SCS Concentrations

The School of Computer Science (SCS) offers concentrations for SCS students in various aspects of computing to provide greater depth to their education. Computer Science majors can substitute an SCS concentration for the minor requirement. Artificial Intelligence and Computational Biology majors can complete an SCS concentration if they wish, but it is not required for these degrees.

Note: At the present time, concentrations are not shown on official transcripts.

SCS Concentrations are currently available to SCS students only and assume these students have taken most/all of the CS core: 15-122/15-150/15-210/15-213/15-251. For SCS students entering in Fall 2018 or later, these students may not pursue a minor within SCS; instead they can pursue the related concentration. For example, instead of pursuing the Software Engineering minor, these SCS students could pursue the new Software Engineering concentration.

Consult the SCS undergraduate concentrations website (https://www.cs.cmu.edu/undergraduate-concentrations/) for information about these concentrations as they are approved. For SCS students, consult with your academic advisor for more information about available concentrations and requirements.

- Algorithms and Complexity
- Computational Biology
- Computer Systems
- Human-Computer Interaction
- Language Technologies (to be approved in late 2019)
- Machine Learning
- Principles of Programming Languages
- Robotics
- Security and Privacy
- Software Engineering

Algorithms and Complexity Concentration

This concentration is available to SCS students only.

Ryan O’Donnell, Concentration Director
Location: GHC 7213

The goal of the Algorithms and Complexity concentration is to give SCS students a deep background in the theory of computation as it relates to algorithms and computational complexity. The expectation is that students who complete this concentration will have the background to pursue topics at the PhD level at any top program in the country. Furthermore we expect the reasoning skills gained as part of this concentration could be a significant help in a wide variety of positions in industry.

The concentration is designed to be reasonably flexible covering a wide area of topics within the area of algorithms and complexity. This includes central topics within the area such as complexity theory, and algorithms, but also includes theory as used in areas such as Computational Geometry, Graph Theory, Cryptography, Machine Learning, Algorithms for Large Data, Error Correcting Codes, and Parallel Algorithms.

Common themes of all courses covered by the concentration are the following:
- Clearly defined formalisms of the subject matter.
- A substantial component involving rigorous mathematical analysis, including proofs.
- Abstracting away from specific applications to a more general context.
- Relating algorithms and/or complexity of computation to a variety of complexity measures such as space, time, communication, or information content.

Any given course does not have to exclusively cover these themes and can, for example, also cover experimental aspects of algorithms, or examples applied to quite specific applications.

Learning Objectives

We do not expect students to have high proficiency in all the examples listed, but to gain at least some proficiency from each category.
- The ability to take a loosely defined problem and clearly pose it as a well defined problem specification.
- The understanding of several advanced algorithms beyond what is covered in the core.
- The appreciation a variety of models for bounding resources, such as information theory, space complexity, parallel complexity, communication complexity, proof complexity, query complexity, and hardness of approximation.
- The ability to understand and apply a variety of advanced algorithmic techniques and proof techniques, such as Lovasz Local Lemma, Johnson Lindenstrauss, Chernoff Bounds, sparsification, expanders, probabilistic method, regret bounds, spectral graph theory, fixed parameter tractability and semi-indefinite programming.
- The ability to recognize flaws in ill-formed proofs.
- The ability to formulate new questions about the field.

Prerequisites

The following courses must be completed before the concentration can be completed:

15-210 Parallel and Sequential Data Structures and Algorithms 12
15-251 Great Ideas in Theoretical Computer Science 12
15-259 Probability and Computing or 21-325 Probability or 36-218 Probability Theory for Computer Scientists 12
15-451 Algorithm Design and Analysis 12

It is expected that all students will start the concentration after having finished all but 15-451.

Course Requirements

The curriculum consists of one required course and at least three elective courses. The three elective courses must sum to at least 30 units. The elective courses will vary from year to year.

Required:

15-455 Undergraduate Complexity Theory 9

Electives (at least three courses with a total of 30 units or more):

15-354 Computational Discrete Mathematics 12
15-356 Introduction to Cryptography 12
15-456 Computational Geometry 9
15-458 Discrete Differential Geometry 12
15-483 Truth, Justice, and Algorithms 9
21-301 Combinatorics 9
21-484 Graph Theory 9

Special permission required:

47-834 Linear Programming 6
47-835 Graph Theory 6
47-836 Advanced Graph Theory 6

Other graduate-level courses as approved by the concentration director

A student can also use a senior thesis or research-based independent study as one of the elective courses (for 12 units). The topic must be related to algorithms and complexity, and approved by the director. An independent study must be for at least 12 units, and there must be a submission paper writeup on the research topic, and a poster or other presentation. The choice of available elective courses will be posted prior to registration each semester.

Double Counting

The concentration will require that 3 courses (at least 27 units) are not double counted with any other requirements of any Major, Minor, or other concentration the student is pursuing.

Advising and Management

Courses in the list of electives will be approved by the director on a yearly basis under consultation of the algorithms and complexity group (to help evaluate the relevance of the courses) and the Assistant Dean (to help
flag any logistical issues). Any special requests by a student for counting a course out of the list, will go to the director. The director will also approve any research units.

Students interested in this concentration should contact the concentration director for an initial advising consultation.

Computational Biology Concentration

This concentration is available to SCS students only.

Phillip Compeau, Concentration Director
Location: GHC 7403

Samantha Mudrinich, Concentration Coordinator
Location: GHC 7414

The general goal of the Computational Biology Concentration is to provide foundational coursework in computational biology that will allow undergraduate students in the Carnegie Mellon University School of Computer Science to start building a skillset useful for understanding many of the modern technologies developed by researchers as well as companies in the biotech and biomedical arenas.

This concentration consists of four core courses providing breadth in computational biology across laboratory methods, machine learning, genomics, and modeling of biological systems, as well as one elective that allows students to complete depth coursework in an area of interest, including undergraduate research.

Learning Objectives

Students will, by way of completing this concentration:

- model biological systems at the molecular and cellular levels using a variety of approaches;
- generate their own high throughput molecular biology data in a laboratory setting, and apply computational techniques to analyze the data they generate;
- transform hazy biological problems involving genomic data into well-defined computational problems, design algorithms to solve these problems, and adapt them to biological data;
- explore additional coursework of interest in genomics, biological research automation, biological image analysis, or computational biology research.

This concentration also provides students completing a computational degree other than the major in computational biology (http://www.cbd.cmu.edu/education/bs-in-computational-biology/) with the opportunity to make a transition toward a career in computational biology. We have compiled information on over 250 companies working on computational biology into a unique web resource for students both inside and outside of Carnegie Mellon (http://careers.cbd.cmu.edu/). These companies work on diverse topics from the automation of biological research to drug discovery to wearable medical devices to genetic diagnostics. Increasingly, when we interact with these companies, they want computationally minded candidates with as much knowledge of standard approaches in computational biology as possible.

Prerequisites

Note that not all of the prerequisites below are required to take every course in this concentration (for example, 02-251 does not have any of the pre-requisites below), but these courses are required to complete all of the required coursework and should be completed early within this concentration.

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-122</td>
<td>Principles of Imperative Computation</td>
<td>10</td>
</tr>
<tr>
<td>15-151</td>
<td>Mathematical Foundations for Computer Science</td>
<td>10</td>
</tr>
<tr>
<td>15-210</td>
<td>Parallel and Sequential Data Structures and Algorithms</td>
<td>12</td>
</tr>
<tr>
<td>21-241</td>
<td>Matrices and Linear Transformations</td>
<td>10</td>
</tr>
<tr>
<td>36-218</td>
<td>Probability Theory for Computer Scientists</td>
<td>9</td>
</tr>
</tbody>
</table>

Further, the following two courses are not technically required as prerequisites to the courses in this concentration, but they are strongly suggested prerequisites because they provide students with helpful surveys of fundamental topics in biology and computational biology.

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>02-251</td>
<td>Great Ideas in Computational Biology</td>
<td>12</td>
</tr>
<tr>
<td>03-121</td>
<td>Modern Biology</td>
<td>9</td>
</tr>
</tbody>
</table>

Requirements

Five courses in total are required for this concentration. The following four courses are required as part of a central core of coursework; they consist of three computational biology courses as well as an introductory machine learning course, which today is fundamental for even an introductory understanding of the field.

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>02-261</td>
<td>Quantitative Cell and Molecular Biology Laboratory</td>
<td>Var.</td>
</tr>
<tr>
<td>02-510</td>
<td>Computational Genomics</td>
<td>12</td>
</tr>
<tr>
<td>02-512</td>
<td>Computational Methods for Biological Modeling and Simulation</td>
<td>9</td>
</tr>
<tr>
<td>10-315</td>
<td>Introduction to Machine Learning (SCS Majors)</td>
<td>12</td>
</tr>
</tbody>
</table>

In addition to these four courses above, one elective course is required. Any 02-listed (Computational Biology Department) undergraduate course of at least 9 units at the 300-level or above may satisfy this requirement; graduate courses may be applied to this category with permission. The Computational Biology Department is growing quickly, but at the time of writing, the courses that are regularly offered by the department that would satisfy this requirement are the following:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>02-317</td>
<td>Algorithms in Nature</td>
<td>9</td>
</tr>
<tr>
<td>02-319</td>
<td>Genomics and Epigenetics of the Brain</td>
<td>9</td>
</tr>
<tr>
<td>02-425</td>
<td>Computational Methods for Proteogenomics and Metabolomics</td>
<td>9</td>
</tr>
<tr>
<td>02-450</td>
<td>Automation of Scientific Research</td>
<td>9</td>
</tr>
<tr>
<td>02-499</td>
<td>Independent Study in Computational Biology</td>
<td>Var.</td>
</tr>
<tr>
<td>02-500</td>
<td>Undergraduate Research in Computational Biology</td>
<td>Var.</td>
</tr>
</tbody>
</table>

Double Counting

At most two courses can double count with all program requirements for majors, minors and other concentrations being pursued by the student. Courses used as free electives for a major are not considered double counted.

Accordingly, this concentration is expressly closed to majors and additional majors in computational biology.

CS and AI majors completing this concentration are encouraged to double-count 10-315 as well as 02-261 as their lab science course. Suggested prerequisites 03-121 and 02-251 also count as requirements for these degrees (as a Science & Engineering course and CS Domains course, respectively).

Advising and Management

The day-to-day management of this concentration (including declaration of the concentration, exception requests, overseeing student audits, advising, etc.) is handled by Phillip Compeau, Assistant Department Head for Education in the Computational Biology Department. Administrative support for the concentration is provided by Samantha Mudrinich. Curricular organization and annual review will be managed by the Computational Biology Undergraduate Review Committee.

SCS students interested in this concentration should set up an appointment with Phillip Compeau for a brief interview.

Computer Systems Concentration

This concentration is available to SCS students only.

Brian Railing, Concentration Director and Advisor
Location: GHC 6005

The goal of the Computer Systems concentration is to give students a broad background in the practical understanding of designing and building systems. Students who complete this concentration are expected to be able to both pursue topics at the Ph.D. level at top programs, as well as industry work, either applying these concepts or directly working within the areas of kernel development, compiler improvements, designing distributed systems, et cetera.

The concentration is designed to be flexible in covering the wide area of systems topics. Two courses from the Computer Science major’s “systems” constrained elective are required (List A below). The other courses come
from a larger list of related courses (List B below). A limited amount of research credit can count toward the requirements.

Typically, systems courses include three aspects:

- A systems course educates students about how a class of computer systems works, both at a conceptual level and in practice. This includes the study of concrete problems faced in building a particular class of systems and successful solutions to these problems.
- Systems courses address how properties of modern hardware (e.g., processors, networks, storage, hierarchies) influence the design and implementation of a class of software systems. This typically includes reasoning about concurrency, understanding and measuring performance.
- To solidify the key systems organization principles, there is a significant project/system implementation aspect to the course, both to reinforce understanding of how these systems work, and to learn system building skills (i.e., not just programming, but also design, debugging, testing, etc.). The size of the programming tasks is course dependent, but a significant fraction of the course grade (e.g., at least 40%) is derived from project work.

Learning Objectives

Students completing this concentration will be able to demonstrate the following skills and learning:

- Students will be able to design, develop and deploy large computer systems and justify their design decisions.
- Students will synthesize the interaction and tradeoffs between different layers and components in computer systems.
- Students will demonstrate debugging expertise on complex and diverse bugs and issues during software development.
- Students will recognize diverse granularities of parallelism, apply them toward solving problems, and implement solutions that achieve correct execution while accounting for reliability, fault tolerance, performance, security, and scalability.

Prerequisites

All students will start the concentration after having finished 15-213 Introduction to Computer Systems (or its cross-listed equivalents) with a C or better, as 15-213 is a prerequisite either directly or indirectly for all courses in the concentration.

Course Requirements

The curriculum will consist of at least four courses: two courses from List A and at least two elective courses from List B. The courses taken from list A and B must sum to at least 51 units, where each course must be passed with a C or better. The courses in List A will follow the Systems constrained elective list as part of the degree requirements for a B.S. in Computer Science. The elective courses on List B may vary from year to year, with a plan to review these requirements every three years.

List A (select two):

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-410</td>
<td>Operating System Design and Implementation</td>
<td>15</td>
</tr>
<tr>
<td>15-411</td>
<td>Compiler Design</td>
<td>15</td>
</tr>
<tr>
<td>15-418</td>
<td>Parallel Computer Architecture and Programming</td>
<td>12</td>
</tr>
<tr>
<td>15-440</td>
<td>Distributed Systems</td>
<td>12</td>
</tr>
<tr>
<td>15-441</td>
<td>Networking and the Internet</td>
<td>12</td>
</tr>
<tr>
<td>15-445</td>
<td>Database Systems</td>
<td>12</td>
</tr>
</tbody>
</table>

List B (select at least two):

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-319</td>
<td>Cloud Computing</td>
<td>12</td>
</tr>
<tr>
<td>15-330</td>
<td>Introduction to Computer Security</td>
<td>12</td>
</tr>
<tr>
<td>15-348</td>
<td>Embedded Systems</td>
<td>9</td>
</tr>
<tr>
<td>15-412</td>
<td>Operating System Practicum</td>
<td>Var.</td>
</tr>
<tr>
<td>15-415</td>
<td>Database Applications</td>
<td>12</td>
</tr>
<tr>
<td>17-422</td>
<td>Building User-Focused Sensing Systems</td>
<td>12</td>
</tr>
<tr>
<td>18-341</td>
<td>Logic Design and Verification</td>
<td>12</td>
</tr>
<tr>
<td>18-349</td>
<td>Introduction to Embedded Systems</td>
<td>12</td>
</tr>
<tr>
<td>18-447</td>
<td>Introduction to Computer Architecture</td>
<td>12</td>
</tr>
</tbody>
</table>

Special permission required for:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-719</td>
<td>Advanced Cloud Computing</td>
<td>12</td>
</tr>
</tbody>
</table>

Other graduate-level courses in CSD as approved by the concentration director

Students can also apply a senior thesis or other significant research for credit in a topic related to Systems, as approved by the concentration advisor, as one of the elective courses for List B. Any significant research credit will include an identifiable output, such as paper or technical report. Any research course counts for at most 12 units, and can be done once.

Double Counting

The concentration will require that 3 courses (at least 27 units) are not double counted with any other requirements of any major, minor, or other concentration.

Advising and Management

The courses on the list of electives will be reviewed yearly by the concentration advisor through consultation with the Systems group (to help evaluate the relevance of the courses) and the Assistant Dean for undergraduate studies (to help flag any logistical issues). Any special requests by a student for counting a course outside of the list will go to the concentration advisor. The concentration advisor will also approve any research units.

Students interested in this concentration should set up an initial advising consultation with Brian Railing.

Human-Computer Interaction Concentration

This concentration is available to SCS students only.

Vincent Aleven, Concentration Coordinator
Location: Newell-Simon Hall 3531
Andrea Gnesin, Concentration Manager
Location: Newell-Simon Hall 3607

In this concentration, students learn techniques, processes, principles, and theory of Human-Computer Interaction (HCI). This interdisciplinary field aims at understanding how interactions with digital technologies and services can augment what humans do. It also aims at understanding what design, prototyping, and evaluation processes lead to innovative digital technologies and services that fulfill human needs. The concentration enhances what is learned in the SCS majors by addressing how digital products and services can be designed and evaluated so they benefit individuals, small groups, organizations, larger networks, and societies. It is synergistic with SCS majors in that envisioning, designing, and implementing innovative digital interactions benefit from superior technical skill. The concentration consists of 5 courses (2 required courses and 3 electives).

The concentration helps prepare students for jobs as technically-skilled specialists in design and development of interactive systems. The concentration will give students a broader perspective on how technologies impact humans, which may help them move faster into product management positions. It also lays a foundation for graduate study in the field of Human-Computer Interaction.

Learning Objectives

Students will learn skills and methods for:

- Eliciting and understanding human objectives, preferences, and needs through qualitative and quantitative methods for data collection and analysis
- Generating and imagining possible solutions and design concepts that involve human/technology partnerships
- Basic visual design, including typography, grids, color and the use of images
- Design of interactive systems, experiences, and technologies
- Developing and evaluating interactive prototypes as a way of iteratively refining designs
- Evaluating interactive technologies to assess and improve their functioning through data-driven redesign, including discount and empirical evaluation methods

Students will also learn knowledge about

- Digital technologies, including, possibly, web and mobile platforms, conversational technologies, wearable computing, gadgets, digital fabrication, virtual reality and mixed reality
- Human psychology, regarding individuals, groups, organizations, societies, and cultures, as it relates to interactions with digital products and services
Prerequisites
For this concentration, students should have completed the following courses prior to starting the concentration:

- 15-122 Principles of Imperative Computation 10
- 15-150 Principles of Functional Programming 10

Course Requirements
Students in the HCI concentration will be advised by the HCII Undergraduate Program Director and/or the HCII Undergraduate Program Manager, who will oversee and direct the HCI second major and the HCI minor. They will meet once a semester will each student in the concentration.

SCS Students interested in this concentration should contact the program director for an initial advising consultation.

Machine Learning Concentration
This concentration is available to SCS students only.
Matt Gormley, Concentration Director/Advisor
Location: GHC 8103
Dorothy Holland-Minkley, Concentration Coordinator
Location: GHC 8008
ml-concentration@cs.cmu.edu

Machine learning and statistical methods are increasingly used in many application areas including natural language processing, speech, vision, robotics, and computational biology. The Concentration in Machine Learning allows undergraduates to learn about the core principles of this field. The Concentration requires five courses (two core courses and three electives) from the School of Computer Science (SCS) and the Department of Statistics & Data Science. The electives primarily focus on core machine learning skills that could be broadly applicable to either industry or graduate work. A CS Senior Honors Thesis or two semesters of Senior Research may be used to satisfy part of the electives requirement, which could provide excellent research experience for students interested in pursuing a PhD.

Learning Objectives
Upon completion of this concentration, students should be able to:
- Formulate real-world problems involving data such that they can be solved by machine learning
- Implement and analyze existing learning algorithms
- Employ probability, statistics, calculus, linear algebra, and optimization in order to develop new predictive models or learning methods
- Select and apply an appropriate supervised learning algorithm for problems of different kinds, including classification, regression, structured prediction, clustering, and representation learning
- Describe the formal properties of models and algorithms for learning and explain the practical implications of those results
- Compare and contrast different paradigms for learning

Prerequisites
The following courses are expected to be completed before the Core courses in the ML Concentration:

- Computer Science:
  - 15-122 Principles of Imperative Computation 10
- Calculus:
  - 21-120 Differential and Integral Calculus 10
  - 21-122 Integration and Approximation 10
- Probability and Statistics:
  - 36-218 Probability Theory for Computer Scientists 9
  - 15-259 Probability and Computing
  - 15-235 Probability
- 36-215 Mathematical Statistics (Honors)

Students interested in doing research or project work in the field of Human-Computer Interaction can do an independent study with an HCII faculty member. The independent study (05-589) will count as an elective for the HCI concentration.

Double Counting
At most 2 courses can be double counted with any major, minor or other concentration being pursued by the student.

Advising and Management
Management will fall on the HCII Undergraduate Program Director and the HCII Undergraduate Program Manager. The requirements for the courses will be reviewed annually by the HCII Curriculum Committee, in consultation with the URC.

Students in the HCI concentration will be advised by the HCII Undergraduate Program Director and/or the HCII Undergraduate Program Manager, who will be reviewed annually by the HCII Curriculum Committee, in consultation with the URC.

Electives (3 courses)
1. At least one of the electives must have strong technical content and must be selected from the following list:
   - 05-434 Machine Learning in Practice 12
   - 05-499 Special Topics in HCI 12
   - 05-839 Interactive Data Science 12
   - 10-315 Introduction to Machine Learning (SCS Majors) 12
   - 11-411 Natural Language Processing 12
   - 15-281 Artificial Intelligence: Representation and Problem Solving 12
   - 15-365 Experimental Animation 12
   - 15-398 Practical Data Science 9
   - 15-464 Technical Animation 12
   - 15-466 Computer Game Programming 12
   - 15-494 Cognitive Robotics: The Future of Robot Toys 12
   - 16-467 Human Robot Interaction 12
   - 17-422 Building User-Focused Sensing Systems 12
   - 17-428 Machine Learning and Sensing 12
   - 17-437 Web Application Development 12
   - 17-537 Artificial Intelligence Methods for Social Good 9

Other courses as approved by the concentration director

2. At least one of the electives must have strong design content and must be selected from the following list:
   - 05-391 Designing Human Centered Software 12
   - 05-392 Interaction Design Overview 9

3. The remaining elective must be a course in HCI offered by the Human-Computer Interaction Institute, meaning it has a 05 number, and is included in the pre-approved list of electives maintained on the HCII website.

Required courses (2 courses)
- 05-391 Designing Human Centered Software 12
- 05-392 Interaction Design Overview 9

Electives (3 courses)
1. At least one of the electives must have strong technical content and must be selected from the following list:
   - 05-434 Machine Learning in Practice 12
   - 05-499 Special Topics in HCI 12
   - 05-839 Interactive Data Science 12
   - 10-315 Introduction to Machine Learning (SCS Majors) 12
   - 11-411 Natural Language Processing 12
   - 15-281 Artificial Intelligence: Representation and Problem Solving 12
   - 15-365 Experimental Animation 12
   - 15-398 Practical Data Science 9
   - 15-464 Technical Animation 12
   - 15-466 Computer Game Programming 12
   - 15-494 Cognitive Robotics: The Future of Robot Toys 12
   - 16-467 Human Robot Interaction 12
   - 17-422 Building User-Focused Sensing Systems 12
   - 17-428 Machine Learning and Sensing 12
   - 17-437 Web Application Development 12
   - 17-537 Artificial Intelligence Methods for Social Good 9

Other courses as approved by the concentration director

2. At least one of the electives must have strong design content and must be selected from the following list:
   - 05-391 Designing Human Centered Software 12
   - 05-392 Interaction Design Overview 9

3. The remaining elective must be a course in HCI offered by the Human-Computer Interaction Institute, meaning it has a 05 number, and is included in the pre-approved list of electives maintained on the HCII website.

Students interested in doing research or project work in the field of Human-Computer Interaction can do an independent study with an HCII faculty member. The independent study (05-589) will count as an elective for the HCI concentration.
Electives (minimum 33 units):

Students need to take three courses from the following list. Students may substitute one of these courses with one semester of an SCS Senior Honors Thesis or equivalent senior research credit.

- 10-405 Machine Learning with Large Datasets (Undergraduate) 12
- 10-417 Intermediate Deep Learning 12
- 10-418 Machine Learning for Structured Data 12

Important Notes:
- To avoid excessive overlap in covered material, at most one of the core Deep Learning courses may be used to fulfill concentration course requirements: 10-417, 10-617, 11-485, 10-707. In general, students are discouraged from taking more than one of these.
- 15-281 Artificial Intelligence: Representation and Problem Solving covers several topics (i.e. reinforcement learning and Bayesian networks) that are complementary to 10-515. While not part of the ML Concentration curriculum, this course is also one to consider.
- Students should note that some of these elective courses (those at the 600-level and higher) are primarily aimed at graduate students, and so should make sure that they are adequately prepared for them before enrolling. Graduate-level cross-listings of these courses can also be used for the ML Concentration, if the student is adequately prepared for the more advanced version and the home department approves the student's registration.
- Please be aware that not all graduate-level courses in the Machine Learning Department may be used as electives. In particular, 10-606/10-607 Computational Foundations for Machine Learning may not be used as electives for the Machine Learning Concentration.

CS Senior Honors Thesis

The CS Senior Honors Thesis consists of 36 units of academic credit for this work. Up to 12 units may be counted towards the ML Concentration. Students must consult with the Computer Science Department for information about the CS Senior Honors Thesis. Once both student and advisor agree upon a project, the student should submit a one-page research proposal to the Machine Learning Concentration Director to confirm that the project will count for the Machine Learning Concentration.

Senior Research

Senior Research consists of 2 semesters of 10-500 Senior Research Project, totaling 24 units. Up to 12 units may be counted towards the ML Concentration. The research must be a year-long senior project, supervised or co-supervised by a Machine Learning Core Faculty member. It is almost always conducted as two-semester-long projects, and must be done in senior year. Some samples of available Machine Learning Senior Projects are available on the Machine Learning Department webpage. Interested students should contact the faculty they wish to advise them to discuss the research project, before the semester in which research will take place. Once both student and advisor agree upon a project, the student should submit a one-page research proposal to the Machine Learning Concentration Director to confirm that the project will count for the Machine Learning Concentration. The student will present the work and submit a year-end write-up to the Concentration Director at the end of Senior year.

Double Counting

At least 3 courses (each being at least 9 units) must be used for only the Machine Learning Concentration, not for any other major, minor, or concentration. (These double counting restrictions apply specifically to the Core Courses and the Electives. Prerequisites may be counted towards other majors, minors, and concentrations and do not count towards the 3 courses that must be used for only the Machine Learning Concentration.)

Advising and Management

The ML Concentration Director will hold advising office hours leading up to registration week each semester. In addition, the ML Concentration Program Coordinator will hold regular office hours to address general questions. All office hours will be detailed on the ML Concentration website.

SCS Students interested in pursuing this concentration should contact Matt Gormley for an initial advising consultation.

Principles of Programming Languages Concentration

This concentration is available to SCS students only.

Robert Harper, Concentration Director and Advisor
Location: GHC 9229

Programming languages play a central role in computer science. All programs are written in a language, and it is obvious that some are better than others, at least for some purposes. The constant demand for new languages reflects the changing demands for constructing reliable and maintainable software systems. Academic research in programming language principles has led to numerous advances in language design, language implementation, and program verification intended to meet these changing expectations through the development of a rigorous theory of programming languages.

Carnegie Mellon is a recognized leader in programming languages, characterized by a strong emphasis on the centrality of type theory, a comprehensive understanding of the deep connection between the theory and practice of programming languages, and a strong tradition in academic research in programming language design and implementation. The purpose of the PoPL concentration is to teach the comprehensive view of the field that has been developed here over many decades. Type theory teaches how to define a language, and how to show that it is well-defined, free of internal contradictions. It teaches the mathematical foundations for abstraction and modularity, concepts that are fundamental to building maintainable systems. It teaches how to use a rigorous language definition as the basis for building a compiler that correctly implements the definition, and provides the tools necessary to achieve it. It teaches the logical foundations of program development, how to precisely specify the intended behavior of a program, and how to use machine tools to verify that a program meets those expectations. It gives precise meaning to language concepts, relating them to one another, and distinguishing concepts that are often confused or conflated. It teaches how to specify and verify the resource usage of a program (such as its sequential and parallel time and space complexity) without resorting to a model of how it is implemented on a machine; it supports using actual code, rather than pseudo-code, for defining and analyzing algorithms.

The PoPL concentration is of value to a broad range of students. For the practically minded it will provide the foundation for structuring and validating programs, using type systems or more advanced forms of specification. For the theoretically minded it will provide the foundation for understanding the close relationship between specification and programs on one hand and mathematical conjecture and proof on the other. The elegance of the PoPL lies in the unification of these two perspectives: the theory applies directly to the practice, and the practice informs the theory.

Learning Objectives

The PoPL concentration is characterized by a collection of learning outcomes that it seeks to achieve. These may be summarized by the knowledge that students may expect to gain by concentrating in the area. By their choice of electives each student will choose an emphasis within the area; the required courses ensure that this includes at least the first five objectives:

- Specify the concrete and abstract syntax of a programming language, including a precise specification of the binding and scope of declarations.
- Define the static semantics (compile-time constraints) of a programming language using typing judgments, and how to state and prove that it properly defined.
- Define the dynamics semantics (run-time behavior) of a language using operational and denotational methods.
- Verify rigorously that the statics and dynamics of a language are coherent, a property commonly called type safety.
- Understand the propositions-as-types principle, which relates programs to proofs and specifications to theorems, and how to apply it in language design and program verification.
- Formulate type and assertion languages for specifying the behavior of a program, and how to verify that a program satisfies such a specification.
• Specify the cost (sequential and parallel time and space complexity) for a program written in a precisely defined language, and how to verify that a given program meets stated cost bounds.
• Use software tools to verify both the properties of languages and the specifications of programs written in well-defined languages.
• Use the static and dynamic semantics of a language to derive a compiler for it that complies with these definitions, and how to use type and verification tools to ensure compiler correctness.
• Relate a language definition to its implementation, both in terms of the run-time structures required, but also to validate abstract cost measures in an implementation.

Prerequisites
This concentration requires students to complete the following courses before the concentration can be completed:

15-122 Principles of Imperative Computation 10
15-150 Principles of Functional Programming 10
15-151 Mathematical Foundations for Computer Science 10
15-210 Parallel and Sequential Data Structures and Algorithms 12
15-213 Introduction to Computer Systems 12
15-251 Great Ideas in Theoretical Computer Science 12

Course Requirements
This concentration requires two courses along with two additional electives.

Required Courses (complete all of the following):
15-312 Foundations of Programming Languages 12
15-317 Constructive Logic 9

Electives (complete two of the following):
15-314 Programming Language Semantics 12
15-316 Software Foundations of Security and Privacy 9
15-414 Bug Catching: Automated Program Verification 9
15-417 HOT Compilation 12
15-424 Logical Foundations of Cyber-Physical Systems 12

Any graduate-level Programming Languages course(s), with prior permission of the concentration advisor and the course instructor(s).

Students may use one semester of a senior thesis supervised by a member of the Principles of Programming faculty in the Computer Science Department as a replacement for one of the two electives.

Transfer of credit for courses taken outside of Carnegie Mellon University toward this concentration will not be allowed.

Double Counting
Either 15-312 or 15-317 (but not both) may be double counted towards any major, minor or other concentration being pursued by the student. No other double counting is permitted.

Advising and Management
Participation in this concentration is supervised by the concentration coordinator in cooperation with the students academic advisor, course instructors, and, as appropriate, thesis supervisor. The current coordinator is Robert Harper. Content for this concentration will be reviewed yearly by the Principles of Programming faculty in the Computer Science Department.

Students interested in pursuing this concentration should contact Robert Harper for an initial advising consultation.

Robotics Concentration
This concentration is available to SCS students only.

Howie Choset, Concentration Director/Advisor
Location: NSH 3205

Barbara (‘B.J.’) Fecich, Concentration Administrator
Location: NSH 4121

The SCS Robotics Concentration provides an opportunity for SCS undergraduate students at Carnegie Mellon to learn the principles and practices of robotics through theoretical studies and hands-on experience with robots. Students initially learn the basics of robotics in an introductory robotics overview course. Additional required courses teach control systems and robotic kinematics. Students also choose from a wide selection of electives in mobile systems, machine learning, computer vision, cognition and cognitive science, or computer graphics. Students have a unique opportunity to undertake independent research projects, working under the guidance of Robotics Institute faculty members; this provides an excellent introduction to robotics practice, for those considering industry and research for those considering graduate studies.

Learning Objectives
Students completing this concentration will be able to demonstrate the following skills and learning:

• construct robots which are driven by a microcontroller through several projects, with each reinforcing the basic principles of: vision, motion planning, mobile mechanisms, kinematics, inverse kinematics, and sensing
• apply feedback control theory to the development of robotic systems, including the principles of classical linear control theory, linear state-space methods, nonlinear systems theory, and elementary control using computer learning techniques
• program a robot arm using the principles of kinematics and dynamics; transformations, forward kinematics, inverse kinematics, differential kinematics (jacobians), manipulability, and the basic equations of motion
• apply related fields of computing to the construction and testing of robotic systems: machine learning, AI, graphics and computer vision, cognitive science and learning models, cyber-physical and embedded systems
• work effectively in a team include computer and mechanical engineers to solve challenging robotics problems

Prerequisites
The following courses are expected to be completed before the Core courses in the Robotics Concentration:

CS background:
15-122 Principles of Imperative Computation 10
15-213 Introduction to Computer Systems 12

One year of calculus:
21-120 Differential and Integral Calculus 10
21-122 Integration and Approximation 10

Matrix Algebra (one of the following):
21-241 Matrices and Linear Transformations 10
21-242 Matrix Theory 10

Probability (one of the following):
15-259 Probability and Computing 12
21-325 Probability 9
36-218 Probability Theory for Computer Scientists 9
36-225 Introduction to Probability Theory 9

The probability course can be taken concurrently with the concentration requirements. Depending on specific electives chosen, additional prerequisites may be required (e.g. 21-259).

Course Requirements
The Robotics Concentration requires that students complete three core courses and their choice of two elective courses of at least 9 units each. The electives can be chosen from a specific set of stand-alone courses. Students can opt to do an undergraduate research project as one of their electives.

Required core courses (36 units)
16-311 Introduction to Robotics 12
16-384 Robot Kinematics and Dynamics 12
16-299 Introduction to Feedback Control Systems 12
16-362 Mobile Robot Algorithms Laboratory 12

Electives (minimum 18 units)
Students must complete 2 electives from the following list of courses for a minimum of 18 units. At least one of the two electives must be from the Robotics Institute (16-xxx). A maximum of 12 units of research (16-597) can be used toward this requirement.

16-264 Humanoids 12
16-362 Mobile Robot Algorithms Laboratory 12
After completing this concentration, students should:

- Be familiar with the breadth of concerns and topics relevant to computer security and privacy, ranging from technical topics to ethics, regulation, usability, and economics.
- Be familiar with the key concepts in privacy, ranging from conceptions of privacy to privacy algorithms to regulation and policy.
- Gain a more in-depth understanding of one “context” area: usable security and privacy, or policy.

### Prerequisites

Students interested in pursuing this concentration should have the following courses completed before starting the concentration:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-151</td>
<td>Mathematical Foundations for Computer Science</td>
<td>10</td>
</tr>
<tr>
<td>15-213</td>
<td>Introduction to Computer Systems</td>
<td>12</td>
</tr>
<tr>
<td>15-251</td>
<td>Great Ideas in Theoretical Computer Science</td>
<td>12</td>
</tr>
</tbody>
</table>

### Curriculum

A distinguishing feature of this field is the ubiquitous need to consider an adversary, and the resulting interplay between attack and defense that routinely advances both theory and practice. In order to understand widely-deployed offensive techniques and secure-by-design approaches, students must also understand the attacks that motivate them and the “adversarial mindset” that leads to new forms of attack. The curriculum is designed around this principle.

Students in the Security & Privacy concentration will take courses that cover the basic principles (Introduction and Basics Course Area), the underlying theory (Theoretical Foundations Course Area), and the practical application (System Design Course Area) of security and privacy. Additionally, they will be required to select a course which covers either usability or policy (Context Course Area). Finally, students will have the opportunity to dive deep on a particular security & privacy topic by completing an elective of their choosing (Depth Course Area).

#### Requirements (5 courses, minimum 48 units):

- **Introduction/Portal Entry course**
  - 15-330 Introduction to Computer Security — 12 units

- **Theoretical Foundations course (choose one option):**
  - 15-356 Introduction to Cryptography — 12 units

- **System Design course (choose one):**
  - 15-316 Software Foundations of Security and Privacy — 9 units
  - 18-335 Secure Software Systems — 12 units

- **Usability or Policy course (select one):**
  - 17-334 Usable Privacy and Security — 9 units
  - 17-333 Privacy Policy, Law, and Technology — 9 units

- **Other graduate-level courses as approved by the concentration director**

**Depth course (complete one option below):**

- Complete an elective course or at least 9 units of independent study in the security or privacy area. Consult with the concentration coordinator for elective options.
- Complete five, rather than four, courses from the list above to satisfy the requirements described above (this might be achieved by taking both a policy and a usability course, or taking the two-course foundations alternative).

#### Anti-requisites

When two (or more) courses overlap significantly in the material they cover, only one can count toward the security and privacy concentration. An example pair is 15-316 Software Foundations of Security and Privacy and 18-335 Secure Software Systems. Other such anti-requisites may occur; please consult the concentration director when scheduling courses.

#### Excluded Courses

Some security and privacy courses may not be counted towards concentration requirements. These courses all serve specific important different purposes, but do not fit into the concentration as currently

### Security & Privacy Concentration (SCS)

This concentration is available to SCS students only. (ECE students should consult their department for an equivalent concentration.)

Lujo Bauer, Concentration Director and Advisor
Location: CIC 2203

In a world where data breaches and cyber-attacks are ever-present, the need for technologists who have a solid understanding of the principles that underlie strong security and privacy practices is greater than ever. The Security & Privacy concentration is designed to expose students to the key facets of and concerns about computer security and privacy that drive practice, research, and legislation. On completing the curriculum, students will be well prepared to continue developing their interests in security or privacy through graduate study: to take jobs in security or privacy that will provide further training in applicable areas; and to be informed participants in public and other processes that shape how organizations and society develop to meet new challenges related to computer security or privacy.

#### Learning Objectives

After completing this concentration, students should:

- Understand how to reason about the adversary in computer systems.
- Be familiar with common security vulnerabilities, from buffer overflows and return oriented programming to cross-site scripting, and widely deployed defenses against these vulnerabilities.
- Be familiar with and understand how to apply the basic concepts in cryptography and secure system design and analysis.
- Understand the key properties of commonly used cryptographic primitives and properties commonly desired of cryptographic protocols.

- Be familiar with current and upcoming research directions in secure system design, software analysis, and cryptography.
- Be familiar with the breadth of concerns and topics relevant to computer security and privacy, ranging from technical topics to ethics, regulation, usability, and economics.
- Be familiar with the key concepts in privacy, ranging from conceptions of privacy to privacy algorithms to regulation and policy.
- Gain a more in-depth understanding of one “context” area: usable security and privacy, or policy.
software engineering. Graduates of the program should have the technical, process, and teamwork skills to be immediately productive in a mature engineering organization.

Prerequisites
SCS students should have completed the following courses before completing this concentration:

15-122 Principles of Imperative Computation 10
15-151 Mathematical Foundations for Computer Science 10
15-213 Introduction to Computer Systems 12

In addition, students must ensure they have larger-scale software development experience which can be gained by taking the following course:

17-214 Principles of Software Construction: Objects, Design, and Concurrency 12

Students can have the 17-214 prerequisite waived by the director if the student can show significant development experience.

Course Requirements
Overall, the concentration requires five (5) courses and an internship. One of the five courses consists of a 6-credit course that serves as a writing workshop in which the student reflects upon and integrates the lessons of the internship.

Required Courses (complete all of the following):

17-313 Foundations of Software Engineering 12
17-413 Software Engineering Practicum 12

Electives (complete one from each category):

A domain-independent course focused on technical software engineering material:

- 15-141 Bug Catching: Automated Program Verification 9
- 17-355 Program Analysis 12
- 17-356 Software Engineering for Startups 12
- 17-651 Models of Software Systems 12
- 17-652 Methods: Deciding What to Design 12
- 17-653 Managing Software Development 12
- 17-654 Analysis of Software Artifacts 12
- 17-655 Architectures for Software Systems 12

Other courses, with prior approval from the Director of the Software Engineering Program:

- 15-390 Entrepreneurship for Computer Science 9
- 17-200 Ethics and Policy Issues in Computing 9
- 17-331 Information Security, Privacy, and Policy 12
- 17-333 Privacy Policy, Law, and Technology 9
- 17-334 Usable Privacy and Security 9
- 17-562 Law of Computer Technology 9
- 17-801 Dynamic Network Analysis 12
- 17-821 Computational Modeling of Complex Socio-Technical Systems 12
- 19-402 Telecommunications Technology and Policy for the Internet Age 12
- 70-311 Organizational Behavior 9
- 70-415 Entrepreneurship for Computer Scientists 9
- 70-471 Supply Chain Management 9

The concentration requires a software engineering internship of a minimum of 8 full-time weeks in an industrial setting (i.e., integrated into a team and exposed to industry pressures). The student may work in development, management, quality assurance, or other relevant positions. Students should confirm with the director that an internship is appropriate, but internships that fulfill the criteria will be accepted after the fact. Students must further complete:

- 17-415 Software Engineering Reflection 6

Double Counting
No more than two of the courses used to fulfill the concentration requirements may be counted towards any other degree or concentration. This rule does not apply to 17-214 (a prerequisite for the concentration) or courses counted for general education requirements.

Advising and Management
The concentration coordinator, Michael Hilton, is responsible for academic advising, handling exceptions and updating the curriculum each year, in consultation with faculty in the Institute for Software Research.

Students who are interested in pursuing this concentration should contact Michael Hilton for an initial advising consultation.