in the context of the workplace scenarios that emphasize situated learning. As such, rather than teaching communication as a wholly separate topic, it is taught as a part of the core computer science topics. The course has incorporated communication outcomes in a couple of occasions since 2010. The course is considered challenging by the students for a number of reasons, primarily technical.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Professional Communication	• Reading, understanding and summarizing technical material, including source code and documentation • Writing effective technical documentation and materials	1
SDF	Fundamental Data Structures	All	12
AL	Basic Analysis	All in Core-Tier 1	2

The communication topics not covered in this course are covered elsewhere in the curriculum.

Additional topics

None.

Other comments

This exemplar demonstrates the results of an NSF-funded collaborative project between Miami University and North Carolina State University (NSF CPATH-II Awards CCF-0939122 and CCF-0939081). The project emphasizes integration of communication outcomes across the entire curriculum. Details on the project can be found at the following dissemination website: http://cs-comm.lib.muohio.edu/.

Software Engineering Practices, Embry Riddle Aeronautical University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Engineering (SE)	42

Where does the course fit in your curriculum?

This is a junior level course required for students majoring in software engineering, computer engineering, or computer science. The course is also required by those students seeking a minor in computer science.

The course has an introductory computer science course as a prerequisite.

The typical population of students in the course is between 30-35 students.

What is covered in the course?

Typical outline of course topics includes:

- Introduction to Software Engineering
- Models of Software Process
- Project Planning and Organization
- Software Requirements and Specifications
- Software Design Techniques
- Software Quality Assurance
- Software Testing
- Software Tools and Environments

What is the format of the course?

The course meets twice a week for two hours each day. The course is a mixture of lecture (about 1.5 hours a week) and group project work. The course is structured around the project development where the students are constantly producing artifacts related to software development life cycle.

How are students assessed?

Students are assessed through multiple means. This includes

- Individual programming assignments (about 3 per semester)
- In class quizzes
- Homework assignments
- Two midterms
- Semester long team project

Students peer evaluation is also part of the assessment process.

Course textbooks and materials

Watts Humphrey's *Introduction to the Team Software Process* is the primary book for the course, but this is also complemented with multiple reading assignments including journals and other book chapters.

Why do you teach the course this way?
The course is taught as a mini capstone course. It has been taught this way for the last 7 years at least. Students' comments indicate that the course is challenging in the sense that it drives them away from the perceived notion that software engineering is mostly about programming. Course is only reviewed annually as part of the department assessment and accreditation process.

I believe teaching the course based on a semester project is the easiest way to force students to apply the concepts and get familiar with the artifacts associated with a typical software development process.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SE	Software Process	System Level Consideration Relation of software engineering to Systems Engineering Software systems' use in different domains Outcome: Core-Tier1 # 1	1
SE	Software Process	Software Process Models Waterfall model Incremental model Prototyping V model Agile methodology Outcome: Core-Tier1 # 2 Outcome: Core-Tier1 # 3 Outcome: Core-Tier2 # 1 Outcome: Core-Tier2 # 2	2
SE	Software Process	Software Quality Concepts Outcome: Elective # 1 Outcome: Elective # 4 Outcome: Elective # 6 Outcome: Elective # 7	4
SE	Software Project Management	Team Participation Outcome: Core-Tier2 # 7 Outcome: Core-Tier2 # 8 Outcome: Core-Tier2 # 9 Outcome: Core-Tier2 # 11	2
SE	Software Project Management	Effort Estimation Outcome: Core-Tier2 # 12	2
SE	Software Project Management	Team Management Outcome: Elective # 2 Outcome: Elective # 4 Outcome: Elective # 5	1
SE	Software Project Management	Project Management Outcome: Elective # 6 Outcome: Elective # 7	2

SE	Requirements Engineering	Fundamentals of software requirements elicitation and modelling Outcome: Core-Tier1 # 1	1
SE	Requirements Engineering	Properties of requirements Outcome: Core-Tier2 # 1	1
SE	Requirements Engineering	Software Requirement Elicitation Outcome: Core-Tier2 # 2	1
SE	Requirements Engineering	Describing functional Requirements using use cases Outcome: Core-Tier2 # 2	1
SE	Requirements Engineering	Non-Functional Requirements Outcome: Core-Tier2 # 4	1
SE	Requirements Engineering	Requirements Specifications Outcome: Elective # 1 Outcome: Elective # 2	2
SE	Requirements Engineering	Requirements validation Outcome: Elective # 5	1
SE	Requirements Engineering	Requirements Tracing Outcome: Elective # 5	1
SE	Software Design	Overview of Design Paradigms Outcome: Core-Tier1 # 1	1
SE	Software Design	Systems Design Principles Outcome: Core-Tier1 # 2 Outcome: Core-Tier1 # 3	1
SE	Software Design	Design Paradigms (OO analysis) Outcome: Core-Tier2 # 1	1
SE	Software Design	Measurement and analysis of design qualities Outcome: Elective # 3	1
SE	Software Construction	Coding Standards Outcome: Core-Tier2 # 4	2
SE	Software Construction	Integration strategies Outcome: Core-Tier2 # 5	1

SE	Software Validation and Verification	V&V Concepts Outcome: Core-Tier2 # 1	1
SE	Software Validation and Verification	Inspections, Reviews and Audits Outcome: Core-Tier2 # 3	3
SE	Software Validation and Verification	Testing Fundamentals Outcome: Core-Tier2 # 4 Outcome: Core-Tier2 # 5	2
SE	Software Validation and Verification	Defect Tracking Outcome: Core-Tier2 # 6	1
SE	Software Validation and Verification	Static and Dynamic Testing Outcome: Elective # 1	2
SE	Software Validation and Verification	Test Driven Development Test Driven Development Programming Assignment No available outcome	1
SE	Software Evolution	Characteristics of maintainable software Lecture on software maintenance and the different types of maintenance No available outcome	1
SE	Software Evolution	Reengineering Systems Lecture on reverse engineering No available outcome	1
FM	Formal Methods	Role of formal specifications in software development cycle Outcome 1 Outcome 2 Outcome 3	2

Additional topics
Ethics

CS169: Software Engineering, University of California, Berkeley

Armando Fox & David Patterson
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https://sites.google.com/site/ucbsaas/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Engineering (SE)	39

Where does the course fit in your curriculum?

This course is for juniors and seniors majoring in computer science or computer engineering.
The prerequisites are 3 lower-division courses: "61A: Great ideas in Computer Science," "61B: Programming with Data Structures," and "61C: Great Ideas in Computer Architecture."

The population of students in the course has grown from 35 students in 2010 to 240 students in 2013, due in part to the extensive revision of the course content described below.

This course is the basis of two massive open online courses (MOOCs) from UC Berkeley and EdX: CS169.1X covers the first six weeks of the Berkeley course, and CS169.2X covers the next six weeks.

What is covered in the course?

- Introduction to SaaS and software lifecycles: Waterfall, Spiral, RUP, Agile
- Project Management: Pair programming and Scrum vs. Planning and Project manager
- Requirements Elicitation: User Stories vs. Contracts
- Testing: Behavior Driven Design and Test Driven Development vs. Code then test
- Maintenance: Legacy, Refactoring, and Agile
- Version control systems and releases
- Design patterns
- Performance, reliability, and security

What is the format of the course?

One semester (14 weeks), 3 hours of lecture per week, and 1 hour of TA-led discussion per week.

How are students assessed?

Students are assessed through multiple means. This includes

- Seven programming assignments, which are autograded
- Two midterm exams
- Semester long team project for external non-technical customer done in 4 iterations. Customers give feedback with each iteration, and a TA grades each iteration.
- Final poster session, including demonstrating the application to the customer.

Course textbooks and materials

Engineering Software as a Service: An Agile Approach Using Cloud Computing,
by Armando Fox and David Patterson, Strawberry Canyon Publisher, 2013.

Why do you teach the course this way?

(The full answer is in the *Communications of the ACM* article "Viewpoint: Crossing the Software Education Chasm," May 2012, pp. 17-22.)

Cloud computing and the shift in the software industry toward Software as a Service (SaaS) using Agile development has led to tools and techniques that are a much better match to the classroom than earlier software development methods. We leverage the productivity of modern programming frameworks like Ruby on Rails to allow students to experience the whole software life cycle repeatedly within a single college course, which addresses many criticisms from industry about software education. By using free-trial online services, students can develop and deploy their SaaS apps in the cloud without using (overloaded) campus resources. For each software engineering topic, we describe both the Agile and the "plan-and-document" methodologies: Waterfall, Spiral, and RUP. This contrast allows students to decide for themselves when each methodology is appropriate for SaaS and non-SaaS applications.

The experience of many instructors (including ourselves) is that students enjoy learning and using Agile in projects. Its iteration-based, short-planning-cycle approach is a great fit for the reality of crowded undergraduate schedules and fast-paced courses. Busy students by nature often procrastinate, and then pull several all-nighters to get a demo cobbled together and working by the project deadline. Agile not only thwarts this tactic (since students are evaluated on progress being made each iteration), but in our experience actually leads to real progress using responsible practices on a more regular basis. We even show how to use Agile techniques on legacy code that wasn't developed that way to begin with; that is, Agile is good for more than just writing new code from scratch. Students are much more likely to actually follow the Agile methodology because the Ruby on Rails tools make it easy to do so, and because the advice is genuinely helpful for their projects. Moreover, our surveys of alumni say that Agile teaches skills that transfer to non-Agile projects.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SE	Software Processes	Software lifecycle Waterfall, Spiral, RUP Agile Software quality Outcome: Core-Tier1 #1, #2, #3, #4, #5 Outcome: Core-Tier2 #6, #7 Outcome: Elective #8, #12, #13, #14	3
SE	Software Project Management	Pair Programming Scrum Conflict Resolution Meetings and Agendas Software Development Estimation Software risks and risk reduction Outcome: Core-Tier2 #1, #2, #3, #4, #5, #6, #7, #8, #9 Outcome: Elective #10, #11, #12, #13, #14, #15, #16, #17, #18, #19, #20, #21, #22, #24, #25	3
SE	Tools and Environments	Configuration management Version control systems Tool selection and use Outcome: Core-Tier2 #1, #2, #3, #4	3

SE	Requirements Engineering	Requirements Elicitation Use cases and User Stories Lo-Fi UI Functional vs. Non-functional requirements Forward and Backward Tracing Risk mitigation via prototypes Outcome: Core-Tier1 #1, #2, #3 Outcome: Core-Tier2 #4, #5, #6 Outcome: Elective #7, #8, #10, #11	4
SE	Software Design	Design principles System design paradigm (SaaS, OO) Design patterns Software architectures Software components Outcome: Core-Tier1 #1, #2, #3, #4, #5 Outcome: Core-Tier2 #6, #9, #10, #11, #12, #13, #14 Outcome: Elective #14, #17, #18, #20	8
SE	Software Construction	Implementing reliability, efficiency, robustness Secure and defensive programming Exception handling Integration strategies: top-down, bottom-up, sandwich Enhancing legacy code Security principles of least privilege and fail-safe defaults Outcome: Core-Tier2 #1, #2, #3, #4, #5, #6, #7 Outcome: Elective #8, #9	4
SE	Software Verification and Validation	Verification vs. Validation Validation tools Design and Code Inspections Testing types and levels: unit, integration, system, etc. Defect tracking tools Test plan Verification and Validation of non-code artifacts Outcome: Core-Tier2 #1, #2, #3, #4, #5, #6 Outcome: Elective #8, #11, #14	6
SE	Software Evolution	Software evolution and life cycles Change requests Regression testing Software reuse Release management Outcome: Core-Tier2 #1, #2, #3, #4, #5, #6	5
SE	Formal Methods	Role of formal methods Formal specification languages Outcome: Elective #1, #3	1
SE	Software Reliability	Challenges of very high reliability Software reliability vs. system reliability Fault tolerance via redundancy Outcome: Core-Tier2 #1, #2 Outcome: Elective #7	2

SE-2890 Software Engineering Practices, Milwaukee School of Engineering

Walter Schilling
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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Engineering (SE)	29

Where does the course fit in your curriculum?
Second-year course for computer engineers covering SE fundamentals.

Prerequisites: one year of Java software development including use and simple analysis of data structures. Students have had two one-quarter courses in 8-bit microprocessor development with assembly language and C.

What is covered in the course?
Week 1 - Introduction to software engineering practices
Week 2 - Requirements and Use Cases
Week 3 - Software Reviews, Version Control, and Configuration Management
Week 4/5 - Design: Object domain analysis, associations, behavior
Week 6 - Design and Design Patterns
Week 7 - Java Review (almost a year since last use)
Week 8/9 - Code reviews and software testing
Week 10 - Applications to embedded systems

What is the format of the course?
One-quarter (10-week), two one-hour lectures and one two-hour closed (instructor directed) lab per week.

How are students assessed?
Midterm and final exams, two individual lab projects and on 8-week team development project.

Course textbooks and materials
Gary McGraw, *Real Time UML*, Third Edition.
Bruce Powel Douglass, *Advances in the UML for Real-Time Systems*, Addison-Wesley, 2004.

Why do you teach the course this way?
The major goal is to prepare computer engineering students (not SE majors) to work in a small team on a small project, and to gain an introduction to software engineering practices.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SE	Software Processes		4
SE	Software Project Management		2
SE	Tools and Environments		3
SE	Requirements Engineering		6
SE	Software Design		10
SE	Software Verification & Validation		4

Software Development, Quinnipiac University

Hamden CT
Mark E. Hoffman
mark.hoffman@quinnipiac.edu
http://cs-comm.lib.muohio.edu/collections/show/4

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Engineering (SE)	8 – core tier 2, 10 – elective
Software Development Fundamentals (SDF)	6 – core tier 1
Social Issues and Professional Practice (SP)	6 – core tier 1

Where does the course fit in your curriculum?

The Software Development course is numbered 225 in our program. Typical computer science majors take this course the first semester of their second year. The course is the third course in a three-course programming sequence preceded by CSC 110 (Programming and Problem Solving) and CSC 111 (Data Structures and Abstraction), our equivalents of CS1 and CS2, respectively.

What is covered in the course?

Catalog Description
This course presents introductory software engineering concepts including group development, large-scale project work, and theoretical aspects of object-oriented programming. The course expands on material from previous courses. Professional behavior and ethics represent an important component of this course.

Course Description:
This course is being used as an exemplar of how we incorporate communication outcomes into the core curriculum. The catalog description looks very much like other courses for software development; however, the real difference is in the execution of the course and how the communication skills are integrated into the assignments.

CSC 225 (Introduction to Software Development) is an experiential introduction to software development that focuses on learning basic software development principles and communications skills by developing an ongoing project (i.e., the project is carried over and developed during each iteration of the course). Students work as software development teams in the context of a workplace scenario where assignments are reports to a supervisor who uses the information reported for subsequent tasks such as reports for upper management. This strategy focuses students' learning on selecting critical information for the supervisor to use and presenting it in an accessible and persuasive manner. Student learning occurs through two sets of linked assignments that use formative assessment to achieve competence at the first-semester sophomore level.

Communication Assignments:
Examples of communication assignments for this course can be found at this site:
http://cs-comm.lib.muohio.edu/collections/show/4.
The following assignments may be found in the Software Engineering Collection.

- Program Review Report
- Customer Requirements Report
- Prioritized Bug/Enhancement Report

- Project Management Tools Report
- Preliminary Test Plan
- Scrum Process Management

What is the format of the course?

This is a project-based course where students work in teams of 4-6 students to develop a project carried over from the prior semester. At the end of the course, student teams package the project for the next semester. Over the first five weeks of the semester, teams install and learn to operate the inherited project, work with potential customers to identify bugs and enhancements, develop a prioritized list of bugs and enhancements, select project management tools, and develop a preliminary test plan. At the end of each week, student teams submit a report and make a presentation of their findings. The assignments over the first five weeks are linked and cumulative.

The next eight weeks consists of four two-week Scrum Cycles. Teams select items from their backlog (prioritized list of bug and enhancements) and implement them in one Scrum Cycle. During the Scrum Cycle, students create and update a work plan and hold short (5 minute) status meetings. At the end of each Scrum Cycle, teams report (written and oral) progress and demonstrate their work. The assignments over the four two-week Scrum Cycles are linked and cumulative.

At the end of the course, teams package their project, make a Final Report of their work, and demonstrate their project to a group of invited guests.

How are students assessed?

Each assignment has a technical rubric and a communications rubric. The technical rubric is specific to each assignment. Student work is assess holistically.

The communications rubric is the same for all assignments. Subsets of communications items are added cumulatively with each assignment. Items in the current and prior subsets are assessed holistically.

Students work on a set of linked assignments and receive continuous formative feedback from instructors on technical and communication skills. By the end each set of linked assignments student teams achieve competence at a first-semester sophomore level.

Course textbooks and materials

- Andrew Hunt and David Thomas, *The Pragmatic Programmer*, Addison-Wesley, Reading, MA, 2000. (Pdf file available on Blackboard.)
- F.P. Brooks, *The Mythical Man-Month*, Addison-Wesley, Boston, MA, 1995.
- Richard G. Epstein, *The Case of the Killer Robot*, John Wiley & Sons, Inc., New York, NY, 1997.

Additional material may come from *Communications of the ACM, IEEE Computer*, or other relevant sources.

Why do you teach the course this way?

Communication in this course is taught as an integrated part of the technical content. In particular, communication is taught in the context of the workplace scenarios that emphasize situated learning. As such, rather than teaching communication as a wholly separate topic, it is taught as a part of the core computer science topics. While the general process of the course (i.e., teams working on an ongoing project with a communications skills emphasis) has been course since 2005, participation in the CPATH II Project (2010-2012) described in Other Comments afforded targeted development of assignments integrating technical content and communication skills. The course is considered challenging by the students for a number of reasons, both technical and communication skills.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Professional Communication	• Reading, understanding and summarizing technical material, including source code and documentation • Writing effective technical documentation and materials • Dynamics of oral, written, and electronic team and group communication • Communicating professionally with stakeholders • Utilizing collaboration tools	6

SDF	Development Methods	• Program comprehension
		• Program correctness
		  ○ The concept of a specification
		  ○ Testing fundamentals and test-case generation
		  ○ Test-driven development
		  ○ Unit testing
		• Modern programming environments
		  ○ Programming using library components and their APIs
		• Debugging strategies
		• Documentation and program style
			6

SE	Process Management	All in Core-Tier 2 and Elective	12
SE	Tools and Environments	• Software configuration management and version control; release management • Requirements analysis and design modeling tools • Testing tools including static and dynamic analysis tools Programming environments that automate parts of program construction processes ○ Continuous integration • Tool integration concepts and mechanisms	6

Additional topics

None.

Other comments

This exemplar demonstrates the results of an NSF-funded collaborative project between Miami University and North Carolina State University (NSF CPATH-II Awards CCF-0939122 and CCF-0939081). The project emphasizes integration of communication outcomes across the entire curriculum. Details on the project can be found at the following dissemination website: http://cs-comm.lib.muohio.edu/.

CS2200: Introduction to Systems and Networking, Georgia Institute of Technology

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http://www.cc.gatech.edu/~rama/CS2200-External/

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Systems Fundamentals (SF)	42

Where does the course fit in your curriculum?

This course is taken in the second semester of the sophomore year. The pre-requisite for this course is a good knowledge of C and logic design. It is required for all CS majors wishing to specialize in: operating systems, architecture, programming language and compilers, system security, and networking. It provides a thorough understanding of the hardware and the system software and the symbiotic inter-relationship between the two. Students may take advanced courses in operating systems, architecture, and networking following this course in the junior and senior years. The course is offered 3 times a year (Fall, Spring, Summer) and the enrolment is typically around 100 students.

What is covered in the course?

The course represents a novel integrated approach to presenting side by side both the architecture and the operating system of modern computer systems, so that students learn how the two complement each other in making the computer what it is. The course consists of five modules, corresponding to the five major building blocks of any modern computer system: processor, memory, parallelism, storage, and networking. Both the hardware and system software issues are covered concomitantly in presenting the five units. Topics covered include

- Processor design including instruction-set design, processor implementation (simple as well as pipelined with the attendant techniques for overcoming different kinds of hazards), processor performance (CPI, IPC, execution time, Amdahl's law), dealing with program discontinuities (interrupts, traps, exceptions), and design of interrupt handlers
- Processor scheduling algorithms including FCFS, SJF, priority, round robin, with Linux scheduler as a real world example
- Memory system including principles of memory management in general (paging in particular) and the necessary hardware support (page tables, TLB), page replacement algorithms, working set concepts, the inter-relationship between memory management and processor scheduling, thrashing, and context switching overheads
- Memory hierarchy including different organizations of processor caches, the path of memory access from the processor through the different levels of the memory hierarchy, interaction between virtual memory and processor caches, and page coloring
- Parallel programming (using pthreads), basic synchronization (mutex locks, condition variables) and communication (shared memory), program invariants, OS support for parallel programming, hardware support for parallel programming, rudiments of multiprocessor TLB and cache consistency
- Basics of I/O (programmed data transfer, DMA), interfacing peripherals to the computer, structure of device driver software
- Storage subsystem focusing on hard disk (disk scheduling), file systems (naming, attributes, APIs, disk allocation algorithms), example file systems (FAT, ext2, NTFS)

- Networking subsystem focusing on the transport layer protocols (stop and wait, pipelined, congestion control, windowing) , network layer protocols (Dijkstra, distance vector) and service models (circuit-, message-, and packet-switching), link layer protocols (Ethernet, token ring)
- Networking gear (NIC, hubs/repeater, bridge, switch, VLAN)
- Performance of networking (end-to-end latency, throughput, queuing delays, wire delay, time of flight, protocol overhead).

What is the format of the course?

Three hours of lecture per week; Two hours of TA-led recitation per week to provide help on homeworks and projects; and 3 hours of unsupervised laboratory per week. Video recordings of classroom lectures (from past offering) available as an additional study aid.

How are students assessed?

Two midterms, one final, 5 homeworks, 5 projects (two architecture projects: processor datapath and control implementation, and augmenting processor to handle interrupts; three OS projects: paged virtual memory management, multithreaded processor scheduler using pthreads, and reliable transport layer implementation using pthreads). Plus an extra-credit project (a uniprocessor cache simulator).

Course textbooks and materials

Ramachandran and Leahy Jr., *Computer Systems: An Integrated Approach to Architecture and Operating Systems*, Addison-Wesley, 2010.

Why do you teach the course this way?

There is excitement when you talk to high school students about computers. There is a sense of mystery as to what is "inside the box" that makes the computer do such things as play video games with cool graphics, play music—be it rap or symphony—send instant messages to friends, and so on. What makes the box interesting is not just the hardware, but also how the hardware and the system software work in tandem to make it all happen. Therefore, the path we take in this course is to look at hardware and software together to see how one helps the other and how together they make the box interesting and useful. We call this approach "unraveling the box"—that is, resolving the mystery of what is inside the box: We look inside the box and understand how to design the key hardware elements (processor, memory, and peripheral controllers) and the OS abstractions needed to manage all the hardware resources inside a computer, including processor, memory, I/O and disk, multiple processors, and network. Since the students take this course in their sophomore year, it also whets the appetite of the students and gets them interested in systems early so that they can pursue research as undergraduates in systems. The traditional silo model of teaching architecture and operating systems in later years (junior/senior) restricts this opportunity. The course was first offered in Fall 1999. It has been offered 3 times every year ever since. Over the years, the course has been taught by a variety of faculty specializing in architecture, operating systems, and networking. Thus the content of the course has been revised multiple times; the most recent revision was in 2010. It is a required course and it has gotten a reputation as a "tough" one, and some students end up taking it multiple times to pass the course with the required "C" passing grade.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SF	Processor architecture	HLL constructs and Instruction-set design, datapath and control, microprogrammed implementation, example (MIPS)	6
SF	Program discontinuities	Interrupts, traps, exceptions, nesting of interrupts, hardware for dealing with interrupts, interrupt handler code	2
SF	Processor performance metrics	Space and time, memory footprint, execution time, instruction frequency, IPC, CPI, SPECratio, speedup, Amdahl's law	1
SF	Principles of pipelining	Hardwired control, datapath of pipeline stages, pipeline registers, hazards (structural, data, and control) and solutions thereof (redundant hardware, register forwarding, branch prediction), example (Intel Core microarchitecture)	5
SF	Processor Scheduling	Process context block, Types of schedulers (short-, medium-, long-term), preemptive vs. non-preemptive schedulers, short-term scheduling algorithms (FCFS, SJF, SRTF, priority, round robin), example (Linux O(1) scheduler)	2
SF	Scheduling performance metrics	CPU utilization, throughput, response time, average response time/waiting time, variance in response time, starvation	1
SF	Memory management	Process address space, static and dynamic relocation, memory allocation schemes (fixed and variable size partitions), paging, segmentation	2
SF	Page-based memory management	Demand paging, hardware support (page tables, TLB), interaction with processor scheduling, OS data structures, page replacement algorithms (Belady's Min, FIFO, LRU, clock), thrashing, working set, paging daemon	2
SF	Processor caches	Spatial and temporal locality, cache organization (direct mapped, fully associative, set associative), interaction with virtual memory, virtually indexed physically tagged caches, page coloring	3
SF	Main memory	DRAM, page mode DRAM, Memory buses	0.5
SF	Memory system performance metrics	Context switch overhead, page fault service time, memory pressure, effective memory access time, memory stalls	0.5
SF	Parallel programming	Programming with pthreads, synchronization constructs (mutex locks and condition variables), data races, deadlock and livelock, program invariants	3
SF	OS support for parallel programming	Thread control block, thread vs. process, user level threads, kernel level threads, scheduling threads, TLB consistency	1.5
SF	Architecture support for parallel programming	Symmetric multiprocessors (SMP), atomic RMW primitives, T&S instruction, bus-based cache consistency protocols	1.5

SF	Input/output	Programmed data transfer, DMA, I/O buses, interfacing peripherals to the computer, structure of device driver software	1.5
SF	Disk subsystem	Disk scheduling algorithms (FCFS, SSTF, SCAN, LOOK), disk allocation algorithms (contiguous, linked list, FAT, indexed, multi-level indexed, hybrid indexed)	1.5
SF	File systems	Naming, attributes, APIs, persistent and in-memory data structures, journaling, example file systems (FAT, ext2, NTFS)	2
SF	Transport layer	5-layer Internet Protocol Stack, OSI model, stop-and-wait, pipelined, sliding window, congestion control, example protocols (TCP, UDP)	2
SF	Network layer	Dijkstra's link state and distance vector routing algorithms, service models (circuit-, message-, and packet-switching), Internet addressing, IP network	2
SF	Link layer	Ethernet, CSMA/CD, wireless LAN, token ring	0.5
SF	Networking gear	NIC, hub/repeater, bridge, switch, router, VLAN	1
SF	Network performance	End-to-end latency, throughput, queuing delays, wire delay, time of flight, protocol overhead	0.5

CS61C: Great Ideas in Computer Architecture, University of California, Berkeley

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Systems Fundamentals (SF)	39

Where does the course fit in your curriculum?

This is a third course in the computer science curriculum for intended majors, following courses in "great ideas in Computer Science" and "Programming with Data Structures." It provides a foundation for all of the upper division systems courses by providing a thorough understanding of the hardware-software interface, the broad concepts of parallel programming to achieve scalable high performance, and hands-on programming experience in C.

What is covered in the course?

Introduction to C: this includes coverage of the Hardware/Software Interface (e.g., machine and assembly language formats, methods of encoding instructions and data, and the mapping processes from high level languages, particularly C, to assembly and machine language instructions). Computer architectures: how processors interpret/execute instructions, Memory Hierarchy, Hardware Building Blocks, Single CPU Datapath and Control, and Instruction Level Parallelism. The concept of parallelisms, in particular, task level parallelism, illustrated with Map-Reduce processing; Data Level Parallelism, illustrated with the Intel SIMD instruction set; Thread Level Parallelism/multicore programming, illustrated with openMP extensions to the C programming language.

What is the format of the course?

Three hours of lecture per week, one hour of TA-led discussion per week, two hours of laboratory per week.

How are students assessed?

Laboratories, Homeworks, Exams, Four Projects (Map-Reduce application on Amazon EC2), MIPS Instruction Set Emulator in C, Memory and Parallelism-Aware Application Improvement, Logic Design and Simulation of a MIPS processor subset).

Course textbooks and materials

Patterson and Hennessy, *Computer Organization and Design*, revised 4th Edition, 2012; Kernighan and Ritchie, *The C Programming Language*, 2nd Edition; Borroso, *The Datacenter as a Computer*, Morgan and Claypool publishers.

Why do you teach the course this way?

The overarching theme of the course is the hardware-software interface, in particular, focusing on what a programmer needs to know about the underlying hardware to achieve high performance for his or her code. Generally, this concentrates on harnessing parallelism, in particular, task level parallelism (map-reduce), data level parallelism (SIMD instruction sets), multicore (openMP), and processor instruction pipelining. The six "great" ideas presented in the course are (1) Layers of Representation/Interpretation, (2) Moore's Law, (3) Principle of Locality/Memory Hierarchy, (4) Parallelism, (5) Performance Evaluation, and (6) Dependability via Redundancy.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SF	Computational Paradigms	C Programming/Cloud	10.5
SF	Cross-Layer Communications	Compilation/Interpretation	1.5
SF	State-State Transition-State Machines	Building Blocks, Control, Timing	4.5
SF	Parallelism	Task/Data/Thread/Instruction	10.5
SF	Performance	Figures of merit, measurement	1.5
SF	Resource Allocation and Scheduling		0
SF	Proximity	Memory Hierarchy	4.5
SF	Virtualization and Isolation	Virtual Machines and Memory	3.0
SF	Reliability Through Redundancy	RAID, ECC	3.0

CSE333: Systems Programming, University of Washington

Department of Computer Science & Engineering
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http://www.cs.washington.edu/education/courses/cse333/11sp

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Systems Fundamentals (SF)	8
Operating Systems (OS)	7
Programming Languages (PL)	5
Networking and Communication (NC)	3
Architecture and Organization (AR)	3
Software Engineering (SE)	3
Information Management (IM)	1

Where does the course fit in your curriculum?

This is an optional course taken by undergraduates in their second year, following at least CS1, CS2, and a hardware/software interface course. Students are encouraged to have taken data abstractions/structures. The course is a prerequisite for several senior-level courses, including operating systems, networking, and computer graphics. Approximately 60 students take the course per offering; it is offered four times per year (i.e., once each quarter, including summer).

What is covered in the course?

The major goal of the course is to give students principles, skills, and experience in implementing complex, layered systems. The course includes a quarter-long programming project in which students: (a) build rudimentary data structures in C, such as linked lists, chained hash tables, AVL trees; (b) use them to build an in-memory inverted index and file system crawler; (c) construct a C++-based access methods for writing indexes to disk and accessing disk-based indexes efficiently; and (d) construct a concurrent (threaded or event-driven) web server that exposes a search application.

A substantial portion of the course focuses on giving students in-depth C and C++ skills and experience with practical engineering tools such as debuggers, unit testing frameworks, and profilers. The course stresses the discipline of producing well-structured and readable code, including techniques such as style guidelines and code reviews. Additionally, the course covers topics such as threaded vs. event-driven concurrency, the Linux system call API, memory management, and some security and defensive programming techniques.

The full list of course topics is:

C programming

- pointers, structs, casts; arrays, strings
- dynamic memory allocation

- C preprocessors, multifile programs
- core C libraries
- error handling without exceptions

C++ programming

- class definitions, constructors and destructors, copy constructors
- dynamic memory allocation (new / delete), smart pointers, classes with dynamic data
- inheritance, overloading, overwriting
- C++ templates and STL

Tools and best practices

- compilers, debuggers, make
- leak detectors, profilers and optimization, code coverage
- version control
- code style guidelines; code review

Systems topics: the layers below (OS, compiler, network stack)

- concurrent programming, including threading and asynchronous I/O
- file system API
- sockets API
- understanding the linker / loader
- fork / join, address spaces, the UNIX process model

What is the format of the course?

The course is 10 weeks long, with students meeting for 3 1-hour lectures and a 1-hour lab session per week.

How are students assessed?

Over the 10 weeks, students complete 4 major parts of the programming assignment, ~15 small programming exercises (handed out at the end of each lecture), ~8 interactive lab exercises, a midterm, and a final exam. Students spend approximately 10-15 hours per week outside of class on the programming assignment and exercises.

Course textbooks and materials

Required texts:

Bryant and O'Hallaron, *Computer Systems: A Programmer's Perspective*
Harbison & Steele, *C: A Reference Manual*
Lippman, Lajoie & Moo*, C++ Primer*

Optional text:

Myers, *Effective C++* (optional)

Why do you teach the course this way?

As mentioned above, a major goal of the course is to give students principles, skills, and experience in implementing complex, layered systems. The course as structured emphasizes significant programming experience in combination with exposure to systems programming topics.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SF	Cross-layer Communications	abstractions, interfaces, use of libraries; applications vs. OS services	4
SF	Support for Parallelism	thread parallelism (fork-join), event-driven concurrency, client/server web services	3
SF	Proximity	memory vs. disk latency, demonstrated by in-memory vs. on-disk indexes	1
AR	Assembly level machine org.	heap, stack, code segments	2
AR	Memory system org. and arch.	virtual memory concepts	1
IM	Indexing	building an inverted file / web index; storing and accessing indexes efficiently on disk	1
NC	Networked applications	client/server; HTTP; multiplexing with TCP; socket APIs	3
OS	Principles	abstractions, processes, APIs, layering	3
OS	Concurrency	pthreads interface, basics of synchronization	3
OS	File systems	files and directories; posix file system API; basics of file search	1
PL	Object-oriented Programming	OO design, class definition, subclassing, dynamic dispatch (all taught based on C++)	3
PL	Event-driven programming	Events and event handlers, asynchronous I/O and non-blocking APIs	2
SE	Tools and environments	Unit testing, code coverage, bug finding tools	1
SE	Software construction	Coding practices, standards; defensive programming	1
SE	Software verification validation	Reviews and audits; unit and system testing	1

Ethics in Technology (IFSM304), University of Maryland

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http://www.umuc.edu/undergrad/ugprograms/ifsm.cfm

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Social Issues and Professional Practice (SP)	48

Brief description of the course's format and place in the undergraduate curriculum
Recommended pre-requisite: IFSM 201: Concepts and Applications of Information Technology.

IFSM 304 is a required foundation course typically open to all levels from freshman to senior. It is a required course for all programs in IFSM. The course is typically taught in an eight week on-line and hybrid format.

Course description and goals
This course is a comprehensive study of ethics and of personal and organizational ethical decision making in the use of information systems in a global environment. The aim is to identify ethical issues raised by existing and emerging technologies, apply a structured framework to analyze risk and decision alternatives, and understand the impact of personal ethics and organizational values on an ethical workplace. The objectives of this course are to:

- apply relevant ethical theories, laws, regulations, and policies to decision making to support organizational compliance
- recognize business needs, social responsibilities, and cultural differences of ethical decision making to operate in a global environment
- identify and address new and/or increased ethical issues raised by existing and emerging technologies
- foster and support an ethical workforce through an understanding of the impact of personal ethics and organizational values
- apply a decision-making framework to analyze risks and decision alternatives at different levels of an organization

Course topics

- Technology-related Ethical Global issues (multi-national corporation)
- Decision making frameworks to technology-related ethical issues
- Organizational policy to address the technology-related ethical issue
- Research existing or emerging technology and its ethical impact
- Study group presentation of research on existing or emerging technology and related ethical issues
- a reflective piece on class learning as it applies to ethics in information technology

Course textbooks, materials, and assignments
Reynolds, George Walter (2012) *Ethics in Information Technology*, 4th edition, Cengage (ISBN: 1111534128)

The course is taught as both hybrid and on-line. It is a writing intensive course requiring written assignments and student-to-teacher (as well as student-to-student interactions) in discussion conferences. The major assignment consists of eight weekly conferences, including the analysis of an ethical issue drawn from current events with global impact/implications. The conference topics consist of privacy, crime, corporate ethics, social media, and current ethical dilemmas. The significant written assignments include a policy paper, a research paper, a study

group developed PowerPoint presentation and the development of a decision matrix to help in analyzing ethical decisions. The course uses the portfolio method to determine student comprehension of the learning outcomes.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Social Context	Investigate the implications of social media on individualism versus collectivism and culture.	2
SP	Analytical Tools	Evaluate stakeholder positions in a given situation. Analyze basic logical fallacies in an argument. Analyze an argument to identify premises and conclusion. Illustrate the use of example and analogy in ethical argument.	6
SP	Professional Ethics	The strengths and weaknesses of relevant professional codes as expressions of professionalism and guides to decision-making. Analyze a global computing issue, observing the role of professionals and government officials in managing the problem. The consequences of inappropriate professional behavior. Develop a computer use policy with enforcement measures. The consequences of inappropriate personal behavior	7
SP	Intellectual Property	The philosophical bases of intellectual property. The rationale for the legal protection of intellectual property. Describe legislation aimed at digital copyright infringements. Identify contemporary examples of intangible digital intellectual property. Justify uses of copyrighted materials. The consequences of theft of intellectual property	4
SP	Privacy and Civil Liberties	The philosophical basis for the legal protection of personal privacy. The the fundamental role of data collection in the implementation of pervasive surveillance systems. The impact of technological solutions to privacy problems. The global nature of software piracy	12
SP	Professional Communication	Write clear, concise, and accurate technical documents following well-defined standards for format and for including appropriate tables, figures, and references. Develop and deliver a good quality formal presentation. Plan interactions (e.g. virtual, face-to-face, shared documents) with others in which they are able to get their point across, and are also able to listen carefully and appreciate the points of others, even when they disagree, and are able to convey to others that they have heard.	5

Other comments, such as teaching modality: face-to-face, online or blended.

IFSM 304 is taught as both hybrid and on-line. It is a writing intensive course requiring both written assignments and student to teacher discussion conferences. Both formats are completed in eight weeks. Both formats use the same sequence of events, the primary difference is that the hybrid utilizes a face-to-face component. Both the hybrid and on-line course rely heavily on a faculty led discussion forum to equate theory to practice.

Attachment 1,

Hours Assignment relating to outcomes

Social Context (SP)	**5 hours**
Investigate the implications of social media on individualism versus collectivism and culture.	Week 2 conference, Facebook
Analytical Tools (SP)	**10 hours**
Evaluate stakeholder positions in a given situation.	Current Events Article; Privacy-related Matrix

Analyze basic logical fallacies in an argument.	Current Events Article; Privacy-related Matrix. Week 4 conference Hewlett Packard
Analyze an argument to identify premises and conclusion.	Current Events Article; Privacy-related Matrix. Week 6 conference, contributions to economy
Illustrate the use of example and analogy in ethical argument.	Current Events Article; Privacy-related Matrix. Week 6 conference, contributions to economy
Professional Ethics (SP)	**10 hours**
Describe the strengths and weaknesses of relevant professional codes as expressions of professionalism and guides to decision-making.	
Analyze a global computing issue, observing the role of professionals and government officials in managing the problem.	Current Events Article. Week 5 conference, Computer Crime
Describe the consequences of inappropriate professional behavior.	
The consequences of inappropriate personal behavior	Current Events Article. Week 5 conference, Computer Crime
Develop a computer use policy with enforcement measures.	Organizational Policy paper
Intellectual Property (SP)	**7 hours**
Discuss the philosophical basis of intellectual property.	Week 2 conference, Facebook
Discuss the rationale for the legal protection of intellectual property.	Week 2 conference, Facebook
Describe legislation aimed at digital copyright infringements.	Week 2 conference, Facebook
Identify contemporary examples of intangible digital intellectual property	Week 2 conference, Facebook
Justify uses of copyrighted materials. The consequences of theft of intellectual property	Week 2 conference, Facebook
Privacy and Civil Liberties (SP)	**10 hours**
Discuss the philosophical basis for the legal protection of personal privacy.	Reflective paper on class learning; Week 2 conference, Facebook
Recognize the fundamental role of data collection in the implementation of pervasive surveillance systems (e.g., RFID, face recognition, toll collection, mobile	Individual research paper on existing or emerging technology and related ethical issue. Week 2 conference, Facebook
Investigate the impact of technological solutions to privacy problems.	Individual research paper on existing or emerging technology and related ethical issue. Week 2 conference, Facebook
Identify the global nature of software piracy.	Individual research paper on existing or emerging technology and related ethical issue. Week 2 conference, Facebook
Professional Communication (SP)	**6 hours**
Write clear, concise, and accurate technical documents following well-defined standards for format and for including appropriate tables, figures, and references.	Individual research paper on existing or emerging technology and related ethical issue
Develop and deliver a good quality formal presentation.	Group PowerPoint presentation
Plan interactions (e.g. virtual, face-to-face, shared documents) with others in which they are able to get their point across, and are also able to listen carefully and appreciate the points of others, even when they disagree, and are able to convey to others that they have heard	Group PowerPoint presentation

Technology Consulting in the Community, Carnegie Mellon University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Social Issues and Professional Practice (SP)	45

Where does the course fit in your curriculum?

This course is taught at the undergraduate and graduate level.

At the undergraduate level, it is an offered in an Information System major and is one option fulfilling a required core professional course. The prerequisites are meant to filter students who have some maturity to handle the ambiguous nature of working with a client and some technical skills to share. Therefore they include sophomore standing, a required freshman writing course, and two courses in computer science (introduction to programming and data structures). The course is offered each spring semester and typically has 15-20 students enrolled. Most students are juniors or seniors.

At the graduate level, it is taught in a Masters of Information Systems and Management program as an elective. There are no prerequisites, but given the timeline of the graduate program, students are always in their 2nd or 3rd semester when it is offered. It typically has 15-20 students enrolled.

The course has also been offered as an undergraduate Computer Science course.

What is covered in the course?

This course has service, personal, and intellectual goals. Its service goal is to build the technical capacity of community organizations by providing effective technology consultants. To promote this effectiveness, and to enrich the intellectual preparation of Carnegie Mellon students, the course teaches students how to:

- Establish a professional working relationship
- Quickly assess a complex technical environment and identify problem areas
- Systematically bring structure to unstructured problems
- Communicate technical ideas to an often non-technical audience
- Negotiate with the client acceptable deliverables for the consulting period
- Develop and execute a work plan
- Use writing skills to maintain working documents that describe, plan, persuade, and coordinate work with others
- Reflect and learn from their experience as well as the experience of their colleagues
- Broaden their understanding of the relevance of information systems and computer science.

Students routinely find the experience to be very personally satisfying. Student consultants learn that they can be effective in helping a community organization make better use of its computers, and help its staff and/or volunteers understand more about the technology. Students also often express that it is refreshing to step outside the grind of Carnegie Mellon life and do something worthwhile in the community.

Specific topics include:

- Capacity-Building Consulting and Alternative Consulting Models
- Establishing and Managing Professional Relationships
- Gathering and Analyzing Information
- Structuring unstructured problems
- Researching alternative solutions
- Analyzing Buy vs. Build
- Technology Planning
- Developing and Communicating a Scope of Work and Work Plan
- Modelling Technical Problem Solving
- Communicating Difficult Technical Concepts to a Nontechnical Audience
- Documenting and Analyzing Outcomes
- Formulating Persuasive Recommendations
- Synthesizing a Final Consulting Report
- Orally Presenting Project Outcomes
- Reflecting on the Consulting Experience

More detail on these topics and the course materials are available from the course web site or contact me.

What is the format of the course?

Each student in the course is individually matched with a leader in a local community organization. This is typically a nonprofit organization, school, or a department of municipal government. The student and the partner are expected to spend at least 3 hours a week together, typically onsite at the organization, and each will be doing work outside of that time as well.

The course meets twice a week for 80 minutes each class. About half of class time is lecture, and the rest is small or large group discussion. Four class meetings are special. One is the students' initial meeting with their community partner. Three class meetings are held in small group discussions lead by senior IT professionals who volunteer to mentor students in the class.

How are students assessed?

Assessment is based on:

24% - Homework / Preparation for Class. There are around 15 small assignments.
6% - Status Reports. Students email short updates to all stakeholders after each meeting.
5% - Peer Reviews. Students assess the quality of feedback they get from other students.
15% - Project Report 1: Describes their consulting situation and proposes a scope of work
15% - Project Report 2: Analyses project outcomes & makes recommendations for future work
20% - Project Report 3: Final Consulting Report
5% - Final presentation
5% - Exam reflecting on the consulting process
5% - Community Partner Evaluations

For the major Project Reports, students are given very clear requirements and outlines of desired content. Furthermore, the report goes through at least two cycles of review and revision.

The course models good professional conduct. This requires students to keep or reschedule in advance all meetings, deadlines, and work commitments. To reinforce good professional behavior, unexcused absences and missed deadlines carry very heavy penalties. However, students who communicate early and well concerning meeting conflicts or the need for extended time are given that time liberally.

Course textbooks and materials

All materials are available on the course web site. There is no textbook for the class.

Why do you teach the course this way?
I created the course in Spring 1998. In its history over 400 students have worked one-on-one with nearly 300 local organizations. It has evolved significantly over the past 14 years and continues to do so.

The course goals were stated earlier. In more succinct terms, the course focuses on developing students' professional leadership and communication skills, and to help them understand the social context of computing. Leadership skills cannot be learned from a lecture or book. Rather, they can only be learned by doing. Therefore the class puts students in a leadership position where they are expected to lead a consulting engagement with a client. They are not working *for* the client, rather they are leading a process *with* the client. And they are expected to investigate the situation, propose and execute a plan, and direct the clients' participation in that plan. Similarly, students cannot learn good professional communication skills except by using them in an authentic context.

A more thorough discussion of the course and these learning goals can be found in:

> Mertz, J. and McElfresh, S. 2010. "Teaching communication, leadership, and the social context of computing via a consulting course." In *Proceedings of the 41st ACM Technical Symposium on Computer Science Education* (Milwaukee, Wisconsin, USA, March 10 - 13, 2010). SIGCSE '10. ACM, New York, NY, 77-81. DOI= http://doi.acm.org/10.1145/1734263.1734291

Students find the amount of writing that is required to be challenging. They enjoy the class, however, and by the end of the semester when they see the effects of their work, they tend to be very satisfied. They especially appreciate their experience in working with a community partner. Course evaluations are very good.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Social Context	Social implications of computing in a networked world	3
SP	Analytical Tools	Evaluate stakeholder positions in a given situation.	8
SP	Professional Ethics	The nature of professionalism including care, attention and discipline, fiduciary responsibility, and mentoring	9
SP	Professional Ethics	Accountability, responsibility and liability	1
SP	Professional Communication	Reading, understanding and summarizing technical material, including source code and documentation	2
SP	Professional Communication	Writing effective technical documentation and materials	10
SP	Professional Communication	Dynamics of oral, written, and electronic team and group communication	12
SP	Professional Communication	Communicating professionally with stakeholders	5
SP	Professional Communication	Dealing with cross-cultural environments	1
SP	Professional Communication	Tradeoffs of competing risks in software projects, such as technology, structure/process, quality, people, market and financial	3

Additional topics

The sustainability of technical solutions within a social context is missing from the current draft of the CS Curricula 2013.

Therefore additional significant topics worth mentioning include:

- Being a sustainable practitioner by taking into consideration cultural and environmental impacts of implementation decisions (e.g., organizational policies, economic viability, and resource consumption).
- How the sustainability of software systems are interdependent with social systems, including the knowledge and skills of its users, organizational processes and policies, and its societal context (e.g., market forces, government policies).
- Plan sustainability into projects by accounting for the social context in which the software application will be embedded and deliberately building the capacity to sustain it.

Other comments

This course has been enhanced by the collaboration and teaching of Scott McElfresh who co-taught and taught the course at a few times at Carnegie Mellon. It has been replicated by Steven Andrianoff at St. Bonaventure. It has also inspired a similar course at the University of Alaska in Anchorage where Alex Hills uses the same consulting philosophy and consulting steps and has used and adapted some of my original materials.

Finally, the same approach is embodied in a summer program called *Technology Consulting in the Global Community* that places students in a 10-week summer consulting assignment with a government ministry, nonprofit organization, school, or small business in a developing country.
(See http://cmu.edu/tcingc)

Issues in Computing, Saint Xavier University

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Per University requirements, all course materials are password-protected. Resources are available upon request.

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Social Issues and Professional Practice (SP)	42

Where does the course fit in your curriculum?

Issues in Computing is a *required* 300-level course intended for all junior and senior computing majors. All students must have successfully completed English composition and Speech courses prior to their enrollment in the course. We do admit students who are not at the junior/senior level if they are computing practitioners or have been computing practitioners prior to enrolling in our program. The course is offered annually and has an average enrollment of 25.

What is covered in the course?

In the context of widespread computer usage and society's ever-growing dependence on computer technology, the course focuses on issues of ethics for the computing professional. A list of topics:

- Introduction to Computer Ethics
- Survey of the tools of ethical analysis
- Practical applications of the tools of ethical analysis
- Professional ethics
- Privacy issues
- Intellectual property protection issues
- Freedom of expression and the Internet
- Ethical dimensions of computer system reliability
- Digital Divide
- Social impact of technology in the workplace, in education, in healthcare

What is the format of the course?

It is a 3 credit hour class that has traditionally been face-to-face, with a growing blended online component. Plans to offer it completely online are underway. It has been offered in two 1.5 blocks as well as in one 3 hour block. Within the three contact hours, the distribution of activity is roughly:

- Lecture 15%
- Full class discussion 20%
- Small group work 25%
- Student reports on small group work 15%
- Peer review of assignments 20%
- Individual student presentation 5%

How are students assessed?

The basic grading scheme is designed to emphasize student participation, writing and reflection. Students are expected to spend 9-12 hours per week on outside classwork:

Homework and class participation……. 40%
- All classroom discussions
- Quizzes/short writing assignments on readings
- Web-based forum discussion postings

Essays on specified topics……30%
- Ethical analyses of given situations

Exams……30%
- Take-home midterm
- In-class final

Course textbooks and materials

Current textbook is Brinkman & Sanders, *Ethics in a Computing Culture*, which is supplemented by Abelson et al, *Blown to Bits*, available free of charge in pdf format from bitsbook.com. These books are supplemented *heavily* by current and recent articles from the New York Times, Atlantic Monthly, Technology Review, New Yorker, Chicago Tribune (local), Huffington Post, etc. Readings on computer ethics theory come from the ACM and IEEE digital libraries as well as other sources. We also make use of a variety of websites, including those sponsored by civil liberties organizations (e.g., eff.org, aclu.org), privacy advocacy groups (e.g., epic.org, privacyrights.org), intellectual property rights groups, free/open source advocates (e.g., fsf.org), government sites (e.g., ftc.gov, fcc.gov); we also draw from ethics education sites such as Michael Sandel's Justice website (justiceharvard.org) and Lawrence Hinman's ethics education site (ethics.sandiego.edu). Additionally, we reference a library collection of books and films on a variety of computer ethics and social impact themes.

Why do you teach the course this way?

The overarching goal is to educate students about the practice of professional ethics in the computing field. We situate the special problems faced by computer professionals in the context of widespread computer usage and society's ever-growing dependence on computer technology. We work to develop within our students the critical thinking skills required to identify ethical issues and apply the tools of ethical analysis to address them. Students find this course to be very demanding; they almost always outside their comfort zones. The curriculum for *Issues in Computing* was last reviewed in 2010.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Social Context	All	6
SP	Analytical Tools	All	6
SP	Professional Ethics	All	6*
SP	Intellectual Property	All	6
SP	Privacy/Civil Liberties	All	6
SP	Professional Communication**	Dynamics of oral, written, electronic team communication Communicating effectively with stakeholders Dealing with cross-cultural environments Trade-offs of competing risks in software projects	3
SP	Economies of Computing**	Effect of skilled labor supply & demand on quality of products Impacts of outsourcing & off-shoring software development on employment Consequences of globalization on the computing profession Differences in access to computing resources and their effects	6
SP	Security Policies, Laws, Computer Crime	All	3

*Overlaps many other topics – these instructional hours are dedicated to the topic of professional ethics
**Topics missing from these Knowledge Units are found in other courses in our curriculum, most notably our Software Engineering course and our Capstone Professional Practice Seminar.

Other comments

Many topics in this course can be integrated throughout the computing curriculum in a manner suggested by the cross-listings in CS2013 document. This integration can nicely complement a stand-alone course as described here.

At its core, this course is interdisciplinary, drawing content and pedagogy from computer science, philosophical ethics, sociology, psychology, law and other disciplines. There is great value in placing primary responsibility for this course on the computing faculty, who are recognized by students as content experts who know the computing field's potentials, limitations and realities. The primary instructor can be joined by faculty members from other disciplines in the delivery of the course.

Ethics & the Information Age (CSI 194), Anne Arundel Community College

Arnold, MD
Cheryl Heemstra (crheemstra@aacc.edu), Jonathan Panitz (japanitz@aacc.edu),
Kristan Presnell (lkpresnell@aacc.edu)

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Social Issues and Professional Practice (SP)	41 (plus 4 hours testing)

Where does the course fit in your curriculum?

The course covers two requirements: it is a general education humanities course and it is a program requirement for the Information Assurance and Cybersecurity degree. The course is cross-listed as a Philosophy course since it fulfills the general education (core) requirement. Students are free to take the course at any time but are encouraged to take it in the second year. The only prerequisite for the course is eligibility for college English.

What is covered in the course?

Students learn ethics and moral philosophy as a means for providing a framework for ethically grounded decision making in the information age. Topics include the basic concepts and theories of ethics (moral reasoning and normative frameworks); basic concepts of argumentation and inductive reasoning; an introduction to cyberethics; issues related to networking and network security (threats related to breaches, countering breaches; privacy and personal autonomy (anonymity and accountability, identity theft); intellectual property and ownership rights (Digital Millennium Copyright Act, digital rights management, alternatives to the property model); computing and society, social justice, community, and self-identity digital divide, free speech and censorship; professional ethics and codes of conduct. Four hours are assigned to testing.

What is the format of the course?

CSI 194 Ethics & the Information Age is taught online and face-to-face. Faculty teaching the course are free to present the material in any way they like. Generally there is a combination of lectures, class discussion, case studies, written term papers, and team research and presentation.

Course textbooks and materials

Herman T. Tavani. *Ethics & Technology, Ethical Issues in an Age of Information and Communication Technology,* 3rd Edition*,* John Wiley & Sons, Inc., 2011

Why do you teach the course this way?

Early in our computer security and networking programs, students are trusted with access to the practices, procedures and technologies used to attack and protect valuable information assets and systems. This trust requires an uncompromising commitment to the highest moral and ethical standards. The increasing dependence on and use of technology has created many ethical dilemmas across many disciplines and professions. Many schools are requiring this type of course in programs to address these realities. This is a relatively new area and we would like to be on the cutting edge and provide the work force with students that understand how to apply sound ethical reasoning to various situations. The goal of this course is to provide students in computer and business-related fields with the framework and tools for ethical decision-making in their professions and to heighten ethical awareness of the standards of conduct in these areas.

Ethical decision making is an inductive thought process that is not routinely taught in any normative educational area. This class, which exists on the cutting edge of technological advance, equips the student to think outside the box and apply the new rubric of ethical deliberation to the expanding world of the cyber-arena. The course equips students majoring in Cyberforensics and Cybersecurity to apply practical knowledge to the monumental challenges they will face in their careers as the world of the cyber-arena becomes more and more pervasive and invasive.

When developing this course, we looked at requiring a philosophical ethics class that would count as a general education requirement in the humanities. But the issue we had is that the cases in that course would be divorced from the situations faced by information system security professionals. We wanted the cases to be those that would fit in with our curriculum. In addition, there was not room in our program to have two courses, so we decided to develop one that would count as a general education ethics course and present ethical theory as the basis for examining cases.

We looked at many computer/cyber ethics textbooks and discovered that most of them only provided a cursory overview of ethical theory, if any. This was not enough to warrant classification under general education. We also did not want to require two textbooks because we are mindful of textbook costs for our students. We then found Herman T. Tavani's text that covered ethical theory in depth and provided the practical cases in the field of computer ethics.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Social Context	Social Justice Digital divide Distributive justice theories Accessibility issues Social interaction Cultural issues Commerce, Free Speech and Censorship Define the Internet as public or private space Regulatory agencies and laws regarding regulation in physical space Jurisdictional issues with regulating cyberspace Free speech and hate speech Free speech and pornography	6
SP	Analytical Tools	Introduction to Ethical Thought – values, morals, normative analysis Introduction to Cyberethics Ethical theories – Virtue Ethics, Utilitarianism, Deontology, Just Consequentialism, Social Contract Theory Evaluate stakeholder positions Concepts of argumentation and debate	12
SP	Professional Ethics	Moral responsibility of a professional Pervasive nature of computing applies to all, not only professionals Professional Codes of Conduct Principles of the Joint IEEE-CS/ACM Code of Ethics and Professional Practice Purpose of a code of ethics Weaknesses of codes of ethics Accountability, responsibility and liability	4

SP	Intellectual Property	Overview and history of intellectual property – trade secrets, patents, trademarks, copyrights Philosophical views of property – Labor Theory, Utilitarian Theory, Personality Theory Fair Use Digital Millennium Copyright Act. Digital Rights management Alternatives to the property model – GNU project, Open Source Initiative, Creative Commons Software piracy	6
SP	Privacy and Civil Liberties	Technology's impact on privacy Difference between naturally private and normatively private situations Philosophical foundations of privacy rights Three types of personal privacy – accessibility, decisional, and informational How different cultures view privacy Public and personal information Information matching technique's impact on privacy Legal rights to privacy Solutions for privacy violations	6
SP	Security Policies, Laws and Computer Crimes	Need to protect computer data, systems, and networks Ethical issues related to computer security Social engineering Identity theft Computer hacking Security issues related to anonymity on the Internet Cyberterrorism and information warfare Ethical issues related to cybercrime and cyber-related crimes.	7

Additional topics

Artificial Intelligence and Ambient Intelligence and the impact upon ethical and moral deliberations

Professional Development Seminar, Northwest Missouri State University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Social Issues and Professional Practice (SP)	15 hours

Where does the course fit in your curriculum?

Professional Development Seminar, a required, three hour 200 level course for computer science majors, is taken in the fall of the sophomore year. The student population for this course is approximately 30 undergraduate computer science majors that are required to take this course for their major and 10 international graduate computer science students that elect to take this course.

What is covered in the course?

While the course covers Social and Professional Practice topics such as social context, analytical tools, professional ethics, intellectual property, privacy and civil liberties, this exemplar will focus on professional communications.

The course provides opportunities for students to develop their professional communication skills. This exemplar includes examples of four Professional Communication outcomes:

- Write clear, concise, and accurate technical documents following well-defined standards for format and for including appropriate tables, figures, and references.
- Develop and deliver a good quality formal presentation.
- Plan interactions (e.g. virtual, face-to-face, shared documents) with others in which they are able to get their point across, and are also able to listen carefully and appreciate the points of others, even when they disagree, and are able to convey to others that they have heard.
- Describe the strengths and weaknesses of various forms of communication (e.g. virtual, face-to-face, shared documents)

What is the format of the course?

The course format is face-to-face weekly class meetings with some online threaded discussions which are used to augment face-to-face class discussions. Most class meetings include a short instructor lecture of no more than 10-15 minutes followed by small group topic discussions, consisting of groups of no more than 4-5 students. Additionally, the course utilizes group discussions (face-to-face and online threaded discussion), a group research project, a group research presentation and a unit on preparing for professional interviews which includes a unit on technical resume preparation and technical and situational interview preparation. .

Group Discussions

Students are provided a current news article or issue that pertains to the class topic, asked to read the article before class and then discuss the merits of the article with their group members. Groups of no more than 4-5 students self-select a note taker and spokesperson. The role of the note taker is to record the summary of the group discussion and submit the summary of their discussion by the end of the class period. The spokesperson provides a short summary of their group findings orally to the rest of the class and is provided the opportunity to communicate the group views with the entire class.

Students are also provided online opportunities to discuss topics using online threaded discussions. The instructor selects an article or case study that illustrates issues surrounding a particular topic, such as intellectual property or

privacy. Students are asked to share their individual opinions supported by facts to agree either for or against their particular view. They are also required to respond to other student's threaded discussions and explain why they either agree or disagree with the other person's posts.

Group Research Paper and Presentation
A group of students work to select a research topic, write a group research paper and give a group presentation on the research topic. The group research paper must utilize peer reviewed references as well as follow APA formatting. The group research paper and presentation include several individual and group milestones to encourage students to complete their paper in a timely manner. Students use group collaboration tools in the preparation of their paper.

Student groups give their group research presentation twice during the semester. The first presentation is videotaped and posted online. Students are asked to view their portion of the presentation and write a short paper critiquing their portion of the presentation. Student groups then carry out their final class presentation and are graded on their group presentation.

Professional Interviews Preparation
Students are asked to prepare a professional technical resume and prepare for a mock interview with a "real" industry employer. Students are instructed regarding how to write a professional resume that highlights their technical skills and relevant experiences. Three drafts of their resume are developed in progressive stages. During this process, students receive critiques on their resume from the instructor, the Career Services Office and an industry professional. Students are also required to write a cover letter and prepare a list of references.

Students are instructed on how to prepare for a technical and situational interview. Students participate in a class interview with another student. This practice interview with another student heightens their awareness of what may occur during a "real" interview. Students are also critiqued on their interview skills through a Mock Interview Day in which "real" industry professionals conduct a face-to-face interview and provide feedback on the student's resume and interview skills.

Students are also required to attend a Career Day to meet "real" employers. They are encouraged to set up interviews for summer internships or to make contacts for future internships or full-time employment. In short, students are encouraged to network with employers.

Cross Cultural Skills
Undergraduate and graduate international students work together in groups and are exposed different cultural viewpoints as well as approaches to problem solving.

How are students assessed?

Students receive course points for their professional communication through group work participation, their research paper and presentation and their technical resume development and interview practice and preparation.

Professional Communication Assessment is as follows:

Topic	*Percentage of Final Grade*
Technical Resume Development	10%
Technical Interview Development	14%
Group Research Paper	16%
Group Research Presentation	16%
Discussion Threads	7%
Class/Group Participation	20%
Other Assignments	17%

Course textbooks and materials

A textbook is utilized but most materials for the group work, group research paper and presentation and the professional interview preparation are offered through hand-outs and oral instructions. Students are encouraged to use online library resources and online current articles to support their work.

Why do you teach the course this way?

Professional communication has been emphasized in this course since 2002. This approach has impacted our students' abilities to develop their written and oral communication skills, to learn to discuss social and professional issues with other students, and has enhanced student's ability to obtain internships. A side effect of this intense component of professional communication has allowed students to apply technical skills in a professional environment.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SP	Professional Communication	All	15

The following outcomes are covered in the course under the Professional Communication area.

- Write clear, concise, and accurate technical documents following well-defined standards for format and for including appropriate tables, figures, and references.
- Develop and deliver a good quality formal presentation.
- Plan interactions (e.g., virtual, face-to-face, shared documents) with others in which they are able to get their point across, and are also able to listen carefully and appreciate the points of others, even when they disagree, and are able to convey to others that they have heard.
- Describe the strengths and weaknesses of various forms of communication (e.g., virtual, face-to-face, shared documents)

The Digital Age, Grinnell College

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http://www.cs.grinnell.edu/~davisjan/csc/105/2013S

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Algorithms and Complexity (AL)	2
Architecture and Organization (AR)	8
Graphics and Visualization (GV)	1
Human-Computer Interaction (HCI)	2
Networking and Communication (NC)	2
Software Development Fundamentals (SDF)	6
Social Issues and Professional Practice (SP)	12

Where does the course fit in your curriculum?

The Digital Age is an introductory course for non-majors. It has no prerequisites and does not serve as a prerequisite for any other course. The student population for this course is approximately 25 students each year from all three divisions of the college (science, humanities, and social studies) and all four class years.

What is covered in the course?

The course provides both an introduction to a broad range of computer science topics and discussion of social and ethical issues. Topics vary according to faculty interest and current events.

The technical topics for spring 2013 include:

- Algorithms & efficiency
- Data representation
- Digital logic
- Computer organization
- HTML
- Usability
- Networks
- Programming in Python

Discussion topics include:

- Ethics
- Software reliability
- Digital data & copyright
- Software as intellectual property
- Artificial intelligence
- Data mining
- Privacy & security
- Online education
- Online voting
- Energy

What is the format of the course?
The course meets face-to-face for 3.25 contact hours per week, split into three 65-minute class sessions. Two sessions each week consist of lectures and laboratory exercises on technical topics. The third session is a discussion of social/ethical issues. Students prepare for these discussions by reading several articles and writing a short response paper.

How are students assessed?
Students are assigned:

- 11 homework assignments (slightly fewer than one per week) – typically one large problem or 2-5 medium sized problems, often including writeups of in-class lab exercises. For example, when students learn HTML, they create their own Web site of 2-3 interlinked pages. When they learn digital logic, they design simple circuits.
- 2 in-class exams: a midterm and a cumulative final.
- 10 reading response papers, 1-2 pages each, one for each discussion topic.
- An "emerging technology analysis": a 4-5 page paper accompanied by a 4-minute "lightning" presentation. Students identify a new technology (reported within the last two years) and analyze its social or ethical implications.

Course textbooks and materials
The course currently does not use a textbook. Online readings are used to augment lectures on some technical topics.

Readings on social and ethical issues are drawn from the *CACM*, particularly the columns, which often focus on social and ethical issues. For example, the following readings are assigned for the topic of energy and sustainability:

- P. Kurp. Green computing. *CACM* 51(10): 11-13.
- G. Mone. Redesigning the data center. *CACM* 55(10): 14-16.
- M. Garrett. Powering down. *CACM* 51(9): 43-46.
- R.T. Watson. Corbett, M.C. Boudreau, and J. Webster. An information strategy for environmental sustainability. *CACM* 55(7): 28-30.
- T. Kostyk and J. Herkert. Societal implications of the emerging smart grid. *CACM* 55(11): 34-36.

Readings from the *CACM* are sometimes augmented with online news articles about current events.

Why do you teach the course this way?
The course is intended to appeal to a broad range of students, but particularly those who are interested in approaching computing from the perspective of intellectual curiosity and informed citizenship. Students who want to learn to program or who intend to become computer science majors typically begin with our other introductory course, CSC 151, *Functional Problem Solving*.

Major objectives for the course include:

- Fluency in basic computing concepts, components, and operation
- Learning how computers can be used to solve problems and create new things
- Sharpening analytical and problem-solving skills
- Understanding legal, social, and ethical implications of both existing and potential technologies

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Best, expected, worst case Empirical measurements of performance	1
AL	Basic Automata Computability and Complexity	Intractable problems Halting problem	1

AR	Digital logic and digital systems	Logic circuits Building blocks of a computer	2
AR	Machine-level representation of data	Bits, bytes, and words Numeric data representation and number bases Fixed- and floating-point systems Signed and twos-complement representations Representation of non-numeric data (character codes, graphical data)	4
AR	Assembly level machine organization	Basic organization of the von Neumann machine Control unit; instruction fetch, decode, and execution Assembly/machine language programming Instruction formats	2
GV	Fundamental Concepts	Standard image formats, including lossless and lossy formats	1
HCI	Foundations	Contexts for HCI (anything with a user interface: webpage, business applications, mobile applications, games, etc.) Different measures for evaluation: utility, efficiency, learnability, user satisfaction. Physical capabilities that inform interaction design: color perception, ergonomics Cognitive models that inform interaction design: attention, perception and recognition, movement, and memory. Gulfs of expectation and execution. Accessibility: interfaces for differently-abled populations (e.g., blind, motion-impaired)	2
NC	Introduction	Organization of the Internet (Internet Service Providers, Content Providers, etc.) Physical pieces of a network (hosts, routers, switches, ISPs, wireless, LAN, access point, firewalls, etc.) Roles of the different layers (application, transport, network, datalink, physical)	1
NC	Networked Applications	Naming and address schemes (DNS, IP addresses, Uniform Resource Identifiers, etc.) Distributed applications (client/server, peer-to-peer, cloud, etc.) HTTP as an application layer protocol	1
SDF	Algorithms and Design	The concept and properties of algorithms ○ Informal comparison of algorithm efficiency (e.g., operation counts) The role of algorithms in the problem-solving process Problem-solving strategies ○ Iterative traversal of data structures ○ Divide-and-conquer strategies	2
SDF	Fundamental Programming Concepts	Basic syntax and semantics of a higher-level language Variables and primitive data types (e.g., numbers, characters, Booleans) Expressions and assignments Simple I/O including file I/O Conditional and iterative control structures	4

SP	Social Context	Online education Electronic voting Robots and artificial intelligence Self-directed research & presentations on emerging technology	5
SP	Analytical Tools	Ethical argumentation Ethical theories and decision-making Moral assumptions and values	1
SP	Professional Ethics	Accountability, responsibility and liability (e.g. software correctness, reliability and safety)	1
SP	Intellectual Property	Intellectual property rights Intangible digital intellectual property (IDIP) Legal foundations for intellectual property protection Digital rights management Copyrights, patents Foundations of the open source movement Software piracy	2
SP	Privacy and Civil Liberties	Legal foundations of privacy protection Privacy implications of widespread data collection	2
SP	Sustainability	Explore global social and environmental impacts of computer use and disposal (particularly energy)	1

Additional topics
HTML (2 hours)

COS 126: General Computer Science, Princeton University

Princeton, NJ
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http://www.cs.princeton.edu/courses/archive/spring12/cos226/info.php
http://algs4.cs.princeton.edu

Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	11
Algorithms and Complexity (AL)	11
Architecture and Organization (AR)	5
Programming Languages (PL)	4
Computational Science (CN)	1
Social Issues and Professional Practice (SP)	1
Intelligent Systems (IS)	1

Where does the course fit in your curriculum?

This course is an introduction to computer science, intended for all first-year students. It is intended to be analogous to commonly accepted introductory courses in mathematics, physics, biology, and chemistry. It is not just a "first course for CS majors" but also an introduction to the field that is taken by over 60% of all Princeton students.

What is covered in the course?

We take an interdisciplinary approach to the traditional CS1 curriculum, where we teach students to program while highlighting the role of computing in other disciplines, then take them through fundamental precepts of the field of computer science. This approach emphasizes for students the essential idea that mathematics, science, engineering, and computing are intertwined in the modern world, while at the same time preparing students to use computers effectively for applications in computer science, physics, biology, chemistry, engineering, and other disciplines. Instructors teaching students who have successfully completed this course can expect that they have the knowledge and experience necessary to enable them to adapt to new computational environments and to effectively exploit computers in diverse applications. At the same time, students who choose to major in computer science get a broad background that prepares them for detailed studies in the field.
Roughly, the first half of the course is about learning to program in a modern programming model, with applications. The second half of the course is a broad introduction to the field of computer science.

- Introduction to programming in Java. Elementary data types, control flow, conditionals and loops, and arrays.
- Input and output.
- Functions and libraries.
- Analysis of algorithms, with an emphasis on using the scientific method to validate hypotheses about algorithm performance.
- Machine organization, instruction set architecture, machine language programming.
- Data types, APIs, encapsulation.
- Linked data structures, resizing arrays, and implementations of container types such as stacks and queues.

- Sorting (mergesort) and searching (binary search trees).
- Programming languages.
- Introduction to theory of computation. Regular expressions and finite automata.
- Universality and computability.
- Intractability.
- Logic design, combinational and sequential circuits.
- Processor and memory design.
- Introduction to artificial intelligence.

What is the format of the course?

The material is presented in two one-hour lectures per week, supported by two one-hour sections covered by experienced instructors teaching smaller groups of students. Roughly, one of these hours is devoted to presenting new material that might be covered in a lecture hour; the other is devoted to covering details pertinent to assignments and exams.

How are students assessed?

Programming projects. The bulk of the assessment is weekly programming assignments, which usually involve solving an interesting application problem that reinforces a concept learned in lecture. Students spend 10-20 hours per week on these assignments and often consult frequently with section instructors for help. Examples include:

- Monte Carlo simulation of random walks.
- Graphical simulation of the N-body problem.
- Design and plot a recursive pattern.
- Implement a dynamic programming solution to the global DNA sequence alignment problem.
- Simulate a linear feedback shift register and use it to encrypt/decrypt an image.
- Simulate plucking a guitar string using the Karplus-Strong algorithm and use it to implement an interactive guitar player.
- Implement two greedy heuristics to solve the traveling salesperson problem.
- Re-affirm the atomic nature of matter by tracking the motion of particles undergoing Brownian motion, fitting this data to Einstein's model, and estimating Avogadro's number.

In-class programming tests. At mid-term and at the end of the semester, students have to solve mini-programming assignments (that require 50-100 lines of code to solve) in a supervised environment in 1.5 hours. Practice preparation for these tests is a significant component in the learning experience.
Hourly exams. At mid-term and at the end of the semester, students take traditional hourly exams to test their knowledge of the course material.

Course textbooks and materials.

The first half of the course is based on the textbook *Introduction to Programming in Java: An Interdisciplinary Approach* by Robert Sedgewick and Kevin Wayne (Addison-Wesley, 2008). The book is supported by a public "booksite" (http://introcs.cs.princeton.edu) that contains a condensed version of the text narrative (for reference while online), Java code for the algorithms and clients in the book and many related algorithms and clients, test data sets, simulations, exercises, and solutions to selected exercises. The booksite also has lecture slides and other teaching material for use by faculty at other universities.
A separate website specific to each offering of the course contains detailed information about schedule, grading policies, and programming assignments.

Why do you teach the course this way?

The motivation for this course is the idea that knowledge of computer science is for everyone, not just for programmers and computer science students. Our goal is to demystify computation, empower students to use it effectively and to build awareness of its reach and the depth of its intellectual underpinnings. We teach students to program in a familiar context to prepare them to apply their skills in later courses in whatever their chosen field and to recognize when further education in computer science might be beneficial.

Prospective computer science majors, in particular, can benefit from learning to program in the context of scientific applications. A computer scientist needs the same basic background in the scientific method and the same exposure to the role of computation in science as does a biologist, an engineer, or a physicist.
Indeed, our interdisciplinary approach enables us to teach prospective computer science majors and prospective majors in other fields of science and engineering in the same course. We cover the material prescribed by CS1, but our focus on applications brings life to the concepts and motivates students to learn them. Our interdisciplinary approach exposes students to problems in many different disciplines, helping them to more wisely choose a major. Our reach has expanded beyond the sciences and engineering, to the extent that we are one of the most popular science courses taken by students in the humanities and social sciences, as well.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SDF	Algorithms and Design	The concept and properties of algorithms. The role of algorithms in the problem-solving process. Problem-solving strategies. Implementation of algorithms. Fundamental design concepts and principles	2
SDF	Fundamental Programming Concepts	Basic syntax and semantics of a higher-level language. Variables and primitive data types. Expressions and assignments. I/O. Conditional and iterative control structures	3
SDF	Fundamental Data Structures	Arrays, stacks, queues, priority queues, strings, references, linked structures, resizable arrays. Strategies for choosing the appropriate data structure.	3
SDF	Development Methods	Program correctness. Modern programming environments. Debugging strategies. Documentation and program style.	3
PL	Object-Oriented programming	Object-oriented design, encapsulation, iterators.	2
PL	Basic Type Systems	Primitive types, reference types. Type safety, static typing. Generic types.	2
AL	Basic Analysis	Asymptotic analysis, empirical measurements. Differences among best, average, and worst case behaviors of an algorithm. Complexity classes, such as constant, logarithmic, linear, quadratic, and exponential. Time and space trade-offs in algorithms.	2
AL	Algorithmic Strategies	Brute-force, greedy, divide-and-conquer, and recursive algorithms. Dynamic programming, reduction.	2

AL	Fundamental Data Structures and Algorithms	Binary search. Insertion sort, mergesort. Binary search trees, hashing. Representations of graphs. Graph search.	3
AL	Basic Automata, Computability and Complexity	Finite-state machines, regular expressions, P vs. NP, NP-completeness, NP-complete problems	2
AL	Advanced Automata, Computability and Complexity	Languages, DFAs. Universality. Computability.	2
AR	Architecture and Organization	Overview and history of computer architecture, Combinational vs. sequential logic	1
AR	Machine Representation of Data	Bits, bytes, and words, Numeric data representation and number bases, Fixed- and floating-point systems, Signed and twos-complement representations. Representation of non-numeric data. Representation of records and arrays	1
AR	Assembly level machine organization	Basic organization of the von Neumann machine. Control unit; instruction fetch, decode, and execution. Instruction sets and types. Assembly/machine language programming. Instruction formats. Addressing modes	2
AR	Functional Organization	Control unit. Implementation of simple datapaths.	1
CN	Fundamentals	Introduction to modeling and simulation.	1
IS	Fundamental Issues	Overview of AI problems. Examples of successful recent AI applications	1
SP	History	History of computer hardware and software. Pioneers of computing.	1

CSCI 0190: Accelerated Introduction to Computer Science, Brown University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Programming Languages (PL)	13
Software Development Fundamentals (SDF)	10
Software Engineering (SE)	6
Algorithms and Complexity (AL)	5
Parallel and Distributed Computing (PD)	1

Where does the course fit in your curriculum?

Brown has three introductory computing sequences as routes into the curriculum. The other two are spread over a whole year, and cover roughly a semester of content in programming and a semester of algorithms and data structures. This course, which is one of these, compresses most of this material into a single semester.

Students elect into this course, either through high school achievement or performance in the early part of one of the other sequences.

Approximately 30 students it every year, compared to 300-400 in the other two sequences.

What is covered in the course?

The course is a compressed introduction into programming along with basic algorithms and data structures. It interleaves these two. The data structures cover lists, trees, queues, heaps, DAGs, and graphs; the algorithms go up through classic ones such as graph shortest paths and minimum spanning trees. The programming is done entirely with pure functions. It begins with graphical animations (such as simple video games), then higher-order functional programming, and encodings of laziness.

What is the format of the course?

Classroom time is a combination of lecture and discussion. We learn by exploration of mistakes.

How are students assessed?

There are about ten programming assignments. Students spend over 10 and up to 20 hours per week on the course.

Course textbooks and materials

There is no textbook. Students are given notes and code from class.

All programming is done in variations of the Racket programming language using the DrRacket programming environment.

Why do you teach the course this way?
The material of the course is somewhat constrained by the department's curricular needs. However, the arrangement represents my desires.

In interleaving programming and algorithmic content to demonstrate connections between them, I am especially interested in ways in which programming techniques enhance algorithmic ones: for instance, the use of memoization to alter a computation's big-*O* performance (and the trade-offs in program structure relative to dynamic programming).

The course is revised every year, based on the previous year's outcome.

Students consider the course to be extremely challenging, and of course recommend it only for advanced students.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Advanced Data Structures, Algorithms, and Analysis	Balanced trees, graphs, string-based data structures, amortized analysis	5
PD	Parallelism Fundamentals	Parallel data structures, map-reduce	1
PL	Object-Oriented Programming	All	3
PL	Functional Programming	All	6
PL	Event-Driven and Reactive Programming	All	2
PL	Basic Type Systems	All	2
SDF	All	All	10
SE	Software Design	Design recipe	3
SE	Software Verification Validation	Test suites, testing oracles, test-first development	3

An Overview of the Two-Course Intro Sequence, Creighton University

The Computer Science & Informatics program at Creighton University serves students with a wide range of interests. These include traditional computer science students who plan for careers in software development or graduate studies, as well as students whose interests overlap with business analytics, graphics design, and even journalism. All majors in the department take a foundational sequence in information, consisting of introductory informatics, professional writing, Web design, and CS0. The computer science major begins with a two-course introductory programming sequence, which covers almost all of the Software Development Fundamentals (SDF) Knowledge Area, along with Knowledge Units from Programming Languages (PL), Algorithms and Complexity (AL), Software Engineering (SE), and others. The two introductory programming courses are:

CSC 221: Introduction to Programming

- Language: Python
- Focus: Fundamental programming concepts/techniques, writing small scripts

CSC 222: Object-Oriented Programming

- Language: Java
- Focus: object-oriented design, designing and implementing medium-sized projects

It should be noted that in the course exemplars for these two courses, there is significant overlap in SDF Topics Covered. Many of the software development topics are introduced in the first course (in Python, following a procedural approach), then revisited in the second course (in Java, following an object-oriented approach).

CSC 221: Introduction to Programming, Creighton University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	30
Programming Languages (PL)	5
Algorithms and Complexity (AL)	4
Social Issues and Professional Practice (SP)	1

Where does the course fit in your curriculum?

This is the first course in the introductory programming sequence. It is required for all computer science majors. Many students will have already taken or will concurrently take CSC 121, Computers and Scientific Thinking, which is a requirement of the computer science major (but not an explicit prerequisite for this course). CSC 121 is a balanced CS0 course that provides some experience with programming (developing interactive Web pages using JavaScript and HTML) while also exploring a breadth of computer science topics (e.g., computer organization, history of computing, workings of Internet & Web, algorithms, digital representation, societal impact). This course is offered every semester, with an enrollment of 20-25 students per course.

What is covered in the course?

This course provides an introduction to problem solving and programming using the Python scripting language. The specific goals of this course are:

- To develop problem solving and programming skills to enable the student to design solutions to non-trivial problems and implement those solutions in Python.
- To master the fundamental programming constructs of Python, including variables, expressions, functions, control structures, and lists.
- To build a foundation for more advanced programming techniques, including object-oriented design and the use of standard data structures (as taught in CSC 222).

What is the format of the course?

The course meets twice a week for two hours (although it only counts as three credit hours). The course is taught in a computer lab and integrates lectures with lab time.

How are students assessed?

Students complete 6-8 assignments, which involve the design and implementation of a Python program and may also include a written component in which the behavior of the program is analyzed. There are "random" daily quizzes to provide student feedback (quizzes are handed out but administered with a 50% likelihood each day). There are two 75-minute tests and a cumulative 100-minute final exam.

Course textbooks and materials

Free Online Texts:

Scratch for Budding Computer Scientists, David J. Malan.
Learning with Python: Interactive Edition, Brad Miller and David Ranum (based on material by Jeffrey Elkner, Allen B. Downey, and Chris Meyers).

Optional Text:

Python Programming: An Introduction to Computer Science (2nd ed.), John Zelle.

Why do you teach the course this way?

This course was revised in 2011 to use Python. Previously, it was taught in Java using an object-oriented approach. It was felt that the overhead of the language was too much for beginners, and the object-orientated approach was not ideal for the range of students taking this course (which include business, graphic design, and journalism majors). A scripting language, such as Python, allowed for a stronger problem-solving focus and prepared non-majors to take high-demand courses such as Web Programming and Mobile Development.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SDF	Algorithms and Design	concept & properties of algorithms; role of algorithms in problem solving; problem solving strategies (iteration, divide & conquer); implementation of algorithms; design concepts & principles (abstraction, decomposition)	8
SDF	Fundamental Programming Concepts	syntax & semantics; variables & primitives, expressions & assignments; simple I/O; conditionals & iteration; functions & parameters	8
SDF	Fundamental Data Structures	arrays; records; strings; strategies for choosing the appropriate data structure	8
SDF	Development Methods	program correctness (specification, defensive programming, testing fundamentals, pre/postconditions); modern environments; debugging strategies; documentation & program style	6
PL	Object-Oriented Programming	object-oriented design; classes & objects; fields & methods	3
PL	Basic Type Systems	primitive types; type safety & errors	1
PL	Language Translation	interpretation; translation pipeline	1
AL	Fundamental Data Structures and Algorithms	simple numerical algorithms; sequential search; simple string processing	4
SP	History	history of computer hardware; pioneers of computing; history of Internet	1

CSC 222: Object-Oriented Programming, Creighton University

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	19
Programming Languages (PL)	11
Algorithms and Complexity (AL)	7
Software Engineering (SE)	3

Where does the course fit in your curriculum?

This is the second course in the introductory programming sequence, following CSC 221 (Introduction to Programming). Students must have completed CSC 221 or otherwise demonstrate competence in some programming language. It is offered every spring, with an enrollment of 20-25 students.

What is covered in the course?

Building upon basic programming skills in Python from CSC 221, this course focuses on the design and analysis of larger, more complex programs using the industry-leading language, Java. The specific goals of this course are:

- To know and use basic Java programming constructs for object-oriented problem solving (e.g., classes, polymorphism, inheritance, interfaces)
- To appreciate the role of algorithms and data structures in problem solving and software design (e.g., objected-oriented design, lists, files, searching and sorting)
- To be able to design and implement a Java program to model a real-world system, and subsequently analyze its behavior.
- To develop programming skills that can serve as a foundation for further study in computer science.

What is the format of the course?

The course meets twice a week for two hours (although it only counts as three credit hours). The course is taught in a computer lab and integrates lectures with lab time.

How are students assessed?

Students complete 5-7 assignments, which involve the design and implementation of a Python program and may also include a written component in which the behavior of the program is analyzed. There are "random" daily quizzes to provide student feedback (quizzes are handed out but administered with a 50% likelihood each day). There are two 75-minute tests and a cumulative 100-minute final exam.

Course textbooks and materials

Objects First with Java, 5th edition, David Barnes and Michael Kolling.

Why do you teach the course this way?

This course was revised in 2011. Previously, it was part of a two-course intro sequence in Java that integrated programming fundamentals, problem solving, and object-oriented design. The new division, in which basic

programming (scripting) is covered in the first course and object-oriented design is covered in this second, is proving much more successful.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
SDF	Algorithms and Design	all topics (including recursion, encapsulation, information hiding)	4
SDF	Fundamental Programming Concepts	all topics (including recursion)	4
SDF	Fundamental Data Structures	all topics, with the possible exception of priority queues, sets and maps (which are covered in the subsequent Data Structures course)	5
SDF	Development Methods	all topics	6
PL	Object-Oriented Programming	all topics	9
PL	Basic Type Systems	reference types; generic types	2
AL	Basic Analysis	best/average/worst case behavior; asymptotic analysis; Big O; empirical measurement	3
AL	Fundamental Data Structures and Algorithms	sequential and binary search; $O(N^2)$ sorts, O(N log N) sorts	4
SE	Software Design	design principles; structure & behavior	1
SE	Software Construction	defensive coding; exception handling	1
SE	Software Verification and Validation	verification & validation; testing fundamentals (unit testing, test plan creation)	1

An Overview of the Mulit-paradigm Three-course CS Introduction at Grinnell College

Consistent with both CS 2008 and CS 2013, the CS program at Grinnell College follows a multi-paradigm approach in its introductory curriculum. Since each course emphasizes problem solving following a specified paradigm, students gain practice by tackling a range of problems. Toward that end, the first two courses utilize application themes to generate interesting problems and generate interest in interdisciplinary connections of computer science. The following list outlines some main elements of this approach:

CSC 151: Functional Problem Solving (CS1)
- Primary Paradigm: Functional problem solving
- Supporting language: Scheme
- Application area: image processing, media scripting

CSC 161: Imperative Problem Solving and Data Structures (CS2)
- Primary Paradigm: Imperative problem solving
- Supporting language: C (no objects as in C++)
- Application area: robotics

CSC 207: Algorithms and Object-Oriented Design (CS3)
- Primary Paradigm: Object-oriented problem solving
- Supporting language: Java
- Application areas: several large-scale problems

Audience: As with many liberal arts colleges, incoming students at Grinnell have not declared a major. Rather students devote their first and/or second year to exploring their possible interests, taking a range of introductory courses, and developing a general background in multiple disciplines. Often students in introductory computer science are taking courses because of some interest in the subject or because they think some contact with computing might be important for their future activities within a technological society. An important role of the introductory courses, therefore, is to generate interest in the discipline. Although some students enter Grinnell having already decided to major in computer science, over half of the CS graduates each year had not initially considered CS as a likely major. Rather, they became interested by the introductory courses and want to explore the discipline further with more courses.

Pedagogy: Each class session of each course meets in a lab, and each course utilizes many collaborative lab exercises throughout a semester. Generally, CSC 151 schedules a lab almost every day, with some introductory comments at the start of class. CSC 161 is composed of about eight 1.5-2 week modules, in which each module starts with a lecture/demonstration, followed by 3-5 labs, and concluded by a project. CSC 207 contains about the same number of class days devoted to lecture as to lab work. Throughout, students work in pairs on labs, and the pairs typically are changed each week. Students work individually on tests and on some additional homework (usually programming assignments).

Spiral Approach for Topic Coverage: The multi-paradigm approach allows coverage of central topics to be addressed incrementally from multiple perspectives. One course may provide some introductory background on a subject, and a later course in the sequence may push the discussion further from the perspective of a different problem-solving paradigm. For example, encapsulation of data and operations arises naturally as higher-order procedures within functional problem solving and later as classes and objects within object-oriented problem solving.

One way to document this spiral approach tracks time spent on various Knowledge Areas through the three-course sequence:

Knowledge Area	**CSC 151 Functional Problem-solving**	**CSC 161 Imperative Problem-solving and Data Structures**	**CSC 207 Algorithms and Object-Oriented Design**	**Total Grinnell Intro-CS Hours**
Algorithms and Complexity (AL)	6	1	14	21
Architecture and Organization (AR)		3		3
Computational Science (CN)		1	1	2
Graphics and Visualization (GV)	2			2
Human-Computer Interaction (HCI)	4			4
Information Assurance and Security (IAS)		1		1
Intelligent Systems (IS)		1		1
Programming Languages (PL)	13	9	12	34
Software Development Fundamentals (SDF)	20	27	16	63
Software Engineering (SE)	3	3	4	10
Social Issues and Professional Practice (SP)		2	1	3

CSC 151: Functional problem solving, Grinnell College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	20
Programming Languages (PL)	13
Algorithms and Complexity (AL)	6
Human-Computer Interaction (HCI)	4
Software Engineering (SE)	3
Graphics and Visualization (GV)	2

Brief description of the course's format and place in the undergraduate curriculum

This course is the first in Grinnell's three-course, multi-paradigm introduction to computer science. As the first regular course, it has no prerequisites. Many students are in their first or second year, exploring what the discipline might involve. Other students (ranging from first-years to graduating seniors) take the course as part of gaining a broad, liberal arts education; these students may be curious about computing, but they think their major interests are elsewhere. (Note, however, that the course recruits a number of these students as majors or concentrators.) Each class session meets in the lab. A class might begin with some remarks or class discussion, but most classes involve students working collaboratively in pairs on problems and laboratory exercises.

Course description and goals

This course introduces the discipline of computer science by focusing on functional problem solving with media computation as an integrating theme. In particular, the course explores
mechanisms for representing, making, and manipulating images. The course considers a variety of models of images based on pixels, basic shapes, and objects that draw.
The major objectives for this course include:

- Understanding some fundamentals of computer science: algorithms, data structures, and abstraction.
- Experience with the practice of computer programming (design, documentation, development, testing, and debugging) in a high-level language, Scheme.
- Learning problem solving from a functional programming perspective, including the use of recursion and higher-order procedures.
- Sharpening general problem solving, teamwork, and study skills.

Course topics

1. Fundamentals of functional problem-solving using a high-level functional language
    1. abstraction
    2. modularity
    3. recursion, including helper procedures
    4. higher-order procedures
    5. analyzing of algorithms
2. Language elements
    1. symbols
    2. data types
    3. conditionals
    4. procedures and parameters
    5. local procedures
    6. scope and binding

3. Data types and structures
    1. primitive types
    2. lists
    3. pairs, pair structures, and association lists
    4. trees
    5. raster graphics and RGB colors
    6. objects in Scheme
4. Algorithms
    1. searching
    2. sorting
    3. transforming colors and images
5. Software development
    1. design
    2. documentation
    3. development
    4. testing, including unit testing
    5. debugging

Course textbooks, materials, and assignments

This course relies upon an extensive collection of on-line materials (readings, labs); there is no published textbook. As with most courses offered by Grinnell's CS Department, this course has a detailed, on-line, day-by-day schedule of topics, readings, labs and assignments. This daily schedule contains a link to all relevant pages, handouts, labs, references, and materials.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Fundamental Data Structures and Algorithms	Max/min, search, two sorts	6
AL	Algorithmic Strategies	Some divide-and-conquer mentioned	0
GV	Fundamental Concepts	Elements of graphics introduced as part of image-processing application theme	2
HCI	Designing Interaction	Overview covers much of Knowledge Unit	4
PL	Object-oriented Programming	Objects as higher-order procedures; much additional material in later courses	2
PL	Functional Problem-solving	Knowledge Unit covered in full	7
PL	Type Systems	Types, primitive types, compound list type, dynamic types, binding	1
PL	Language Translation and Execution	Program interpretation, encapsulation, basic algorithms to avoid mutable state in context of functional language	3
SDF	Algorithms and Design	Coverage of recursion-based topics	8
SDF	Fundamental Programming Concepts	Topics related to recursion and functional problem-solving covered thoroughly	9
SDF	Fundamental Structures	Lists and arrays (vectors) covered, some elements of string processing	3
SE	Software Verification and Validation	Specifications, pre- and post-conditions, unit testing	3

CSC 161: Imperative Problem Solving and Data Structures, Grinnell College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	27
Programming Languages (PL)	9
Architecture and Organization (AR)	3
Software Engineering (SE)	3
Social Issues and Professional Practice (SP)	2
Algorithms and Complexity (AL)	1
Computational Science (CN)	1
Information Assurance and Security (IAS)	1
Intelligent Systems (IS)	1

Brief description of the course's format and place in the undergraduate curriculum

This course is the second in Grinnell's three-course, multi-paradigm introductory CS sequence. Many students are first- or second-year students who are exploring computer science as a possible major (after becoming interested in the subject from the first course). Other students may enroll in the course to broaden their liberal arts background or to learn elements of imperative problems solving and C to support other work in the sciences or engineering. As with Grinnell's other introductory courses, each class session meets in a lab, and work flows seamlessly between lecture and lab-based activities. Work generally is divided into eight 1.5-2 week modules. Each module begins with a lecture giving an overview of topics and demonstrating examples. Students then work collaborative in pairs on 3-5 labs, and the pairs change for each module. Each module concludes with a project that integrates topics and applies the ideas to an interesting problem.

Course description and goals

This course utilizes robotics as an application domain in studying imperative problem solving, data representation, and memory management. Additional topics include assertions and invariants, data abstraction, linked data structures, an introduction to the GNU/Linux operating system, and programming the low-level, imperative language C.

Course topics

This course explores elements of computing that have reasonably close ties to the architecture of computers, compilers, and operating systems. The course takes an imperative view of problem solving, supported by programming in the C programming language. Some topics include:

- *imperative problem solving:* top-down design, common algorithms, assertions, invariants
- *C programming:* syntax and semantics, control structures, functions, parameters, macro processing, compiling, linking, program organization
- *concepts with data:* data abstraction, integer and floating-point representation, string representation, arrays, unions, structures, linked list data structures, stacks, and queues
- *machine-level issues:* data representation, pointers, memory management
- *GNU/Linux operating system:* commands, bash scripts, software development tools

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Fundamental Data Structures and Algorithms	Simple numerical algorithms, searching and sorting within an imperative context	1
AR	Machine level representation of data	Knowledge Unit covered in full	3
CN	Fundamentals	Several examples, problems, and assignments introduce modeling and simulation; Math/Stat Dept. offers a full course in Modeling	1
IAS	Fundamental Concepts	Issues of bounds checking, buffer overflow, impact introduced; other topics mentioned in later courses	1
IS	Robotics	Introduction to problems, progress, control, sensors, inherent uncertainty	1
PL	Type Systems	Static types, primitive and compound times, references, error detection of type errors	2
PL	Program Representation	Use of interpreters, compilers, type-checkers, division of programs over multiple files; higher-level materials in later Programming Language Concepts course	2
PL	Language Translation and Execution	Compilation, interpretation vs. compilation, language translation basics, run-time representation, run-time memory layout, manual memory management	5
SDF	Algorithms and Design	Coverage of iteration-based topics	0
SDF	Fundamental Programming Concepts	Topics related to iteration and imperative problem-solving covered thoroughly	10
SDF	Fundamental Structures	Low-level discussion of arrays, records, structs, strings, stacks, queues, linked structures	14
SDF	Development Methods	Program correctness, pre- and post-conditions, testing, debugging, libraries	3
SE	Tools and Environments	Testing tools, automated builds; additional material in later Software Design course	1
SE	Software Design	System design principles, component structure and behavior	1
SE	Software Verification and Validation	Test plans, black-box, white-box testing	1
SP	Social Context	Some discussion of social implications (e.g., of robots)	1
SP	Professional Communication	Group communications, introduction to writing of technical documents	1

CSC 207: Algorithms and Object-Oriented Design, Grinnell College

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Knowledge Areas that contain topics and learning outcomes covered in the course

Knowledge Area	Total Hours of Coverage
Software Development Fundamentals (SDF)	16
Algorithms and Complexity (AL)	14
Programming Languages (PL)	12
Software Engineering (SE)	3
Computational Science (CN)	1
Systems Fundamentals (SF)	1
Social Issues and Professional Practice (SP)	1

Brief description of the course's format and place in the undergraduate curriculum

This course is the third in Grinnell's three-course, multi-paradigm introductory CS sequence. Many students are second-year students, but the course also attracts third-year and fourth-year students who are majoring in other fields but also want to expand their background on topics they found interesting in the first two courses. As with Grinnell's other introductory courses, each class session meets in a lab, and work flows seamlessly between lecture and lab-based activities. The course includes a significant emphasis on collaboration in pairs during 23 in-class labs. Additional programming assignments and tests are done individually. All course materials, including readings and all labs, are available freely over the World Wide Web.

Course description and goals

CSC 207, Algorithms and Object-Oriented Design, explores object-oriented problem solving using the Java programming language. Topics covered include principles of object-oriented design and problem solving, abstract data types and encapsulation, data structures, algorithms, algorithmic analysis, elements of Java programming, and an integrated development environment (IDE) (e.g., Eclipse).

Course topics

Topics and themes covered include:

- Principles of object-oriented design and problem solving
  - Objects and classes
  - Encapsulation, abstraction, and information hiding
  - Inheritance
  - Polymorphism
  - Unit testing
  - Integration testing
- Abstract data types, data structures, and algorithms
  - Dictionaries
  - Hash tables
  - Binary search trees
  - Priority queues
  - Heaps
- Algorithmic analysis
  - Upper-bound efficiency analysis; Big-O Notation

    - Comparison of results for small and large data sets
    - Introduction of tight-bound analysis (Big-θ)
- Elements of Java programming
    - Basic syntax and semantics
    - Interfaces and classes
    - Exceptions
    - Strings
    - Arrays, ArrayLists, vectors
    - Comparators; sorting
    - Generics
    - Java type system
    - Iterators
    - Introduction to the Java class library
- An integrated development environment (IDE) (e.g., Eclipse)

Course textbooks, materials, and assignments

The main textbook is Mark Allen Weiss, *Data Structures and Problem Solving Using Java,* Fourth Edition, Addison-Wesley, 2009. ISBN: 0-321-54040-5. This is supplemented by numerous on-line readings. In-class work involves an equal mix of lecture and lab-based activities. Students work collaboratively in pairs on the 23 required labs. Students also work individually on several programming assignments and on tests.

Body of Knowledge coverage

KA	Knowledge Unit	Topics Covered	Hours
AL	Basic Analysis	Knowledge Unit covered in full; additional material in later Analysis of Algorithms course	5
AL	Algorithmic Strategies	Divide and conquer ; much more in later Analysis of Algorithms course	1
AL	Fundamental Data Structures and Algorithms	Additional sorting, trees, analysis of algorithms; searching and sorting done in earlier course; graphs in later Analysis of Algorithms course	8
CN	Fundamentals	Several examples, problems, and assignments utilize modeling and simulation; Math/Stat Dept. offers a full course in Modeling	1
PL	Object-Oriented Programming	Knowledge Unit covered in full	10
PL	Type Systems	Supplement to discussion in earlier courses to cover Knowledge Unit in full; additional material in later Programming Language Concepts course	2
PL	Language Translation and Execution	Automatic vs. manual memory management, garbage collection	0
SDF	Algorithms and Design	Comparison of iterative and recursive strategies	3
SDF	Fundamental Programming Concepts	Simple I/O, iteration over structures (e.g., arrays)	2
SDF	Fundamental Structures	Stacks, queues, priority queues, sets, references and aliasing, choosing data structures covered in object-oriented context	5
SDF	Development Methods	Program correctness, defensive programming, exceptions, code reviews, test-case generation, pre- and post-conditions, modern programming environments, library APIs, debugging, documentation, program style	6

SE	Software Design	Design principles, refactoring	1
SE	Software Construction	Exception handling, coding standards	1
SE	Software Verification and Validation	Test case generation, approaches to testing	1
SF	Resource Allocation and Scheduling	Example/assignment introduce kinds of scheduling: FIFO, priority; much additional material in Operating Systems course	1
SP	Professional Ethics	Codes of ethics, accountability, responsibility	1

Appendix D: Curricular Exemplars

There are many ways in which the Body of Knowledge can be instantiated in a complete curriculum. This appendix provides several curriculum exemplars from a variety of institutions. Each exemplar shows how an institution's existing curriculum covers Core-Tier1 and Core-Tier2 topics; in some cases, they also include migration plans to include a greater percentage of CS2013 Core topics. These exemplars are not meant to be taken as models. Rather, they are provided to show ways that the Body of Knowledge may be organized into a complete curriculum.

We recognize that different institutions have different student populations, use different delivery methods for instruction (e.g., lecture, laboratory, blended, online), and have other constraints or opportunities that impact the number of hours spent on various topics. We also note that many of the curricular exemplars will not match the CS2013 Body of Knowledge specification completely. Indeed, this is to be expected, as the Body of Knowledge is forward-looking.

How to read the Knowledge Units Table

Each curricular exemplar contains a large table that maps courses to Knowledge Unit coverage. Within that table, columns represent courses and rows represent Knowledge Units. An entry in the table specifies the number of hours of topic coverage for a Knowledge Unit in a given course. For example, an entry of 3 in row "SDF/Algorithms and Design" and column "CS101" would specify that 3 hours of CS2013 topic coverage occur in this course.

It is important to note that in most cases the basic unit of coverage is a CS2013 hour, which may not be the same as the actual number of hours devoted to the CS2013 core at that institution. For example, if a course covers only two-thirds of the topics in a 3 hour KU, then the mapping would list the corresponding proportion of hours (e.g., two-thirds of 3 hours = 2 hours of coverage). If a course covers all of the topics in a 3 hour KU, the mapping would list 3 hours regardless of the time spent in actual instruction. We note that Grinnell's mapping follows a slightly different

scheme for computing hours. (Please see the explanation in the Grinnell exemplar for more details.)

Each course in the Knowledge Units Table will independently list the number of CS2013 hours it devotes to a particular Knowledge Unit. If there is overlap across courses due to the repeated coverage of topics, then the sum of the course hours across a row will exceed the actual coverage of topics. The summary coverage percentages in the last two columns will take overlap into account.

Bluegrass Community and Technical College (A.S. Degree)

in Lexington, Kentucky

Computer and Information Technologies Department
http://bluegrass.kctcs.edu/en/CSIS.aspx
Contact: Prof. Melanie Williamson (melanie.williamson@kctcs.edu)

Curricular Overview

In the United States, the associate degree is recognized by baccalaureate degree-granting institutions as a critical indicator of academic proficiency at a level deemed appropriate to enter upper-division college programs. Bluegrass Community and Technical College (BCTC) located in Lexington, Kentucky is a comprehensive community college offering both career and transfer associate-degree programs. The enrollment at BCTC is approximately 6,000 full-time students and 7,200 part-time students.

The department of Computer and Information Technologies (CIT) at BCTC offers an Associate in Science (A.S.) degree in computer science designed specially to transfer into baccalaureate degree programs. The transferable computer science core is limited to four courses since the program also consists of all the general education requirements for a baccalaureate degree – deemed as fully "general education" certified. The CIT department offers a variety of computer-related associate-degree programs and has eleven full-time faculty members with varying expertise in software development and engineering, database management, information assurance, and networking.

Computer Science Major

The BCTC computer science A.S. degree program couples the study of computer programming with computational complexity, data structures, software engineering, and proof techniques. The four introductory core courses that all CS majors must take are:

1. CS 115 Introduction to Computer Programming 3 credits
2. CS 215 Introduction to Program Design, Abstraction and Problem Solving 4 credits
3. CS 216 Introduction to Software Engineering 3 credits
4. CS 275 Discrete Mathematics 4 credits

Course descriptions are located in the Appendix A of this curricular exemplar.

Curricular Analysis

The Knowledge Units table below provides an overview of the coverage of CS2013 Core Tier-1 and Core Tier-2 topics in the associate degree CS transfer program at BCTC. The recommended CS course sequencing for this canonical major is as follows:

Year 1 - Fall	Year 1 - Spring	Year 2 - Fall	Year 2 - Spring
CS 115	CS 215	CS 216	CS 275

The canonical computer science major is required to complete a common CS core that includes the four lower-division computer science courses listed above. Mapping this transferable core reveals that 70% of Tier-1 and 35% of Tier-2 topics in the CS2013 core are covered by BCTC's associate in science degree. In comparison of the core topics, 77% and 52%, respectively, are covered by BCTC's associate in applied science degree. Please note that the mapping of the A.A.S. degree is included as a separate CS2013 curricular exemplar.

	Tier 1	*Tier 2*
Canonical major – CS115, CS215, CS216, CS275 – *common core*	70%	35%

Knowledge Units in a Typical Major (Common Core)

This mapping includes the four core courses in the BCTC A.S. computer science transfer degree. The computer science credits together with the required general education (not shown) credits earned at BCTC are accepted for transfer at all public four-year colleges/universities in Kentucky, including the University of Kentucky, a land-grant research institution. Most private Kentucky colleges/universities also fully accept the transfer of this associate-degree program.

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Intro. to Computer Programming	CS 215: Intro. to Program Design, Problem Solving	CS 216: Intro. to Software Engineering	CS 275: Discrete Mathematics	% Tier 1	% Tier 2
AL	Basic Analysis	1	2		1	84	33
	Algorithmic Strategies		2	2	2		
	Fund. DS & Alg.		9				
	Basic Autom. & Comp.						
AR	Digital Logic	1				n/a	44
	Machine-level rep. of data	3					
	Assembly level mach. org.						
	Memory org. and arch.		3				
	Interfacing and comm.						
CN	Fundamentals					0	n/a
DS	Sets, Relations, & Functions				4	100	50
	Basic Logic				9		
	Proof Techniques				11		
	Basics of Counting				5		
	Graphs & Trees		1		3		
	Discrete Probability				6		
GV	Fundamental Concepts					0	0
HCI	Foundations	2		2		100	50
	Designing Interaction			2			

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Intro. to Computer Programming	CS 215: Intro. to Program Design, Problem Solving	CS 216: Intro. to Software Engineering	CS 275: Discrete Mathematics	% Tier 1	% Tier 2
IAS	Fund. Concepts in Security					33	17
	Principles of Secure Design						
	Defensive Programming		1	1			
	Threats and Attacks						
	Network Security						
	Cryptography						
IM	Info. Management Concepts					0	33
	Database Systems						
	Data Modeling	3					
IS	Fundamental Issues					n/a	0
	Basic Search Strategies						
	Basic Knowledge Rep.						
	Basic Machine Learning						
NC	Introduction					0	0
	Networked Applications						
	Reliable Data Delivery						
	Routing and Forwarding						
	Local Area Networks						
	Resource Allocation						
	Mobility						

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Intro. to Computer Programming	CS 215: Intro. to Program Design, Problem Solving	CS 216: Intro. to Software Engineering	CS 275: Discrete Mathematics	% Tier 1	% Tier 2
OS	Overview of OS	2				75	55
	Operating Systems Principles		1				
	Concurrency			3			
	Scheduling and Dispatch						
	Memory Management		3				
	Security and Protection						
PD	Parallelism Fundamentals			1		20	0
	Parallel Decomposition						
	Comm. & Coord.						
	Parallel Algorithms						
	Parallel Architecture						
PL	Object-Oriented Programming	3	5			38	25
	Functional Programming						
	Event-Driven & React. Prog.						
	Basic Type Systems						
	Program Representation						
	Language Translation						
SDF	Algorithms and Design	9	1	1		100	n/a
	Fund. Prog. Concepts	7	3				
	Fund. DS	2	10				
	Development Methods		10				

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Intro. to Computer Programming	CS 215: Intro. to Program Design, Problem Solving	CS 216: Intro. to Software Engineering	CS 275: Discrete Mathematics	% Tier 1	% Tier 2
SE	Software Processes			3		83	90
	Software Project Manage.	0.5		1.5			
	Tools and Environments			2			
	Requirements Engineering			3			
	Software Design	1.5	1.5	5			
	Software Construction			2			
	Software Verif. & Valid.			3			
	Software Evolution						
	Software Reliability			1			
SF	Computational Paradigms					0	22
	Cross-Layer Communications						
	State-State Trans-State Mach.						
	Parallelism						
	Evaluation						
	Resource Alloc. & Sched.		2				
	Proximity						
	Virtualization & Isolation						
	Reliab. through Redundancy						
SP	Social Context					9	0
	Analytical Tools						
	Professional Ethics						
	Intellectual Property						
	Privacy & Civil Liberties						
	Prof. Communication	1					
	Sustainability						

Appendix: Information on Individual Courses for the A.S. degree

CS 115 Introduction to Computer Programming 3 credits (45 contact hours)
http://cs.uky.edu/courses/cs115/

This course teaches introductory skills in computer programming using an object-oriented computer programming language. There is an emphasis on both the principles and practice of computer programming. Covers principles of problem solving by computer and requires completion of a number of programming assignments. Expected preparation: Students should already have basic computing skills, like being able to copy files from one place to another, renaming files, printing files, browsing the Web.

CS 215 Introduction to Program Design, Abstraction and Problem Solving 4 credits (60 contact hours)
http://cs.uky.edu/courses/cs215/

The course covers introductory object-oriented problem solving, design, and programming engineering. Fundamental elements of data structures and algorithm design will be addressed. An equally balanced effort will be devoted to the three main threads in the course: concepts, programming language skills, and rudiments of object-oriented programming and software engineering. Prerequisites: CS 115 or equivalent.

CS 216 Introduction to Software Engineering 3 credits (45 contact hours)
http://cs.uky.edu/courses/cs216/

Software engineering topics to include: life cycles, metrics, requirements specifications, design methodologies, validation and verification, testing, reliability and project planning. Implementation of large programming projects using object-oriented design techniques and software tools in a modern development environment will be stressed. . Prerequisites: CS 215

CS 275 Discrete Mathematics 4 credits (45 contact hours)
http://cs.uky.edu/courses/cs275/

Topics in discrete mathematics aimed at applications in Computer Science. Fundamental principles: set theory, induction, relations, functions, Boolean algebra. Techniques of counting: permutations, combinations, recurrences, algorithms to generate them. Introduction to graphs and trees. Prerequisites: MA 113 (Calculus 1), CS 115

Bluegrass Community and Technical College (A.A.S. Degree)

in Lexington, Kentucky

Computer and Information Technologies Department
http://bluegrass.kctcs.edu/en/CSIS.aspx
Contact: Prof. Melanie Williamson (melanie.williamson@kctcs.edu)

Curricular Overview

In the United States, the associate degree is recognized by baccalaureate degree-granting institutions as a critical indicator of academic proficiency at a level deemed appropriate to enter upper-division college programs. Bluegrass Community and Technical College (BCTC) located in Lexington, Kentucky is a comprehensive community college offering both career and transfer associate-degree programs. The enrollment at BCTC is approximately 6,000 full-time students and 7,200 part-time students.

The department of Computer and Information Technologies (CIT) at BCTC offers an Associate in Applied Science (A.A.S.) computing degree with a concentration in computer science. After earning this associate degree, students have the option of either entering the workforce directly or transferring to a baccalaureate computer science program at one of Kentucky's four-year colleges. The CIT department also offers different A.A.S. degree programs with a variety of concentrations, such as computer science, applications, Internet technologies and network technologies. The department has eleven full-time faculty members with varying expertise in software development and engineering, database management, information assurance, and networking.

Computer Science Major

The A.A.S. degree with a concentration in computer science combines fundamental studies in computer hardware, networks, database design, and security with concentrated studies in computer programming, computational complexity, data structures, software engineering, and proof techniques. The computing courses taken by a typical major in this A.A.S. degree program are:

1.	CS 115 Introduction to Computer Programming	3 credits
2.	CS 215 Introduction to Program Design, Abstraction and Problem Solving	4 credits
3.	CS 216 Introduction to Software Engineering	3 credits
4.	CS 275 Discrete Mathematics	4 credits
5.	CIT 105 Introduction to Computers	3 credits
6.	CIT 111 Computer Hardware and Software	4 credits
7.	CIT 150 Internet Technologies	3 credits
8.	CIT 160 Introduction to Networking Concepts	4 credits
9.	CIT 170 Database Design Fundamentals	3 credits
10.	CIT 180 Security Fundamentals	3 credits

Students will also take other computing courses, such as systems analysis and design, not included in this mapping. Course descriptions included in the mapping are located in the Appendix A of this curricular exemplar.

Curricular Analysis

The Knowledge Units table below provides an overview of the coverage of CS2013 Core Tier-1 and Core Tier-2 topics in the A.A.S. degree with a computer science concentration at BCTC. The recommended CS and CIT course sequencing for this typical A.A.S. major is as follows:

Year 1 - Summer	Year 1 - Fall	Year 1 - Spring	Year 2 - Fall	Year 2 - Spring
CIT 105	CS 115	CS 215	CS 216	CS 275
	CIT 111	CIT 150	CIT 170	CIT 291 Capstone *
	CIT 120 *	CIT 160	CIT 180	

* not included in the mapping

Mapping the required four CS courses and six CIT courses reveals that 77% of Tier-1 and 52% of Tier-2 topics in the CS2013 core are covered by the A.A.S. degree. In comparison, the A.S. CS degree, which includes only the four CS courses, covers 70% and 35%, respectively. Please note that the mapping of the A.S. degree is included as a separate CS2013 curricular exemplar.

In general, A.A.S. degree programs require fewer general education credits than A.S. degrees. In the case of BCTC, fewer general education courses provided the room for more computing courses in their A.A.S. degree, and thereby covering more of the CS2013 core. In particular, the CIT courses provide more core coverage in the following knowledge areas: architecture (AR), graphics (GV), information assurance and security (IAS), information management (IM), networking (NC), operating systems (OS) and social issues and professional practice (SP). However, unlike the A.S. degree in Kentucky, the A.A.S. degree is not considered "general education certified," which means that students will need to complete the requisite number of general education requirements at the transferring institution in order to obtain a computer science baccalaureate degree. According to the American Association of Community Colleges, there is a national trend emerging in higher education where an increasing number of four-year colleges are accepting more of the credits earned from associate in applied science degrees.

	Tier 1	*Tier 2*
The typical A.A.S. major	77%	52%

Knowledge Units in a Typical Major

This mapping includes the four core CS courses along with the six CIT courses of a typical major pursuing the A.A.S. degree with the computer science concentration at BCTC.

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Comp. Programming	CS 215: Problem Solving, etc.	CS 216: Software Engineering	CS 275: Discrete Mathematics	CIT 105: Intro. to Computers	CIT 111: Hardware & Software	CIT 150: Internet Technologies	CIT 160: Networking	CIT 170: Database Fundamentals	CIT 180: Security Fundamentals	% Tier 1	% Tier 2
AL	Basic Analysis	1	2		1							84	55
	Algorithmic Strategies		2	2	2								
	Fund. DS & Alg.			9									
	Basic Autom. & Comp.												
AR	Digital Logic	1					3					n/a	63
	Machine-level rep. of data	3					1						
	Assembly level mach. org.												
	Memory org. and arch.		3				3						
	Interfacing and comm.						1						
CN	Fundamentals											0	0
DS	Sets, Relations, & Functions				4							100	50
	Basic Logic				9								
	Proof Techniques				11								
	Basics of Counting				5								
	Graphs & Trees		1		3								
	Discrete Probability				6								
GV	Fundamental Concepts					1		1				100	0
HCI	Foundations	2		2								100	50
	Designing Interaction			2									

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Comp. Programming	CS 215: Problem Solving, etc.	CS 216: Software Engineering	CS 275: Discrete Mathematics	CIT 105: Intro. to Computers	CIT 111: Hardware & Software	CIT 150: Internet Technologies	CIT 160: Networking	CIT 170: Database Fundamentals	CIT 180: Security Fundamentals	% Tier 1	% Tier 2
IAS	Fund. Concepts in Security											33	83
	Principles of Secure Design												
	Defensive Programming		1	1									
	Threats and Attacks										1		
	Network Security										2		
	Cryptography										1		
IM	Info. Management Concepts									3		100	100
	Database Systems									3			
	Data Modeling	3								4			
IS	Fundamental Issues											n/a	0
	Basic Search Strategies												
	Basic Knowledge Rep.												
	Basic Machine Learning												
NC	Introduction							1.5				100	100
	Networked Applications								1.5				
	Reliable Data Delivery								2				
	Routing and Forwarding								1.5				
	Local Area Networks								1.5				
	Resource Allocation								1				
	Mobility								1				

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Comp. Programming	CS 215: Problem Solving, etc.	CS 216: Software Engineering	CS 275: Discrete Mathematics	CIT 105: Intro. to Computers	CIT 111: Hardware & Software	CIT 150: Internet Technologies	CIT 160: Networking	CIT 170: Database Fundamentals	CIT 180: Security Fundamentals	% Tier 1	% Tier 2
OS	Overview of OS	2				1	1					100	55
	Operating Systems Principles		1				1						
	Concurrency			3									
	Scheduling and Dispatch												
	Memory Management		3										
	Security and Protection												
PD	Parallelism Fundamentals			1								20	0
	Parallel Decomposition												
	Comm. & Coord.												
	Parallel Algorithms												
	Parallel Architecture												
PL	Object-Oriented Programming	3	5									38	25
	Functional Programming												
	Event-Driven & React. Prog.												
	Basic Type Systems												
	Program Representation												
	Language Translation												
SDF	Algorithms and Design	9	1	1								100	n/a
	Fund. Prog. Concepts	7	3										
	Fund. DS	2	10										
	Development Methods		10										

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		CS 115: Comp. Programming	CS 215: Problem Solving, etc.	CS 216: Software Engineering	CS 275: Discrete Mathematics	CIT 105: Intro. to Computers	CIT 111: Hardware & Software	CIT 150: Internet Technologies	CIT 160: Networking	CIT 170: Database Fundamental	CIT 180: Security Fundamentals	% Tier 1	% Tier 2
SE	Software Processes			3								83	90
	Software Project Manage.	0.5		1.5									
	Tools and Environments			2									
	Requirements Engineering			3									
	Software Design	1.5	1.5	5									
	Software Construction			2									
	Software Verif. & Valid.			3									
	Software Evolution												
	Software Reliability			1									
SF	Computational Paradigms											0	22
	Cross-Layer Communications												
	State-State Trans-State Mach.												
	Parallelism												
	Evaluation												
	Resource Alloc. & Sched.		2										
	Proximity												
	Virtualization & Isolation												
	Reliab. through Redundancy												
SP	Social Context					2	1					64	20
	Analytical Tools												
	Professional Ethics					1							
	Intellectual Property					2							
	Privacy & Civil Liberties					2							
	Prof. Communication	1											
	Sustainability												

Appendix: Information on Individual Courses for the A.A.S. degree

CS 115 Introduction to Computer Programming 3 credits (45 contact hours)
http://cs.uky.edu/courses/cs115/

This course teaches introductory skills in computer programming using an object-oriented computer programming language. There is an emphasis on both the principles and practice of computer programming. Covers principles of problem solving by computer and requires completion of a number of programming assignments. Expected preparation: Students should already have basic computing skills, like being able to copy files from one place to another, renaming files, printing files, browsing the Web.

CS 215 Introduction to Program Design, Abstraction and Problem Solving 4 credits (60 contact hours)
http://cs.uky.edu/courses/cs215/

The course covers introductory object-oriented problem solving, design, and programming engineering. Fundamental elements of data structures and algorithm design will be addressed. An equally balanced effort will be devoted to the three main threads in the course: concepts, programming language skills, and rudiments of object-oriented programming and software engineering. Prerequisites: CS 115 or equivalent.

CS 216 Introduction to Software Engineering 3 credits (45 contact hours)
http://cs.uky.edu/courses/cs216/

Software engineering topics to include: life cycles, metrics, requirements specifications, design methodologies, validation and verification, testing, reliability and project planning. Implementation of large programming projects using object-oriented design techniques and software tools in a modern development environment will be stressed. . Prerequisites: CS 215

CS 275 Discrete Mathematics 4 credits (45 contact hours)
http://cs.uky.edu/courses/cs275/

Topics in discrete mathematics aimed at applications in Computer Science. Fundamental principles: set theory, induction, relations, functions, Boolean algebra. Techniques of counting: permutations, combinations, recurrences, algorithms to generate them. Introduction to graphs and trees. Prerequisites: MA 113 (Calculus 1), CS 115

The descriptions for the following CIT courses are located at http://kctcs.edu/students/Programs and Catalog/ in the current catalog.

CIT 105 Introduction to Computers 3 credits (45 contact hours)

Provides an introduction to the computer and the convergence of technology as used in today's global environment. Introduces topics including computer hardware and software, file

management, the Internet, e-mail, the social web, green computing, security and computer ethics. Presents basic use of application, programming, systems, and utility software.

CIT 111 Computer Hardware and Software 4 credits (60 contact hours)

Presents a practical view of computer hardware and client operating systems. Covers computer hardware components; troubleshooting, repair, and maintenance; operating system interfaces and management tools; networking components; computer security; and operational procedures. Prerequisite: CIT 105 or consent of instructor.

CIT 150 Internet Technologies 3 credits (45 contact hours)

Provides students with a study of traditional and emerging Internet technologies. Covers topics including Internet fundamentals, Internet applications, Internet delivery systems, and Internet client/server computing. Provides a hands-on experience and some rudimentary programming in an Internet environment. Prerequisites: CIT 105 AND CIT
120.

CIT 160 Introduction to Networking Concepts 4 credits (60 contact hours)

Introduces technical level concepts of non-vendor specific networking including technologies, media, topologies, devices, management tools, and security. Provides the basics of how to manage, maintain, troubleshoot, install, operate, and configure basic network infrastructure. Prerequisites or Co-requisites: CIT 111

CIT 170 Database Design Fundamentals 3 credits (45 contact hours)

Provides an overview of database and database management system concepts, internal design models, normalization, network data models, development tools, and applications.

CIT180 Security Fundamentals 3 credit (45 contact hours)

Introduces basic computer and network security concepts and methodologies. Covers principles of security; compliance and operational security; threats and vulnerabilities; network security; application, data, and host security; access control and identity management; and cryptography. Prerequisites: CIT 105 AND CIT 160.

Grinnell College

Department of Computer Science
http://www.cs.grinnell.edu
Contacts: Samuel Rebelsky (rebelsky@grinnell.edu) and
Henry Walker (walker@cs.grinnell.edu)

Curricular Overview

Grinnell College is a small, highly selective, liberal arts college with 1600 students. Class sizes are small, faculty members employ modern pedagogy (e.g., active learning, individual and collaborative engagement), most students are well motivated, and the College strongly supports faculty-student scholarship. In the liberal arts tradition, the College encourages breadth of study, formal requirements for graduation are small, and the shape of undergraduate course selections often depends upon advising of students by faculty. The CS faculty encourages students to select courses beyond a minimal major (e.g., more courses to meet some CS 2013 recommendations), but College policy limits any major to 32 credits (typically eight 4-credit courses) in the discipline, along with a few supporting courses outside the department. Although staffing dictates that many courses are offered in alternate years, all required courses are offered annually, and courses in the introductory sequence are offered each semester.

Computer Science Major (2012-2013 Curriculum)

Grinnell's 2012-2013 major was strongly influenced by ACM/IEEE-CS CC 2001 and CS 2008 and by the 2007 Model Curriculum for a Liberal Arts Degree in Computer Science from the Liberal Arts Computer Science Consortium. CS Major requirements cover many elements from the curricular recommendations, and additional courses (encouraged through advising) provide extensive coverage of most recommended topics.

Multi-paradigm, Introductory Sequence (all three 4-credit courses required)
- CSC 151 – Functional Problem Solving
- CSC 161 – Imperative Problem Solving and Data Structures
- CSC 207 – Algorithms and Object-Oriented Problem Solving

Required Upper-Level Courses (both 4-credit courses required)
- CSC 301 – Analysis of Algorithms
- CSC 341 – Automata, Formal Languages, & Computational Complexity (Theory)

Systems (one of two 4-credit courses required; both strongly recommended)
- CSC 211 – Computer Organization and Architecture
- CSC 213 – Operating Systems and Parallel Algorithms

Languages (one of two 4-credit courses required)
- CSC 302 – Programming Language Concepts
- CSC 362 – Compilers

Software Development (one of two 4-credit courses required)
- CSC 323 – Software Design
- CSC 325 – Databases and Web Application Design

Mathematical Foundations (two designated 4-credit courses, plus a 4-credit elective)
MAT 124 or MAT 131 – Calculus I
MAT/CSC 208 – Discrete Mathematics or MAT 218 – Combinatorics
MAT ### – Mathematics elective with calculus I or later course as prerequisite

Regularly offered 4-credit electives include Artificial Intelligence, Computational Linguistics, Computer Networks, Computer Vision, and Human-Computer Interaction. Various 1-credit options and 4-credit special-topics courses may be offered on a regular basis or under special circumstances. The department also provides students with the opportunity to broaden their learning through a weekly seminar series and a weekly reading group. Independent projects and student-faculty research projects are common, particularly during the summer.

Curricular Analysis

With choices in systems, languages, and software engineering, students could follow any of eight paths through a "minimal" major (counting Discrete Mathematics as the lesser of the supporting mathematics options). Through advising, students often took both CSC 211 and CSC 213, as well as additional electives to meet specific educational or career objectives. The following table compares several possible routes through the 2012-2013 major, which aligned well to earlier curricular recommendations.

Grinnell's 2012-2013 Curriculum	*Tier 1*	*Tier 2*
Minimal major: only the basic requirements	59-73%	34-53%
Expanded minimal major: 9 courses including 211 & 213	74-75%	50-57%
Typical major: 10 courses including 211, 213 & either AI or Networks	76-78%	62%

Careful analysis indicated considerable strength in some areas (e.g., algorithms, theory) that fit particularly well within a liberal arts context. However, reduction in some strong areas (e.g., programming languages) could allow expansion in other areas to reflect the evolution of the discipline, particularly in the areas of distributed processing, networking, and security. Also, although the existing curriculum informally highlighted SP content, a 2013 departmental review identified some topics for a more systematic treatment.

In addition, Grinnell's computer science curriculum employs a spiral approach to learning. Students may be introduced to a topic in one course (perhaps at the Familiarity level in CS 2013's terminology), then utilize that material in a second course (perhaps attaining a Usage level of mastery), and still later engage the topic at a deep, Assessment, level in a third course. Our spiral approach may also lead us to repeat the same concept at the same level, but with variations. For example, students build lists and tree using pair structures in CSC 151, build linked lists and worry about memory management in CSC 152, and build doubly and circularly linked lists in CSC 153. Any of these approaches would likely suffice to meet CS 2013 goals, but we find that students have much deeper understanding with this repeated and increasingly nuanced approach. As a result of the spiral approach, many topics that are covered once in CS 2013 are covered multiple times in Grinnell's curriculum, which complicates both hour counts and bookkeeping. The spiral approach is most clearly represented in the AL and SDF sections in the mapping below.

Proposed Curricular Revisions

Although the 2012-2013 CS major and curriculum had many strengths, on-going review identified possibilities for improvement in two substantial ways: the division of some 4-credit courses into 2-credit courses could provide students with opportunities for more breadth in the major, and the design of some of those courses could reflect the evolution of the discipline as represented by CS 2013. The 2-credit courses are likely to meet 1.5 hours per week for the full semester, although we are also considering half-semester courses.

Full implementation of a substantive major and curricular revision requires substantial brainstorming, analysis, attention to detail, review, and consultation. The following comments suggest directions for revised courses and major; adjustments and refinements are likely as planning and development continue.

- Rather than fitting a full range of software engineering topics into a single, required, 4-credit course, one 2-credit course could highlight concepts, principles, and methodology, and a second 2-credit course could allow teams to address community needs. The second course would permit students to join on-going projects for one or more semesters, taking on more advanced roles in subsequent semesters. Core HCI topics could be incorporated in one or both of these courses.
- A 4-credit elective on computer networks could be split into a more focused, 2-credit networks course, and a new 2-credit course on computer security
- Many SP topics could be covered through the department's weekly seminar presentations or through an on-going CS table series of discussions. In particular, an annual presentation and discussion will focus on issues of intellectual property.
- Because the multi-paradigm introductory sequence exposes students to many basic conceptual issues in programming languages, the upper-level course on programming language can be relatively flexible. Elements of the existing programming languages and compilers course could be combined into a single 2-credit, interpreter-based "programming language implementation" course.
- Students who take CSC 211 encounter fewer Core-Tier1 topics than those who take CSC 213 because the AR knowledge unit contains primarily Core-Tier2 topics. The CS faculty considered combining CSC 211 and 213, which some schools have done. However, the current courses provide good depth, and thus seemed appropriate in the revised curriculum.

Since Grinnell's liberal arts context limits major requirements to 32 credits, a minimal major can cover numerous, but not all, learning outcomes recommended by CS 2013. As noted above, many SP topics can be covered in the weekly department seminar and/or in a reading group associated with a weekly CS Table. Also, while many IM learning outcomes fit well within a liberal arts context, a few seem less appropriate.

Advising can encourage students to cover a wide range of topics. The following listing illustrates possible major requirements and also advising recommendations that could extend a program to about 38 credits, plus supporting mathematics. The CS faculty will continue to offer a variety of electives.

Multi-paradigm, Introductory Sequence (12 credits required)

CSC 151 – Functional Problem Solving

CSC 161 – Imperative Problem Solving and Data Structures

CSC 207 – Algorithms and Object-Oriented Problem Solving (updated theme)

Required Upper-Level Courses (10 credits required)

CSC 301 – Analysis of Algorithms

CSC 341 – Automata, Formal Languages, & Computational Complexity (Theory)

CSC 312 – Implementation of Programming Languages (new/revised, 2 credits)

Systems I (4 credits required; 8 credits strongly recommended)

CSC 211 – Computer Organization and Architecture (4 credits)

CSC 213 – Operating Systems and Parallel Algorithms (4 credits)

Systems II (2 credits required, 4 credits strongly recommended)

CSC 264 – Computer Security (new, 2 credits)

CSC 364 – Computer Networks (revised from 4 credits to 2 credits)

Software Development (4 credits required; 6 credits recommended)

CSC 321 – Software development principles and methodology (new, 2 credits)

CSC 322 –Team-based community project (new, 2 credits, may be repeated for credit)

Mathematical Foundations (two designated 4-credit courses, plus a 4-credit elective)

MAT 124 or MAT 131 – Calculus I

MAT/CSC 208 – Discrete Mathematics or MAT 218 – Combinatorics

MAT ### – Mathematics elective with calculus I or later course as prerequisite

Proposed CS Major and Program	*Tier 1*	*Tier 2*
Minimal major – only the basic requirements	70-85%	51-61%
Minimal major plus attendance at IP talk/discussion	73-89%	51-61%
Expanded (38-credit) major – both 211/213, both networks/security	92%	73%
38-credit major plus attendance at IP talk/discussion	96%	73%
38-credit major plus AI course plus attendance at IP talk/discussion	96%	78%

Knowledge Units in a Typical Major – Revised Curriculum

For this analysis, we considered a "typical" student in the revised curriculum, one who takes both Systems I courses (CSC 211 Architecture and CSC 213 Operating Systems) and both of the Systems II courses (CSC 264 Computer Security and CSC 364 Computer Networks).

In these tables, the shading represents the percentage of a knowledge unit covered and the number represents the approximate number of hours spent on the topic. Because deeper understanding requires more time, in computing percentages, we used a value of 1 for "familiarity", a value of 1.5 for "usage", and a value of 2 for "assessment". For example, in a knowledge unit with two "familiarity" outcomes and one "assessment" outcome, a course that covers the one "assessment" outcome is credited with 50% of the unit. For most courses, we computed hours by multiplying this percentage by the expected CS2013 hours for the knowledge unit, and the resulting time estimate generally reflected actual time spent in class. Both computations follow the model used in the Williams curricular mapping.

In using these computations, we found that the computed hours in four courses (CSC 207 Algorithms and Object-Oriented Design, CSC 208 Discrete Structures, CSC 301 Algorithm Analysis, and CSC 341 Theory) misrepresented the time these courses actually spent on knowledge units. Because of the significant discrepancy, an honest presentation of the courses required us to adjust the hours listed.

Grinnell's curriculum often employs a spiral approach in which prerequisite courses provide a foundation for full coverage of an outcome in later courses. Often, a later course (e.g., CSC 207 or CSC 301) achieves the CS2013-recommended "assessment" level outcome, but prior courses provided a foundation by covering material at "familiarity" or "usage" levels. As a result, later courses might actually spend relatively few hours to achieve an outcome, but would be credited with substantially more hours, while earlier courses received no credit at all. In addition, we sometimes revisit an outcome in a second course to reinforce learning. Again, the course is credited for more time than is required. Hence, for the four courses most affected (CSC 207, CSC 208, CSC 301, and CSC 341), we made adjustments to better represent actual time on the topics and reflect the main emphases of these courses. For two courses (CSC 151 and CSC 161), we left the computed hours in place even though they may not precisely reflect actual topic coverage. A more accurate tally may be found in the course exemplars for these courses in Appendix C.

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		151: Func. Prob.	161: Imp. + DS	207: OO + Alg.	208: Discrete	211: Architecture	213: OS	301: Algorithms	341: Theory	312: Prog. Lang.	321: Prin. Soft. Dev.	322: Comm. Proj.	264: Security	364: Networks	% Tier 1	% Tier 2
AL	Basic Analysis			3	½			3	2						100	100
	Algorithmic Strategies	1½	½	2	½			5								
	Fund. DS & Alg.		3½	5	3			6								
	Basic Autom. & Comp.								6							
AR	Digital Logic					2½	½								n/a	94
	Machine-level rep. of data		3			1										
	Assembly level mach. org.					6	1½									
	Memory org. and arch.					2	3									
	Interfacing and comm.					½	½							½		
CN	Fundamentals	½	½	½											80	n/a
DS	Sets, Relations, & Functions				4										100	50
	Basic Logic				8				2							
	Proof Techniques				5½				11							
	Basics of Counting	½	½		3			4	1							
	Graphs & Trees				2			4								
	Discrete Probability				2			2								
GV	Fundamental Concepts	1½		1											78	50
HCI	Foundations										3	1			100	70
	Designing Interaction										1½	1				

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		151: Func. Prob.	161: Imp. + DS	207: OO + Alg.	208: Discrete	211: Architecture	213: OS	301: Algorithms	341: Theory	312: Prog. Lang.	321: Prin. Soft. Dev.	322: Comm. Proj.	264: Security	364: Networks	% Tier 1	% Tier 2
IAS	Fund. Conc. in Security						½					½	1		100	70
	Princ. of Secure Design												2½			
	Defensive Programming	½		1			½						1½			
	Threats and Attacks											½	1			
	Network Security							½	½				½			
	Cryptography							½					1			
IM	Info. Manag. Concepts			1							½	½	½		88	62
	Database Systems										2½					
	Data Modeling			½							1½	½				
IS	Fundamental Issues														n/a	25
	Basic Search Strategies							1½	½							
	Basic Knowledge Rep.				1											
	Basic Machine Learning															
NC	Introduction													1½	100	100
	Networked Applications													1½		
	Reliable Data Delivery													2		
	Routing and Forwarding													1½		
	Local Area Networks													1½		
	Resource Allocation													1		
	Mobility													1		

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		151: Func. Prob.	161: Imp. + DS	207: OO + Alg.	208: Discrete	211: Architecture	213: OS	301: Algorithms	341: Theory	312: Prog. Lang.	321: Prin. Soft. Dev.	322: Comm. Proj.	264: Security	364: Networks	% Tier 1	% Tier 2
OS	Overview of OS						1½								79	80
	OS Principles						1½									
	Concurrency						3									
	Scheduling and Dispatch						1½									
	Memory Management						3									
	Security and Protection						1½									
PD	Parallelism Fundamentals						2								100	73
	Parallel Decomposition						3									
	Comm. & Coord.						2½									
	Parallel Algorithms						2									
	Parallel Architecture						3									
PL	Object-Oriented Prog.			7						4					100	100
	Functional Programming	5		1	2					1½						
	Event-Driven & React. Pr.			2												
	Basic Type Systems		1½	2						5						
	Program Representation		1½							1						
	Language Translation									3						
SDF	Algorithms and Design	5	2	6	3			5	½						100	n/a
	Fund. Prog. Concepts	6	9	3	1			2	1							
	Fund. DS	7½	12	4	3			4½								
	Development Methods	4	3	5				1								

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		151: Func. Prob.	161: Imp. + DS	207: OO + Alg.	208: Discrete	211: Architecture	213: OS	301: Algorithms	341: Theory	312: Prog. Lang.	321: Prin. Soft. Dev.	322: Comm. Proj.	264: Security	364: Networks	% Tier 1	% Tier 2
SE	Software Processes										1	1			100	76
	Software Project Manage.											2	½			
	Tools and Environments										½	1½				
	Requirements Engineering			½							2½	1½				
	Software Design			2							5	4½				
	Software Construction			½							½	1½				
	Software Verif. & Valid.			½							1½	½				
	Software Evolution											2				
	Software Reliability															
SF	Computational Paradigms				½	1	1½	½							90	72
	Cross-Layer Comm.			1			2									
	State and State Machines					2½	1		2							
	Parallelism						1									
	Evaluation					½	3									
	Resource Alloc. & Sched.						2									
	Proximity						3									
	Virtualization & Isolation						1						½			
	Reliab. thru Redundancy															
SP	Social Context	½	½	1									1		65	18
	Analytical Tools			1	1								½			
	Professional Ethics		½	½				½					½			
	Intellectual Property												½			
	Privacy & Civil Liberties												½			
	Prof. Communication			½			½					½				
	Sustainability					1										

Additional Comments

Although the existing curriculum aligned well with previous national curricular recommendations, it had surprisingly low coverage of Core-Tier1 and Core-Tier2 topics in Curricula 2013, due to several primary factors:

- CS 2013 includes some new areas, such as security and professional issues.
- CS 2013 specifies particular learning outcomes, many of which are different than the learning outcomes that might have been specified for some earlier knowledge units.
- CS 2013 has placed lower precedence on some areas, such as architecture.
- The Grinnell curriculum covers many tier 3 topics, particularly in algorithms, theory, and programming languages.

Revision of the curriculum to give students fewer options, to separate 4-credit courses into 2-credit courses, and to align some of those 2-credit courses closely with CS 2013 shows strong potential to achieve reasonably good alignment with CS 2013. The few missing Core-Tier1 topics are not topics Grinnell's faculty consider essential, and the coverage of Core-Tier2 at about 78% is offset by the deep coverage of algorithms, theory, and programming languages at Tier 3.

Appendix: Information on Individual Courses

CSC 151 – Functional Problem Solving

http://www.cs.grinnell.edu/courses/csc151

CSC 151 introduces the discipline of computer science by focusing on functional problem solving with media computation as an integrating theme. Since the course explores mechanisms for representing, making, and manipulating images, some modest revisions may highlight themes in the area of GV. However, this course is expected to continue in largely its present form, taking advantage of a workshop format or "flipped classroom" pedagogy, with substantial utilization of lab-based exercises and collaborative learning. Appendix C of CS 2013, Course Exemplars, provides more detail on CSC 151.

CSC 161 – Imperative Problem Solving and Data Structures

http://www.cs.grinnell.edu/courses/csc161

CSC 161 utilizes robotics as an application domain in studying imperative problem solving, data representation, and memory management. Additional topics include assertions and invariants, data abstraction, linked data structures, an introduction to the GNU/Linux operating system, and programming the low-level, imperative language C. The review of CS 2013 identified some refinements of coverage for CSC 161, but substantial changes are not anticipated. The course follows a workshop format that emphasizes both collaborative learning and individual problem solving. More information on CSC 161 can be found in CS 2013, in Appendix C, on Course Exemplars.

CSC 207 – Object-Oriented Problem Solving and Algorithms

http://www.cs.grinnell.edu/courses/csc207

CSC 207 explores object-oriented problem solving with Java programming. Topics covered include principles of object-oriented design, abstract data types and encapsulation, data structures, algorithms, algorithmic analysis, elements of Java programming, and an integrated development environment (IDE). Recent work on this course has included introducing a general theme of "Computing for Social Good", as well as a modest updating of topics to more clearly reflect the evolution of the discipline as described in CS 2013, including coverage of GUIs. The course involves a workshop environment that encourages collaborative learning. CSC 207 is described in further detail in CSC 2013, Appendix C, on Course Exemplars.

MAT/CSC 208 – Discrete Structures

http://www.cs.grinnell.edu/courses/csc208

CSC 208 is a recent addition to Grinnell's curriculum. It provides the mathematical foundations for upper-division courses, particularly courses in algorithms and data structures. The course has both calculus and CSC 151 as prerequisites, allowing the instructor to mix mathematical and computational concepts. The next offering of MAT/CSC 208 will add more coverage of Discrete Probability in response to CS 2013.

CSC 211 – Computer Organization and Architecture

http://www.cs.grinnell.edu/courses/csc211

CSC 211 is a fairly traditional organization and architecture course. In its last offering, it relied upon the Patterson and Hennessy text. The regular course sessions are accompanied by a weekly one-hour laboratory in which students get experience with a wide variety of topics, including some breadboarding. A few adjustments are anticipated in response to CS 2013, but no major changes are required.

CSC 213 – Operating Systems and Parallel Algorithms

http://www.cs.grinnell.edu/courses/csc213

CSC 213 combines a traditional course in operating systems with a third of a semester coverage of parallel algorithms. As in the case of CSC 211, CSC 213 required a few minor changes, but no significant changes were required by CS 2013.

CSC 264 – Computer Security (2 credits, new course)

http://www.cs.grinnell.edu/courses/csc264

CSC 264 is a newly proposed course, created initially in response to student interest in additional coverage of security topics in the curriculum. It introduces students to an adversarial experience with computer security – students serve as both attackers and security personnel.

CSC 301 – Analysis of Algorithms

http://www.cs.grinnell.edu/courses/csc301

CSC 301 is a CLRS-style algorithms course (although not all faculty use the book). Students delve deeply into algorithm design and analysis. Students prove algorithm correctness and implement many common algorithms. CSC 301 did not require changes under CS 2013.

CSC 312 – Implementation of Programming Languages (2 credits, new course)

http://www.cs.grinnell.edu/courses/csc312

Because Grinnell's introductory sequence follows a multi-paradigm approach, students are exposed to many of the core concepts of a typical programming languages course early in their careers. Hence, in the past, faculty members chose their own approach to the programming languages course. Comparison with CS 2013 recommendations motivated a focus on a smaller core of topics, particularly on parsing and semantics, grounded in implementation. The course will likely draw upon the first half of Friedman and Wand's *Essentials of Programming Languages.*

CSC 321 – Tools and Principles of Software Development (2 credits, new course) and CSC 322 – Community-Based Software Development (2 credits, new course)

http://www.cs.grinnell.edu/courses/csc321
http://www.cs.grinnell.edu/courses/csc322

Over the past few years, the department has been considering revisions to its software development curriculum. At the core of this revision is the idea of having students work on a large, multi-semester project that will serve a community organization. Following the Purdue model, students will have the opportunity to work on the project in multiple semesters, thereby having the chance to work on different stages of a project and to explore different roles in the project. To achieve this approach, earlier 4-credit, project-based courses will be split into two courses. CSC 322 is the "hands on" portion of the course which students will be able to repeat for credit. CSC 321 provides the foundations – training in methodologies of software development, some underlying theory, and a bit of practice in core issues. Exploration of CS 2013 gave further encouragement to try this approach and guided selection of topics essential for CSC 321.

CSC 341 – Automata, Formal Languages, and computational Complexity

http://www.cs.grinnell.edu/courses/csc341

CSC 341 explores the logical and mathematical foundations of computer science. Topics covered in some depth include models of computation, the Chomsky language hierarchy, solvable and unsolvable problems, and P and NP complexity classes. The course follows a formal and rigorous style, and students write many formal proofs to explain logical arguments. Although many of the core topics in CSC 341 are designated as Tier 3 in CS 2013, we consider them essential knowledge for our liberal arts students.

CSC 364 – Computer Networks (2 credits, new version of earlier 4-credit course)

http://www.cs.grinnell.edu/courses/csc364

The previous, 4-credit course focused on the communications protocols used in computer networks — their functionality, specification, verification, implementation, and performance. The course also considered the use of network architectures and protocol hierarchies to provide more complex services. Existing protocols and architectures provided the basis of discussion and study. The revised, 2-credit course is envisioned to discuss network layers and congestion management, but various topics in the 4-credit version will either be reduced or omitted in this smaller version. In addition to collaborative exercises and laboratory assignments, the new course is likely to include a final project.

Stanford University

Computer Science Department
http://cs.stanford.edu
Contact: Mehran Sahami (sahami@cs.stanford.edu)

Curricular Overview

Stanford University is a research university with approximately 18,000 students, of which 7,000 are undergraduates. The university uses the quarter system, with three terms during the regular academic year. Undergraduates are not admitted directly to departments, but to the university as a whole, and are free to choose any major, which must be declared by the start of their junior year.

The Computer Science undergraduate program at Stanford is housed within the School of Engineering and, as a result, requires a year of calculus and a year of science (generally, physics) courses in addition to CS coursework. As a research university, there is large a large faculty in the department and the full set of course offerings is quite large (over 50 distinct courses are offered per year, with many undergraduate courses offered in multiple terms of the year).

Computer Science Major

Stanford has a track-based CS curriculum that requires all students to complete all of:

(i) six CS "core" classes,
(ii) four to five classes in one of nine depth areas (tracks) of a student's choosing,
(iii) two to three additional CS elective courses.

There must be a total of at least seven courses between areas (ii) and (iii).

The six required CS “core” classes are:

- CS103 – Mathematical Foundations of Computing
- CS106B – Programming Abstractions
- CS107 – Computer Organization and Systems
- CS109 – Introduction to Probability for Computer Scientists
- CS110 – Principles of Computer Systems
- CS161 – Design and Analysis of Algorithms

Note that CS “core” does not include our CS1 course (numbered CS106A), so most students with no prior computing background will take this course prior to starting the actual “core” classes.

The nine tracks that students may choose from are:

- Artificial Intelligence
- Theory
- Systems
- Computer Engineering
- Human-Computer Interaction
- Graphics
- Information

- Biocomputation
- Unspecialized (this track provides extensive breadth rather than depth)

The additional CS elective courses that students may choose come from a list of over 50 upper division courses offered in the CS department. Also, each track area provides a list of "track electives" which are additional choices for elective courses specific to that track area, and may include relevant courses from outside CS. For example, the Artificial Intelligence track-specific elective course list includes classes from both the Psychology and Statistics departments.

Additionally, all CS undergraduates are required to take a capstone course (Senior Project) as well as a course in the area of "Science, Technology, and Society". While students have several options for the latter requirement, the vast majority of students complete this requirement by taking a course taught in the CS department entitled "Computers, Ethics, and Public Policy".

Curricular Analysis

While the multitude of options through our CS major makes it impossible to map all the paths through our curriculum, we consider below a very typical (and minimal) program though our undergraduate program. In this program, a student begins in CS106A (our CS1 class), completes the CS "core" and chooses the "Systems" track—one of the most popular undergraduate tracks at Stanford—for the depth area. The additional CS electives in this exemplar program represent a minimal set of courses used to satisfy the elective requirement, sampled from among the most popular elective courses that were not already part of the student's program. Finally, the program includes the required senior capstone course and a course satisfying the "Science, Technology, and Society" requirement. The program is composed of the specific courses listed below. Note that we do not include the additional mathematics and science courses required as a result of our major being housed in the School of Engineering since these courses do not include CS-specific content.

Background (CS1)

- CS 106A – Programming Methodology

CS Core

- CS103 – Mathematical Foundations of Computing
- CS106B – Programming Abstractions
- CS107 – Computer Organization and Systems
- CS109 – Introduction to Probability for Computer Scientists
- CS110 – Principles of Computer Systems
- CS161 – Design and Analysis of Algorithms

Systems Track

- CS140 – Operating Systems and Systems Programming
- CS144 – Introduction to Computer Networking
- CS145 – Introduction to Databases
- EE108B – Digital Systems II

CS Electives

- CS108 – Object-Oriented Systems Design
- CS147 – Introduction to Human-Computer Interaction Design
- CS155 – Computer and Network Security

Senior Project Capstone

- CS194 – Software Project

Science, Technology, and Society (STS)

- CS181 – Computers, Ethics, and Public Policy

In our analysis, we show the Core-Tier1 and Core-Tier2 coverage provided by the typical major listed above. As noted in the table below, this typical program provides fairly comprehensive coverage of the CS2013 Body of Knowledge with nearly complete coverage of Core-Tier1 topics (98%) and the suggested minimum coverage of Core-Tier2 topics (79%). Additionally, if we just consider the courses that are required of all students in our program, not including the particular choice of track or CS elective courses (i.e., including just CS106A, the six CS "core" classes, the Senior Project and the Science, Technology, and Society requirement) then we still achieve 80% coverage of Core-Tier1 topics and 50% coverage of Core-Tier2 topics. While the choice of track and CS electives clearly impacts the amount of core material from CS2013 seen by a student, we believe that the core requirements provide a substantial base so that no matter what the choice of track/electives, students will still get solid coverage of most of the CS2013 core topics in our program, although there may be more substantial difference in which Core-Tier2 topics are covered depending on the choice of track and electives.

	Tier 1	*Tier 2*
Typical major – the sample (minimal) program described above	98%	79%
Core reqs – not complete major (just CS106A + CS core + Capstone + STS)	80%	50%

In the tables below, we consider the learning outcomes from each Knowledge Unit that are covered in each course. If a learning outcome is covered in multiple courses, we report the coverage only once, in the lowest level course where that outcome appears. The number of hours of coverage we report represents the hours of coverage *as specified in the CS2013 Body of Knowledge* necessary for covering the learning outcomes that are covered in the course. The *actual* number of class hours spent covering the topics in each Knowledge Unit may be greater than or less than the number of hours reported in the table below. We note that in most cases the number of actual class lecture hours spent on a Knowledge Unit in a course corresponds fairly well to the hours of coverage specified in the CS2013 for that Knowledge Unit.

Knowledge Units in a Typical Major

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		103: Math. Found.	106A: Prog. Meth.	106B: Prog. Abst.	107: Comp. Org.	109: Probability	110: Comp. Sys.	161: Algorithms	140: Oper. Sys.	144: Networking	145: Databases	EE108B: Dig. Des.	108: Obj. Orient.	147: Intro. HCI	155: Security	194: SW Project	181: Comp. Ethics	% Tier 1	% Tier 2
AL	Basic Analysis			1				3										100	100
	Algorithmic Strategies			1				5											
	Fund. DS & Alg.		2	5				5											
	Basic Autom. & Comp.	6																	
AR	Digital Logic											3						n/a	100
	Machine-level rep. of data				3														
	Assembly level mach. org.				3							3							
	Memory org. and arch.				1				1			1							
	Interfacing and comm.									0.2		0.8							
CN	Fundamentals					0.8												83	n/a
DS	Sets, Relations, & Functions	4																100	75
	Basic Logic	9																	
	Proof Techniques	10																	
	Basics of Counting	1				3		1											
	Graphs & Trees	1.5		0.5				2											
	Discrete Probability					8													
GV	Fundamental Concepts		1.2											1.3				100	50
HCI	Foundations													4				100	100
	Designing Interaction													4					

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		103: Math. Found.	106A: Prog. Meth.	106B: Prog. Abst.	107: Comp. Org.	109: Probability	110: Comp. Sys.	161: Algorithms	140: Oper. Sys.	144: Networking	145: Databases	EE108B: Dig. Des.	108: Obj. Orient.	147: Intro. HCI	155: Security	194: SW Project	181: Comp. Ethics	% Tier 1	% Tier 2
IAS	Fund. Concepts in Security														1			100	100
	Principles of Secure Design														2				
	Defensive Programming														2				
	Threats and Attacks														1				
	Network Security														2				
	Cryptography														1				
IM	Info. Management Concepts										2.4							100	94
	Database Systems										3								
	Data Modeling										4								
IS	Fundamental Issues																0.7	n/a	53
	Basic Search Strategies			0.5				1											
	Basic Knowledge Rep.					0.8		0.8											
	Basic Machine Learning					1.6													
NC	Introduction									1.5								100	100
	Networked Applications									1.5									
	Reliable Data Delivery									2									
	Routing and Forwarding									1.5									
	Local Area Networks									1.5									
	Resource Allocation									1									
	Mobility									1									

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		103: Math. Found.	106A: Prog. Meth.	106B: Prog. Abst.	107: Comp. Org.	109: Probability	110: Comp. Sys.	161: Algorithms	140: Oper. Sys.	144: Networking	145: Databases	EE108B: Dig. Des.	108: Obj. Orient.	147: Intro. HCI	155: Security	194: SW Project	181: Comp. Ethics	% Tier 1	% Tier 2
OS	Overview of OS						1		1									100	95
	Operating Systems Principles						0.8		1.2										
	Concurrency						1.5		1.5										
	Scheduling and Dispatch						0.4		2.6										
	Memory Management								3										
	Security and Protection								1.5										
PD	Parallelism Fundamentals						1		1									100	44
	Parallel Decomposition						1.5		1				0.5						
	Comm. & Coord.						3.1		0.3										
	Parallel Algorithms																		
	Parallel Architecture											1							
PL	Object-Oriented Programming		4	6														100	79
	Functional Programming			3.3									2.3						
	Event-Driven & React. Prog.		1.3										0.7						
	Basic Type Systems		3.3	1															
	Program Representation	0.3																	
	Language Translation				1.5														
SDF	Algorithms and Design		5	6														100	n/a
	Fund. Prog. Concepts		8	2															
	Fund. DS		2	10															
	Development Methods		7												1	2			

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		103: Math. Found.	106A: Prog. Meth.	106B: Prog. Abst.	107: Comp. Org.	109: Probability	110: Comp. Sys.	161: Algorithms	140: Oper. Sys.	144: Networking	145: Databases	EE108B: Dig. Des.	108: Obj. Orient.	147: Intro. HCI	155: Security	194: SW Project	181: Comp. Ethics	% Tier 1	% Tier 2
SE	Software Processes															2.5		100	47
	Software Project Manage.															2			
	Tools and Environments															1.3			
	Requirements Engineering															1			
	Software Design												5.3			2.3			
	Software Construction												0.6		0.3	0.3			
	Software Verif. & Valid.															0.3			
	Software Evolution																		
	Software Reliability																		
SF	Computational Paradigms						0.8		0.8				1.5					92	100
	Cross-Layer Communications						0.6		1.2	1.2									
	State and State Machines	2							3										
	Parallelism						1.5		0.5			0.5							
	Evaluation				0.8							2.3							
	Resource Alloc. & Sched.									2									
	Proximity				3														
	Virtualization & Isolation								2										
	Reliab. through Redundancy								1.6	0.4									
SP	Social Context																3	81	77
	Analytical Tools																2		
	Professional Ethics																2.7		
	Intellectual Property																1.8		
	Privacy & Civil Liberties																1.6		
	Prof. Communication																0.7		
	Sustainability																1		

Additional Comments

We instituted a major revision of the undergraduate CS curriculum at Stanford in 2008. Since then we have continued to make minor revisions in the curriculum, but do not anticipate making another significant change in the foreseeable future. In performing the mapping of our curriculum against the CS2013 guidelines, we realized that there are a few Core-Tier1 learning outcomes that we currently do not cover in our typical program (hence the 98% coverage of Core-Tier1, as opposed to 100%). We believe that we can cover the additional 2% of Core-Tier1 learning outcomes through minor, localized changes in existing courses, so no significant curricular changes are currently planned.

Appendix: Information on Individual Courses

Below is the detailed course information for the courses in the sample program described above. The full set of CS courses offered at Stanford is too large to include here, but is available in the university online course catalog. Courses are listed below in numeric order. Note that numeric order does necessarily reflect the order in which students would likely take these courses. For example, CS103 has CS106A—a higher numbered course—as a prerequisite.

CS 103: Mathematical Foundations of Computing

Mathematical foundations required for computer science, including propositional predicate logic, induction, sets, functions, and relations. Formal language theory, including regular expressions, grammars, finite automata, Turing machines, and NP-completeness. Mathematical rigor, proof techniques, and applications. Prerequisite: 106A or equivalent.

URL: **`http://www.stanford.edu/class/cs103/`**

(Also listed as a course exemplar in CS2013)

CS 106A: Programming Methodology

Introduction to the engineering of computer applications emphasizing modern software engineering principles: object-oriented design, decomposition, encapsulation, abstraction, and testing. Uses the Java programming language. Emphasis is on good programming style and the built-in facilities of the Java language. No prior programming experience required.

URL: **`http://www.stanford.edu/class/cs106a/`**

CS 106B: Programming Abstractions

Abstraction and its relation to programming. Software engineering principles of data abstraction and modularity. Object-oriented programming, fundamental data structures (such as stacks, queues, sets) and data-directed design. Recursion and recursive data structures (linked lists, trees, graphs). Introduction to time and space complexity analysis. Uses the programming language C++ covering its basic facilities. Prerequisite: 106A or equivalent.

URL: **`http://www.stanford.edu/class/cs106b/`**

CS 107: Computer Organization and Systems
Introduction to the fundamental concepts of computer systems. Explores how computer systems execute programs and manipulate data, working from the C programming language down to the microprocessor. Topics covered include: the C programming language, data representation, machine-level code, computer arithmetic, elements of code compilation, memory organization and management, and performance evaluation and optimization. Prerequisites: 106B or consent of instructor.
URL: **http://www.stanford.edu/class/cs107/**

CS 108: Object-Oriented Systems Design
Software design and construction in the context of large OOP libraries. Taught in Java. Topics: OOP design, design patterns, testing, graphical user interface (GUI) OOP libraries, software engineering strategies, approaches to programming in teams. Prerequisite: 107.
URL: **http://www.stanford.edu/class/cs108/**

CS 109: Introduction to Probability for Computer Scientists
Topics include: counting and combinatorics, random variables, conditional probability, independence, distributions, expectation, point estimation, and limit theorems. Applications of probability in computer science including machine learning and the use of probability in the analysis of algorithms. Prerequisites: 103, 106B, and multivariate calculus.
URL: **http://www.stanford.edu/class/cs109/**
(Also listed as a course exemplar in CS2013)

CS 110: Principles of Computer Systems
Principles and practice of engineering of computer software and hardware systems. Topics include: techniques for controlling complexity; strong modularity using client-server design, virtual memory, and threads; networks; atomicity and coordination of parallel activities; security, and encryption; and performance optimizations. Prerequisite: 107.
URL: **http://www.stanford.edu/class/cs110/**

CS 140: Operating Systems and Systems Programming
Operating systems design and implementation. Basic structure; synchronization and communication mechanisms; implementation of processes, process management, scheduling, and protection; memory organization and management, including virtual memory; I/O device management, secondary storage, and file systems. Prerequisite: 110.
URL: **http://www.stanford.edu/class/cs140/**

CS 144: Introduction to Computer Networking
Principles and practice. Structure and components of computer networks, packet switching, layered architectures. Applications: web/http, voice-over-IP, p2p file sharing and socket programming. Reliable transport: TCP/IP, reliable transfer, flow control, and congestion control. The network layer: names and addresses, routing. Local area networks: ethernet and switches. Wireless networks and network security. Prerequisite: 110.
URL: **http://www.stanford.edu/class/cs144/**
(Also listed as a course exemplar in CS2013)

CS 145: Introduction to Databases
The course covers database design and the use of database management systems for applications. It includes extensive coverage of the relational model, relational algebra, and SQL. It also covers XML data including DTDs and XML Schema for validation, and the query and transformation languages XPath, XQuery, and XSLT. The course includes database design in UML, and relational design principles based on dependencies and normal forms. Many additional key database topics from the design and application-building perspective are also covered: indexes, views, transactions, authorization, integrity constraints, triggers, on-line analytical processing (OLAP), JSON, and emerging NoSQL systems. Class time will include guest speakers from industry and additional advanced topics as time and class interest permits. Prerequisites: 103 and 107.
URL: **http://www.stanford.edu/class/cs145/**

CS 147: Introduction to Human-Computer Interaction Design
Introduces fundamental methods and principles for designing, implementing, and evaluating user interfaces. Topics: user-centered design, rapid prototyping, experimentation, direct manipulation, cognitive principles, visual design, social software, software tools. Learn by doing: work with a team on a quarter-long design project, supported by lectures, readings, and studios. Prerequisite: 106B or equivalent programming experience.
URL: **http://www.stanford.edu/class/cs147/**
(Also listed as a course exemplar in CS2013)

CS 155: Computer and Network Security
Principles of computer systems security. Attack techniques and how to defend against them. Topics include: network attacks and defenses, operating system security, application security (web, apps, databases), malware, privacy, and security for mobile devices. Course projects focus on building reliable code. Prerequisite: 140.
URL: **http://www.stanford.edu/class/cs155/**

CS 161: Design and Analysis of Algorithms
Worst and average case analysis. Recurrences and asymptotics. Efficient algorithms for sorting, searching, and selection. Data structures: binary search trees, heaps, hash tables. Algorithm design techniques: divide-and-conquer, dynamic programming, greedy algorithms, amortized analysis, randomization. Algorithms for fundamental graph problems: minimum-cost spanning tree, connected components, topological sort, and shortest paths. Possible additional topics: network flow, string searching. Prerequisites: 103 and 109.
URL: **http://www.stanford.edu/class/cs161/**

CS 181: Computers, Ethics, and Public Policy
Primarily for majors entering computer-related fields. Ethical and social issues related to the development and use of computer technology. Ethical theory, and social, political, and legal considerations. Scenarios in problem areas: privacy, reliability and risks of complex systems, and responsibility of professionals for applications and consequences of their work. Prerequisite: 106B.
URL: **http://www.stanford.edu/class/cs181/**

CS 194: Software Project
Design, specification, coding, and testing of a significant team programming project under faculty supervision. Documentation includes a detailed proposal. Public demonstration of the project at the end of the quarter. Prerequisites: 110 and 161.
URL: **`http://www.stanford.edu/class/cs194/`**

EE 108B: Digital Systems II
The design of processor-based digital systems. Instruction sets, addressing modes, data types. Assembly language programming, low-level data structures, introduction to operating systems and compilers. Processor microarchitecture, microprogramming, pipelining. Memory systems and caches. Input/output, interrupts, buses and DMA. System design implementation alternatives, software/hardware tradeoffs. Labs involve the design of processor subsystems and processor-based embedded systems. Prerequisite: 106B.
URL: **`http://ee108b.stanford.edu/`**

Williams College

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Curricular Overview

Williams College is a highly-selective liberal arts college of about 2200 students. To complete the requirements for the Bachelor of Arts degree, students must take at least 32 regularly graded one-unit courses, satisfy the requirements for a major, and fulfill distribution requirements (3 courses in each Division – Arts and Languages; Social Studies; Science and Mathematics. Students must also complete 1 Exploring Diversity course, 2 writing-intensive courses, and 1 quantitative/formal reasoning course). In order to ensure that students are free to explore a wide range of academic subjects in the liberal arts tradition, the College places a limit on the number of courses that may be required for a major – typically 9. Students are free to take as many courses in their majors as they'd like, provided they complete the distribution requirements.

The Computer Science Department has eight faculty with a wide range of research interests and expertise, including distributed systems, parallel programming, architecture, artificial intelligence, programming languages, algorithms, graph theory, graphics, and networks.

Computer Science Major

The Williams College Computer Science major has been strongly influenced by LACS (Liberal Arts Computer Science Consortium) model curricula.

In all, 10 courses are required for the major.

A minimum of 8 courses is required in Computer Science, including

Introductory Courses (offered every semester)

- CSCI 134: Introduction to Computer Science
- CSCI 136: Data Structures and Advanced Programming

Core Courses (offered once each year)

- CSCI 237: Computer Organization
- CSCI 256: Algorithm Design and Analysis
- CSCI 334: Principles of Programming Languages
- CSCI 361: Theory of Computation

Electives

Two or more electives (bringing the total number of Computer Science courses to at least 8) chosen from 300- or 400-level courses in Computer Science. At least one of these must be a course designated as a PROJECT COURSE. "Reading", "Research", and "Thesis" courses do not normally satisfy the elective requirement.

Current electives are

- Computer Networks
- Digital Design and Modern Architecture
- Distributed Systems [PROJECT]
- Advanced Algorithms
- Computational Graphics [PROJECT]
- Artificial Intelligence [PROJECT]
- Machine Learning
- Operating Systems [PROJECT]
- Compiler Design [PROJECT]
- Computational Biology
- Integrative Bioinformatics, Genomics, and Proteomics Lab

Electives are offered, on average, once every other year.

Required Courses in Mathematics
MATH 200: Discrete Mathematics
and any other Mathematics or Statistics course at the 200-level or higher

In addition, seniors are required to attend weekly computer science colloquia.

Curricular Analysis

Here we provide a high level picture of our coverage of CS2013 Core-Tier1 and Tier2 topics.

For this analysis, we consider a typical major to take the introductory sequence, the four core courses, and three electives, as well as Discrete Mathematics. Though only two electives are required for the major, Computer Science students take, on average, 3.6 electives (computed over the last three years). Many students also enroll in Reading, Research, or Thesis courses, but we do not include those in our analysis.

We have offered two different versions of our Introduction to Computer Science course over the last several years. The one offered most frequently has been a network-themed course. We use that in our mapping below.

The specific electives we have used in the mapping are:

- CSCI 337: Digital Design and Modern Architecture
- CSCI 373: Artificial Intelligence
- CSCI 432: Operating Systems

	Tier 1	*Tier 2*
Typical major – Intro, Core, Discrete Math + Architecture, AI, and OS	83%	60%
Common CS core – Intro, Core, Discrete Math – not the complete major	70%	40%
Typical major from row 1 + either Distributed Systems or Networks	85%	68%

Knowledge Units in a Typical Major

See preceding section for explanation of what we are taking to be a "typical" major. The mapping below (as well as the % coverage) would be different for other paths through the major.

Notation:		134: Intro to CS	136: Data Structures	237: Computer Organization	256: Alg Design and Analysis	334: Principles of Prog Languages	361: Theory of Computation	Discrete Math	373: AI	432: OS	337: Digital Design & Arch	% Tier 1	% Tier 2
< 25% of KU covered #													
25-75% of KU covered #													
> 75% of KU covered #													
AL	Basic Analysis		3		4							100	100
	Algorithmic Strategies		1		4.5				.5				
	Fund. DS & Alg.	1	10		12				1				
	Basic Autom. & Comp.						6						
AR	Digital Logic			3							3	n/a	96
	Machine-level rep. of data			3									
	Assembly level mach. org.			5.5						.5	1.5		
	Memory org. and arch.			2						1.4	2.7		
	Interfacing and comm.	.17		.34						.5	.17		
CN	Fundamentals (336)											0	n/a
DS	Sets, Relations, & Functions							4				98	75
	Basic Logic								9				
	Proof Techniques		2					8.3					
	Basics of Counting							5					
	Graphs & Trees		2.7		2.7			.67					
	Discrete Probability	4			4				6				
GV	Fundamental Concepts	1.8										80	30
HCI	Foundations											0	0
	Designing Interaction												

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		134: Intro to CS	136: Data Structures	237: Computer Organization	256: Alg Design and Analysis	334: Principles of Prog Languages	361: Theory of Computation	Discrete Math	373: AI	432: OS	337: Digital Design & Arch	% Tier 1	% Tier 2
IAS	Fund. Concepts in Security					.7						63	12
	Principles of Secure Design					.8				.14			
	Defensive Programming					.7							
	Threats and Attacks					.4							
	Network Security												
	Cryptography												
IM	Info. Management Concepts	.2	.2						.4			20	7
	Database Systems												
	Data Modeling	.4	.4			.4							
IS	Fundamental Issues								1			n/a	83
	Basic Search Strategies								3.8				
	Basic Knowledge Rep.								3				
	Basic Machine Learning								.3				
NC	Introduction	1.1								.38		83	63
	Networked Applications	.9											
	Reliable Data Delivery	.5								1			
	Routing and Forwarding	1											
	Local Area Networks	1.5											
	Resource Allocation												
	Mobility												

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		134: Intro to CS	136: Data Structures	237: Computer Organization	256: Alg Design and Analysis	334: Principles of Prog Languages	361: Theory of Computation	Discrete Math	373: AI	432: OS	337: Digital Design & Arch	% Tier 1	% Tier 2
OS	Overview of OS									2		92	80
	Operating Systems Principles	.55								1.8			
	Concurrency									2.6			
	Scheduling and Dispatch									2.1	.43		
	Memory Management			1.5						2.3	2		
	Security and Protection									1.5			
PD	Parallelism Fundamentals					2						100	21
	Parallel Decomposition					1							
	Comm. & Coord.					2.2				.6			
	Parallel Algorithms												
	Parallel Architecture									1			
PL	Object-Oriented Programming	2.7	2.7			10						100	100
	Functional Programming					7							
	Event-Driven & React. Prog.	2											
	Basic Type Systems					5							
	Program Representation					1							
	Language Translation					3							
SDF	Algorithms and Design	9	11									97	NA
	Fund. Prog. Concepts	10											
	Fund. DS	4	12										
	Development Methods	4.6	6.2						1.5	.77			

Notation:
< 25% of KU covered #
25-75% of KU covered #
> 75% of KU covered #

		134: Intro to CS	136: Data Structures	237: Computer Organization	256: Alg Design and Analysis	334: Principles of Prog Languages	361: Theory of Computation	Discrete Math	373: AI	432: OS	337: Digital Design & Arch	% Tier 1	% Tier 2
SE	Software Processes					.8						43	28
	Software Project Manage.								1.3	1.3	1.3		
	Tools and Environments			.67						.67			
	Requirements Engineering	1.5											
	Software Design		1			2.4							
	Software Construction		.3			.2				.3			
	Software Verif. & Valid.								.5				
	Software Evolution	.25	.25										
	Software Reliability												
SF	Computational Paradigms	.3		1.4		.65				.3	.6	76	80
	Cross-Layer Communications	.4		1.8						2.4			
	State and State Machines			5.5			2				.5		
	Parallelism			.4						.25	.5		
	Evaluation			1.5						1.5	2.1		
	Resource Alloc. & Sched.									2			
	Proximity			3							3		
	Virtualization & Isolation									1	1		
	Reliab. through Redundancy			.6						1	.33		
SP	Social Context											4	0
	Analytical Tools												
	Professional Ethics												
	Intellectual Property												
	Privacy & Civil Liberties												
	Prof. Communication								.43	.43	.43		
	Sustainability												

Possible Curricular Revisions

Note that here we analyze the *complete* Williams College Computer Science curriculum, rather than the path that any individual student might take through the major.

The major areas of difference between our complete curriculum and the CS2013 core are as follows.

No coverage or very minimal coverage:

- Human-Computer Interaction (HCI)
- Information Management (IM)
- Social Issues and Professional Practice (SP)

More coverage but not close to CS2013 targets:

- Software Engineering (SE)
- Core-Tier 2 of Parallel and Distributed Computing (PD)

Could use more coverage:

- Information Assurance and Security (IAS)

Students are, in general, gaining more knowledge in SP and SE than our formal mapping suggests, through their lab experiences in project courses, research and reading courses, and colloquia. In addition, because our students are required to take courses in the humanities and social sciences, they gain a broad appreciation for social, ethical, and political considerations that students at many engineering institutions do not.

Considerations for possible changes in curriculum:

We begin by noting that the complete Williams CS curriculum is quite strong in Algorithms and Complexity, Architecture, Discrete Mathematics, Graphics, Intelligent Systems, Networking and Communication, Operating Systems, Core-Tier 1 of Parallel and Distributed Computing, Programming Languages, and Software Development Fundamentals. It also covers Systems Fundamentals very well.

In revising our curriculum to better meet the CS2013 recommendations, our goal would be to balance the following considerations. We want to continuously evolve our curriculum to remain current and even cutting-edge. We desire to also maintain our traditional strengths. And we must work within the constraints of a relatively small department and the restriction on the number of courses we can require for the major.

Possible changes:

We have been involved in major curricular discussions over the past year. Among the revisions we have discussed is the following

Remove the following requirements:

- Theory of Computation (but keep as an elective)
- Discrete Mathematics + one additional Mathematics/Statistics course

Add:

- Mathematical Foundations of Computer Science – this course would introduce topics from Discrete Mathematics in a more CS-focused manner. Basic computability topics could be integrated into this course.
- Introduction to Software Design – this could be a third course following our traditional introductory sequence. It would introduce basic topics from software engineering and HCI, preparing students even better for our project electives. This would also have the side effect of freeing up time in those electives that is currently spent on basic project management and design issues.
- Topics in Security and Parallel Processing to existing courses/electives as appropriate.

Though a number of the Information Management learning outcomes fit well within a liberal arts context, quite a few seem less appropriate. Similarly, the topics we would introduce in our Software Design course would not literally follow the CS2013 Software Engineering core.

Appendix: Information on Individual Courses

A note on tutorial format courses: Modeled on Oxford-style tutorials, these courses offer students the opportunity to take a heightened responsibility for their own intellectual development. Tutorials are typically limited to an enrollment of 10. Each week the professor sets the agenda, but the students are responsible for working through the material. Once each week, students meet in pairs with the instructor to present their work and together delve even more deeply into the material.

CSCI 134 – Introduction to Computer Science
This course introduces fundamental ideas in computer science and builds skills in the design, implementation, and testing of computer programs. Students implement algorithms in the Java programming language with a strong focus on constructing correct, understandable, and efficient programs. Students explore the material through the application area of computer networks. Topics covered include object-oriented programming, control structures, arrays, recursion, and event-driven programming.
Format: lecture/laboratory

http://dept.cs.williams.edu/~cs134/

CSCI 136 – Data Structures and Advanced Programming
This course builds on the programming skills acquired in Computer Science 134. It couples work on program design, analysis, and verification with an introduction to the study of data structures. Students are introduced to: lists, stacks, queues, trees, hash tables, and graphs. Students are expected to write several programs, ranging from very short programs to more elaborate systems. Emphasis is placed on the development of clear, modular programs that are easy to read, debug, verify, analyze, and modify.
Format: lecture/laboratory

http://dept.cs.williams.edu/~jeannie/cs136/index.html

CSCI 237 – Computer Organization
This course studies the basic instruction set architecture and organization of a modern computer. Over the semester the student learns the fundamentals of translating higher level languages into assembly language, and the interpretation of machine languages by hardware. At the same time, a model of computer hardware organization is developed from the gate level upward. Final projects focus on the design of a complex control system in hardware or firmware.
Format: lecture/laboratory

CSCI 256 – Algorithm Design and Analysis
This course investigates methods for designing efficient and reliable algorithms. It introduces several algorithm design strategies that build on data structures and programming techniques introduced in Computer Science 136. These include induction, divide-and-conquer, dynamic programming, and greedy algorithms. Particular topics of study include graph theory, hashing, and advanced data structures.
Format: lecture

See course exemplar in Appendix C

CSCI 334 – Principles of Programming Languages
This course examines the concepts and structures governing the design and implementation of programming languages. It presents an introduction to the concepts behind compilers and run-time representations of programming languages; features of programming languages supporting abstraction and polymorphism; and the procedural, functional, object-oriented, and concurrent programming paradigms. Programs are required in languages illustrating each of these paradigms.
Format: lecture

See course exemplar in Appendix C

CSCI 361 – Theory of Computation
This course introduces a formal framework for investigating both the computability and complexity of problems. Students study several models of computation including finite automata, regular languages, context-free grammars, and Turing machines. Topics include the halting problem and the P versus NP problem.
Format: lecture

http://dept.cs.williams.edu/~heeringa/classes/cs361/f12/

CSCI 336 – Computer Networks
This course explores the principles underlying the design of computer networks. It examines techniques for transmitting information efficiently and reliably over a variety of communication media. It looks at the addressing and routing problems that must be solved to ensure that transmitted data gets to the desired destination. Students come to understand the impact that the distributed nature of all network problems has on their difficulty. The course examines the ways

in which these issues are addressed by current networking protocols such as TCP/IP and Ethernet. Format: tutorial – students will meet weekly with the instructor in pairs to present solutions to problem sets and reports evaluating the technical merit of current solutions to various networking problems.

http://dept.cs.williams.edu/~tom/courses/336/

CSCI 337 – Digital Design and Modern Architecture

This tutorial course considers topics in the low-level design of modern architectures. Course meetings review problems of designing effective architectures including instruction-level parallelism, branch-prediction, caching strategies, and advanced ALU design. Readings are taken from recent technical literature. Labs focus on the development of custom CMOS circuits to implement projects from gates to bit-sliced ALU's. Final group projects develop custom logic demonstrating concepts learned in course meetings.
Format: tutorial/laboratory

CSCI 339 – Distributed Systems

This course studies the key design principles of distributed systems. Covered topics include communication protocols, processes and threads, naming, synchronization, consistency and replication, fault tolerance, and security. Students also examine some specific real-world distributed systems case studies, ranging from the Internet to file systems. Class discussion is based on readings from the textbook and research papers. The goals of this course are to understand how large-scale computational systems are built, and to provide students with the tools necessary to evaluate new technologies after the course ends.
Format: lecture/laboratory

http://dept.cs.williams.edu/~jeannie/cs339/index.html

CSCI 336 – Advanced Algorithms

This course explores advances in algorithm design, algorithm analysis and data structures. The primary focus is on randomized and approximation algorithms, randomized and advanced data structures, and algorithmic complexity. Topics include combinatorial algorithms for cut, packing, and covering problems, linear programming algorithms, approximation schemes, hardness of approximation, random search trees, and hashing.
Format: tutorial

http://dept.cs.williams.edu/~heeringa/classes/cs356T/f11/

CSCI 371 – Computational Graphics

This course teaches the fundamental techniques behind applications such as PhotoShop, medical MRIs, video games, and movie special effects. It begins by building a mathematical model of the interaction of light with surfaces, lenses, and an imager. Students then study the data structures and processor architectures that allow for efficiently evaluating that physical model. Students complete a series of programming assignments for both photorealistic image creation and real-time 3D rendering using C++, OpenGL, and GLSL. These assignments cumulate in a multi-week final project. Topics covered in the course include: projective geometry, ray tracing, bidirectional

surface scattering functions, binary space partition trees, matting and compositing, shadow maps, cache management, and parallel processing on GPUs.
Format: lecture/laboratory

See course exemplar in Appendix C

CSCI 373 – Artificial Intelligence
This course introduces fundamental techniques in the field of Artificial Intelligence. It covers methods for knowledge representation, reasoning, problem solving, and learning. It then explores those further by surveying current applications in selected areas such as game playing and natural language processing. Students complete several programming projects, including a large project of their own design that spans most of the second half of the semester.
Format: lecture/laboratory

http://dept.cs.williams.edu/~andrea/cs373/

CSCI 374 – Machine Learning
This tutorial examines the design, implementation, and analysis of machine learning algorithms. It covers examples of supervised learning algorithms (including decision tree learning, support vector machines, and neural networks), unsupervised learning algorithms (including k-means and expectation maximization), and optionally reinforcement learning algorithms (such as Q learning and temporal difference learning). It introduces methods for the evaluation of learning algorithms, as well as topics in computational learning theory.
Format: tutorial

http://dept.cs.williams.edu/~andrea/cs374/

CSCI 432 – Operating Systems
This course explores the design and implementation of computer operating systems. Topics include historical aspects of operating systems development, systems programming, process scheduling, synchronization of concurrent processes, virtual machines, memory management and virtual memory, I/O and file systems, system security, os/architecture interaction, and distributed operating systems.
Format: lecture/laboratory

See course exemplar in Appendix C

CSCI 434 – Compiler Design
This tutorial covers the principles and practices for the design and implementation of compilers and interpreters. Topics include all stages of the compilation and execution process: lexical analysis; parsing; symbol tables; type systems; scope; semantic analysis; intermediate representations; run-time environments and interpreters; code generation; program analysis and optimization; and garbage collection. The course covers both the theoretical and practical implications of these topics. Students construct a full compiler for a simple object-oriented language.
Format: tutorial/laboratory

See course exemplar in Appendix C

CSCI 315 – Computational Biology
This course provides an overview of Computational Biology. Topics covered include database searching, DNA sequence alignment, phylogeny reconstruction, protein structure prediction, microarray analysis, and genome assembly using techniques such as string matching, dynamic programming, suffix trees, hidden Markov models, and expectation-maximization.
Format: lecture/laboratory

CSCI 319 – Integrative Bioinformatics, Genomics, and Proteomics Lab
This course makes use of one well-studied system, the highly conserved Ras-related family of proteins, which play a central role in numerous fundamental processes within the cell. The course integrate bioinformatics and molecular biology, using database searching, alignments and pattern matching, phylogenetics, and recombinant DNA techniques to reconstruct the evolution of gene families by focusing on the gene duplication events and gene rearrangements that have occurred over the course of eukaryotic speciation. By utilizing high throughput approaches to investigate genes involved in the MAPK signal transduction pathway in human colon cancer cell lines, students uncover regulatory mechanisms that are aberrantly altered by siRNA knockdown of putative regulatory components. This functional genomic strategy is coupled with independent projects using phosphorylation-state specific antisera to test hypotheses. Proteomic analysis introduces the students to de novo structural prediction and threading algorithms, as well as data-mining approaches and Bayesian modeling of protein network dynamics in single cells. Flow cytometry and mass spectrometry are used to study networks of interacting proteins in colon tumor cells.
Format: laboratory/lecture

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