Computer Science

http://cs.jhu.edu/

Computing has grown to be pervasive throughout engineering, science, business, society, and entertainment. The availability of relatively inexpensive high performance computing capabilities, ubiquitous high speed and wireless networking, and mobile computing have powered a technology-driven restructuring of the way society and most professions now operate. Information, and its associated processing and transport, is the commodity upon which corporations are built and lives are improved. At the center of this revolution, making it happen, are those who study computer science.

There are two dimensions to the field of computer science that establish it as a unique area. CS can be viewed as a stand-alone discipline worthy of study unto itself, and/or as an empowering discipline to be studied in conjunction with other areas. Core CS careers include (but are not limited to) software design and development, computer systems engineering or administration, and information security. Application areas span a wide range of fields and disciplines such as robotics, medical and health informatics, scientific research, data analytics, entrepreneurship, gaming/entertainment, and business computing to name a few.

Because computer science is a highly diverse and broadly applied field, studies can proceed in many different directions. Accordingly, the undergraduate and graduate programs in the Department of Computer Science at Johns Hopkins are flexible curricula designed to accommodate a wide range of goals. A student at Johns Hopkins can pursue appropriately customized versions of the following computer science programs: minor, bachelor of science, bachelor of arts, masters of science in engineering, and doctor of philosophy. Most of this catalog section is devoted to details regarding these programs.

Computer science research laboratories are currently active in the following areas at Hopkins: algorithm design and analysis, human-computer interaction, machine learning, data intensive computing, health informatics, computational medicine, computer vision and image processing, computer graphics, geometric modeling, programming languages, natural language and speech processing, information retrieval, cryptography and information security, secure and robust systems, storage systems, high-performance and scientific computing, computational genomics, networks and distributed systems, stream processing, parallel and distributed databases, robotics, and computer-integrated surgical systems.

Additionally, interdisciplinary research centers in the university have heavy involvement by Computer Science faculty: the Information Security Institute (ISI), the Center for Computer-Integrated Surgical Systems and Technology (CISST), the Laboratory for Computational Sensing and Robotics (LCSR), the Center for Language and Speech Processing (CLSP), the Institute for Data Intensive Engineering and Science (IDIES), the Institute for Computational Medicine (ICM), and the Malone Center for Engineering in Healthcare (MCEH). An important component of the educational process in the department is the opportunity for undergraduate and graduate student participation in the research programs of the faculty. In particular, original research in close association with individual faculty members is emphasized at the graduate level.

There are several closely related programs at the undergraduate and graduate levels which involve significant coursework and faculty involvement from the Department of Computer Science. The Laboratory for Computational Sensing and Robotics (LCSR) offers a minor in robotics and also a minor in computer integrated surgery through the Engineering Research Center for Computer Integrated Surgical Systems and Technology. Details of these programs may be found elsewhere in this catalog in the section pertaining to the Laboratory for Computational Sensing and Robotics (http://e-catalog.jhu.edu/departments-program-requirements-and-courses/engineering/robotics-computational-sensing). Undergraduates with a strong interest in system design and performance may elect to pursue a bachelor degree in computer engineering (http://e-catalog.jhu.edu/departments-program-requirements-and-courses/engineering/electrical-computer-engineering). This field of study includes course work in computer science, as well as electrical and computer engineering. Although jointly administered by both departments, specific goals and requirements of the computer engineering degree may be found in the catalog section pertaining to the Department of Electrical and Computer Engineering only.

At the graduate level, the LCSR (http://e-catalog.jhu.edu/departments-program-requirements-and-courses/engineering/robotics-computational-sensing) offers a Master of Science in Engineering (M.S.E.) in Robotics, designed for students from a wide variety of engineering, scientific, and mathematical backgrounds to advance their interdisciplinary knowledge in robotics. Details of this program may be found in the LCSR section of this catalog, or on the web at www.lcsr.jhu.edu/MSE. Lastly, the Master of Science in Security Informatics (M.S.S.I.) is a specialized graduate program offered through the Information Security Institute (http://e-catalog.jhu.edu/departments-program-requirements-and-courses/engineering/information-security-institute) (ISI) in the WSE. The field of security informatics is fundamentally based on information security and assurance technologies (hardware, software, and networks) as related to issues such as policy, management, privacy/trust, health care, and law, from both national and international perspectives. Interested students can obtain detailed information regarding the M.S.S.I. online at https://isi.jhu.edu or in the ISI section of this catalog.

For additional information regarding the academic programs available in Computer Science, and the facilities provided, please consult the sections which follow, or the departmental website www.cs.jhu.edu.

Facilities

The CS department is primarily housed in Malone Hall, a state of the art, open concept research facility. Additional department research space is located in the adjacent Hackerman Hall.

The general department computing facilities include numerous workstations and servers. Two undergraduate laboratories combine to provide approximately 24 Linux workstations. One of these is a collaboration room allowing students to work in a team-based environment, with several private breakout rooms as well. At the graduate level there is a Master’s Lab consisting of a collaboration area and workstation area, both consisting of several Linux workstations.

All Ph.D. students are assigned dedicated desks in their research labs. Additionally, multiple high-speed networked laser printers, as well as a networked color copier and remotely accessible Linux labs. These are available to both graduate and undergraduate students.

Focused research laboratories have significant resources that provide greater specialization, including isolated networks of PCs for security studies, high-performance computing clusters, robots and computer vision systems, a mock operating room equipped with medical robots and imaging equipment, and more.
The general department computing facilities are tied together by our own LAN, and access to specialized hardware in other departments, labs, and institutions is available via the university intranet and the Internet. In addition, the university provides wireless access to the JHU intranet and the Internet, as well as server systems that provide e-mail accounts for all students.

(See also General Requirements for Departmental Majors (http://e-catalog.jhu.edu/undergrad-students/academic-policies/requirements-for-a-bachelors-degree))

The objectives of our bachelor degree programs are to train computer scientists who will be able to:

- Successfully engage in professional practice in the computing sciences or apply computer science tools and techniques to another field of interest.
- Pursue advanced study in the computing sciences.
- Work successfully in both independent and team environments.
- Lead teams and provide vision for innovation.
- Behave in a professional and ethical manner.

A successful major program of study leads to either the Bachelor of Science in Computer Science (B.S.) or the Bachelor of Arts in Computer Science (B.A.). Students should decide which degree program to complete by about their junior year. Both degree programs require specific courses and/or credits in several key areas: computer science, math, basic science, humanities and social sciences. However, there is much flexibility in how these requirements are fulfilled. Undergraduate majors may choose to pursue a broad selection of computer science and distributional courses, or to pursue a particular focus area within the field. Current foci primarily reflect departmental and school research strengths: big data, computational biology, fundamentals of computing, information security, natural language processing, robotics, systems and networking, while a few are directed towards career paths: software engineering, entrepreneurship/business computing, and video game design. Further information on these focus areas may be found in the computer science undergraduate advising manual (http://www.cs.jhu.edu/undergraduate-studies/academics/ugrad-advising-manual).

All undergraduate students majoring or minoring in computer science must have a faculty advisor in the department. They will be assigned an advisor as entering freshmen or upon deciding on the major/minor. Every major must follow a program approved by his/her faculty advisor.

The department also offers a minor in computer science, and tangentially, a minor in computer integrated surgery and a minor in robotics. Some students majoring in computer science may be eligible for a combined bachelor’s/master’s degree program. Requirements for these programs are included here as well. Additional details regarding undergraduate programs can be found in the department’s undergraduate advising manual (http://www.cs.jhu.edu/undergraduate-studies/academics/ugrad-advising-manual) or on the website at www.cs.jhu.edu.

### Requirements for the B.S. Degree

The Bachelor of Science in Computer Science degree program is accredited by the Computing Accreditation Commission of ABET, www.abet.org (http://www.abet.org). It provides for the acquisition of the following knowledge base and skill set:

- An ability to apply knowledge of computing and mathematics appropriate to the discipline.
- An ability to analyze a problem, and identify and define the computing requirements appropriate to its solution.
- An ability to design, implement, and evaluate a computer-based system, process, component, or program to meet desired needs.
- An ability to function effectively on teams to accomplish a common goal.
- An understanding of professional, ethical, legal, security, and social issues and responsibilities.
- An ability to communicate effectively with a range of audiences.
- An ability to analyze the local and global impact of computing on individuals, organizations, and society.
- Recognition of the need for and an ability to engage in continuing professional development.
- An ability to use current techniques, skills, and tools necessary for computing practice.
- An ability to apply mathematical foundations, algorithmic principles, and computer science theory in the modeling and design of computer-based systems in a way that demonstrates comprehension of the trade-offs involved in design choices.
- An ability to apply design and development principles in the construction of software systems of varying complexity.

To meet the course credit requirements for the B.S. in computer science, the student must complete a minimum of 126 credits. The basic requirements for the B.S. degree are as follows:

<table>
<thead>
<tr>
<th>Course</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer Science</td>
<td>42</td>
</tr>
<tr>
<td>Mathematics</td>
<td>24</td>
</tr>
<tr>
<td>Basic Sciences</td>
<td>16</td>
</tr>
<tr>
<td>Humanities/Social Sciences</td>
<td>18</td>
</tr>
<tr>
<td>Two Writing Intensive Courses</td>
<td></td>
</tr>
<tr>
<td>Electives</td>
<td>26</td>
</tr>
<tr>
<td>Total Credits</td>
<td>126</td>
</tr>
</tbody>
</table>

Details and course recommendations for these distributional requirements are below. These requirements add up to 100 credits and fulfill general university and WSE requirements, leaving 26 pure elective credits. Except for electives, courses should not be taken on an S/U basis. By university policy, no more than 18 D or D+ credits can be counted toward the total credit requirements for a degree. The Courses and Curriculum Planning section (https://www.cs.jhu.edu/course-info) of the departmental website has lists of course area designations (Analysis, Applications, Systems), approved science courses, and courses approved as “CS other.”

### Computer Science (42 credits)<sup>*</sup>

The following foundational courses in computer science must be included in a student’s program:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.601.104</td>
<td>Computer Ethics (or Practical Ethics for Future Leaders which does not count towards CS credits)</td>
<td>1</td>
</tr>
<tr>
<td>EN.601.107</td>
<td>Introductory Programming in Java (or equivalent)</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.112</td>
<td>or EN.500.112 Gateway Computing</td>
<td></td>
</tr>
<tr>
<td>EN.601.220</td>
<td>Intermediate Programming</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.226</td>
<td>Data Structures</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.229</td>
<td>Computer System Fundamentals</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.231</td>
<td>Automata &amp; Computation Theory</td>
<td>3</td>
</tr>
</tbody>
</table>
At least 16 credit hours must be at the 300-level or above, including 
EN.601.433. At least one course in each classification area of 
Analysis, Applications and Systems must be chosen. An exhaustive 
list of the area classifications for each of our courses may be found 
on the department’s website.

Students must take at least one of the following courses which 
contain oral communication components. The course satisfying the 
oral requirement may overlap other requirements.

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.601.456</td>
<td>Computer Integrated Surgery II</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.520</td>
<td>Senior Honors Thesis</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.437</td>
<td>Neuro Data Design I (counts as ”CS other”)</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.438</td>
<td>Neuro Data Design II (counts as ”CS other”)</td>
<td>4</td>
</tr>
</tbody>
</table>

Eight additional credits of Computer Science are required. **

Mathematics (24 credits)
The following courses or equivalent substitutes such as AP credit must be included:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.108</td>
<td>Calculus I</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.109</td>
<td>Calculus II (For Physical Sciences and Engineering)</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.171</td>
<td>Discrete Mathematics</td>
<td>4</td>
</tr>
</tbody>
</table>

The remaining courses must be 200-level or above, chosen 
from Mathematics (AS.110.xxx) or Applied Math and Statistics 
(EN.553.xxx), and must include coverage of both probability 
and statistics. Note that students will need at least six courses to fulfill 
the credit requirement. Some highly recommended math electives are:***

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.201</td>
<td>Linear Algebra</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.420</td>
<td>Introduction to Probability</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.430</td>
<td>Introduction to Statistics</td>
<td>4</td>
</tr>
</tbody>
</table>

Basic Sciences (16 credits)
At least two semesters of physics or two semesters of chemistry, 
with the associated laboratories, must be included. The remaining 
courses must be chosen in accordance with the list posted on the 
department’s website, which includes most ’N’ (natural science) 
designated courses in the Sciences and Engineering, but not all. At 
most 2 credits from S/U intersession courses may be used to fulfill 
this requirement.

Humanities/Social Sciences (18 credits)
As per WSE requirements, six courses in the Humanities and Social 
and Behavioral Sciences must be taken, with each course at least 
3 credits.**** These courses must have either Humanities (‘H’) or 
Social and Behavioral Sciences (‘S’) area (or both) designators on 
them. Foreign language courses (without an ‘H’ or ‘S’) may also be 
used to satisfy this requirement.

Writing Requirement

Students are required to fulfill the university’s requirement of two 
writing intensive courses, each at least 3 credits. Students must 
receive at least a C- grade or better in these writing courses. At least 
one course must be explicitly focused on writing skills in English (eg. 
Expository Writing, Professional Communication, Fiction & Poetry). 
These courses may overlap other requirements.

Electives
Electives are to be chosen by the student with guidance and approval 
26 of his/her advisor.

Total Credits 173

* No more than 6 independent type credits (courses numbered 
601.5xx) and no more than 3 credits of short courses (1- 
credit special topics courses) can be counted toward this 
requirement. However, B.S. students doing the Senior Honors Thesis 
(EN.601.519-EN.601.520) may use an additional three credits of 
independent work toward their CS requirements, for a total of 9 
credits.

No courses with grades below C- or with S/U grades can be used 
to fulfill this requirement unless they are not offered for a grade. At 
most 4 S/U credits may be applied toward this requirement.

** Up to 6 of the 42 required credits may be from an approved list of 
relevant courses in other departments, which includes courses cross-
listed in CS. These courses may only count as ”CS other” credits, 
not upper level CS credits (regardless of course level in the other 
department). See department website for the list.

*** AP Statistics credits may not be used to satisfy these credit 
requirements; however, they do meet the need for coverage of 
statistics (not probability).

**** See the Distribution tab in the Requirements for a Bachelor’s Degree 
(http://e-catalog.jhu.edu/undergrad-students/academic-policies/
requirements-for-a-bachelors-degree) section for two exceptions to 
the rule that each H/S distribution course be at least 3 credits.

Requirements for the B.A. Degree
To meet the course credit requirements for the B.A. in computer science, 
the student must complete a minimum of 120 credits. The basic 
requirements for the B.A. degree are:

<table>
<thead>
<tr>
<th>Subject</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer Science</td>
<td>32</td>
</tr>
<tr>
<td>Mathematics</td>
<td>20</td>
</tr>
<tr>
<td>Basic Sciences</td>
<td>12</td>
</tr>
<tr>
<td>Humanities/Social Sciences</td>
<td>18</td>
</tr>
<tr>
<td>Foreign Language</td>
<td>6</td>
</tr>
<tr>
<td>4 Writing Intensive Courses</td>
<td></td>
</tr>
<tr>
<td>Electives</td>
<td>32</td>
</tr>
<tr>
<td>Total Credits</td>
<td>120</td>
</tr>
</tbody>
</table>

Details and course recommendations of these distributional 
requirements are below. These requirements add up to 88 credits and 
fulfill general university distribution requirements. Except for electives, 
courses should not be taken on a S/U basis. By university policy, no 
more than 18 D or D+ credits can be counted toward the total credit 
requirements for a degree.

Computer Science (32 credits) *

The following foundational courses in computer science must be 
included in a student’s program:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.601.107</td>
<td>Introductory Programming in Java (or equivalent)</td>
<td>3</td>
</tr>
</tbody>
</table>
Mathematics (20 credits)
The following courses must be included:

<table>
<thead>
<tr>
<th>Course</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.108 Calculus I</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.109 Calculus II (For Physical Sciences and Engineering)</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.171 Discrete Mathematics</td>
<td>4</td>
</tr>
</tbody>
</table>

The remaining courses may be chosen from Mathematics (110.xxx) or Applied Math and Statistics (553.xxx). At least one course must be 200-level or above. Strongly recommended: Linear Algebra, Probability & Statistics. Note that at least five courses will be needed to fulfill this requirement.

Basic Sciences (12 credits)
At least two semesters of physics or chemistry or a combination of both, with the associated laboratories, must be included. The remaining courses must be chosen in accordance with the list posted on the department website, which includes most 'N' designated courses in the Sciences and Engineering, but not all. At most 2 credits from (S/U) intersession courses may be used to fulfill this requirement.

Humanities/Social Sciences (18 credits)
Six courses in the Humanities/Social Sciences must be taken, with each course at least 3 credits.** At least two 3-credit courses at the 300-level or above are required. As befits a B.A. degree, students have ample flexibility to choose courses that broaden the scope of their study, in consultation with their advisors. A subset of the courses selected to satisfy this requirement should demonstrate coherence within an area. Any course with Humanities or Social Sciences area designators may fulfill these distributional requirements.

Foreign Language (6 credits)
At least 6 credits in one foreign language or demonstrated proficiency at the intermediate level are required. These foreign language credits are in addition to the 18 required Humanities/Social Sciences credits.

Writing Requirement
All primary computer science majors pursuing a B.A. degree are required to fulfill the university's requirement of four writing intensive courses, each at least 3 credits. At least one course must be explicitly focused on writing skills in English (eg, Expository Writing, Professional Communication, Fiction & Poetry). Students must receive at least a C- grade in these courses. These courses may overlap other requirement areas.

Electives
Electives are to be chosen by the student with guidance and approval of his/her advisor.

Total Credits 120

Minor in Computer Science
To satisfy the course credit requirements for a minor in computer science, a student must take a minimum of seven courses, with a total of at least 23 credits, earning at least a C- in each course. These must include four core courses, to provide the student with a foundation, and three upper-level courses (300-level and above), to allow the student to pursue an advanced area in depth. Short courses cannot be used toward the minor requirements. All courses must be taken for a grade, not S/U.

Core Courses

<table>
<thead>
<tr>
<th>Course</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.601.107 Introductory Programming in Java (or equivalent)</td>
<td>3</td>
</tr>
<tr>
<td>or EN.500.112 Gateway Computing</td>
<td></td>
</tr>
<tr>
<td>EN.601.220 Intermediate Programming</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.226 Data Structures</td>
<td>4</td>
</tr>
<tr>
<td>Choose one of the following:</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.229 Computer System Fundamentals</td>
<td></td>
</tr>
<tr>
<td>EN.601.231 Automata &amp; Computation Theory</td>
<td></td>
</tr>
</tbody>
</table>

Upper-Level Courses
Minors must take three CS courses (EN.601.xxx) at the 300-level or above. These courses should be chosen to form a cohesive minor and must be accepted by the computer science minor advisor. It is strongly recommended that students choose all three courses from within one of the three research areas of analysis, applications, or systems.*

Total Credits 23

* Each upper-level course description in this catalog includes its area for reference. In addition, a current listing of courses with area designators is provided on the departmental website. Some upper level courses have math pre-requisites as well (Probability/Statistics or Linear Algebra most commonly), so plan ahead.

Students whose primary major is in the Whiting School may use the same courses to satisfy the requirements of the primary major and also those of a computer science minor. Students who plan to fulfill requirements for a minor must go to the Department of Computer Science director of undergraduate studies to declare the minor and be advised on course
follow a program approved by a faculty advisor in the department. The Every graduate student in the Department of Computer Science must of the M.S.E. degree, see the Graduate Programs tab on this page, or ask applied toward the master’s degree. For information on the requirements Computer Science Department who must approve the courses to be as an undergraduate and the corresponding 601.4xx course for the of their performance in courses and their letters of recommendation. Generally, the combined B.S./M.S.E. allows students to simultaneously pursue both an undergraduate and a science in engineering degree in Computer Science. This program combines a B.S. or B.A. degree (in any department) with a master of science, engineers, and the Krieger School of Arts and Sciences. Whether computer science is your primary or secondary major, you will be assigned a faculty advisor in the department. In order to declare a first or second major in computer science, students should see the Director of Undergraduate Studies before the start of senior year. Those students must also inform the Office of Academic Affairs of the Whiting School of Engineering and the Registrar of their double major status. Subject to restrictions set by the department offering a second major, students whose primary major is in the Whiting School may use courses to satisfy both the requirements of the student’s primary major and those of a double major.

Double Majors with Computer Science
It is possible for students to pursue a double major program in which one of the majors is computer science. The computer science requirements are flexible enough to allow for combination with most majors in the Whiting School of Engineering and the Krieger School of Arts and Sciences. Whether computer science is your primary or secondary major, you will be assigned a faculty advisor in the department. In order to declare a first or second major in computer science, students should see the Director of Undergraduate Studies before the start of senior year. Those students must also inform the Office of Academic Affairs of the Whiting School of Engineering and the Registrar of their double major status. Subject to restrictions set by the department offering a second major, students whose primary major is in the Whiting School may use courses to satisfy both the requirements of the student’s primary major and those of a double major.

Combined Bachelor’s/Master’s Program
As early as the end of their sophomore year, qualified students may apply for admission to a combined bachelor’s/master’s program which combines a B.S. or B.A. degree (in any department) with a master of science in engineering degree in Computer Science. This program allows students to simultaneously pursue both an undergraduate and a graduate degree program of study. Generally, the combined B.S./M.S.E. or B.A./M.S.E. program is accomplished in five years, although some students take more or less time. Applicants are judged on the basis of their performance in courses and their letters of recommendation. Double counting of at most two courses is subject to current WSE and departmental policies. Students may not take a 601.3xx course as an undergraduate and the corresponding 601.4xx course for the M.S.E.; likewise for 601.4xx/6xx course offerings. Upon admission to the program students will be assigned a graduate faculty advisor in the Computer Science Department who must approve the courses to be applied toward the master’s degree. For information on the requirements of the M.S.E. degree, see the Graduate Programs tab on this page, or ask in the departmental office for the document that lists those requirements.

Every graduate student in the Department of Computer Science must follow a program approved by a faculty advisor in the department. The advisor assigned to a student may change, subject to the acceptance of the new advisor.

Requirements for the M.S.E. Degree
The Master of Science in Engineering (M.S.E.) is a daytime in-person program offered by the Department of Computer Science. Most students complete the program in three full-time semesters. Two semesters of residence as a full-time graduate student are required. Those interested in part-time evening/remote study should refer to Engineering for Professionals Program at ep.jhu.edu.

Entering students are expected to have completed a program of study equivalent to that required by the B.S. in computer science. Applicants from other disciplines are expected to have coursework (or equivalent experience) in intermediate programming (C++ and Java), data structures, computer system fundamentals, and automata theory. Upon admission to the Master of Science in Engineering program, a student is assigned a graduate advisor from the Department of Computer Science who must approve the courses to be applied to the M.S.E. degree.

The Department of Computer Science classifies its courses into three sub-areas: Analysis, Applications, and Systems. All M.S.E. candidates must complete at least two courses (3 class hours (credits) each) from each of these three areas. Each upper-level course description in this catalog includes its area for reference. A course in multiple areas may only be counted toward one requirement. A current listing of courses with area designators (http://cs.jhu.edu/courses/courseareas.pdf) is provided on the departmental website. While this listing includes a few highly relevant courses outside the Department of Computer Science, only one such course may be applied toward the area requirements. M.S.E. students must also complete an additional two elective courses (chosen from any CS area or from closely related departments such as Electrical and Computer Engineering, Cognitive Science, Mathematics, or Applied Mathematics and Statistics) approved by the advisor, for a total of eight graduate-level courses.

In addition to the eight courses, a student must elect one of the following options in order to fulfill the degree requirements:

- Two additional (graduate-level) courses in Computer Science, approved by the advisor as above.
- A supervised research project including an approved project report that will be made publicly available.
- An original, faculty-approved master’s essay, submitted to the Milton S. Eisenhower Library.

By satisfying the Ph.D. qualifying course requirements and the first qualifying project, a student will also satisfy the M.S.E. degree requirements (unless more than two course requirements have been satisfied using courses transferred from other institutions). Please refer to the Ph.D. program information for details.

All M.S.E. degree candidates are encouraged to regularly attend the department seminars.

Course Requirement Details
- All courses counted toward the M.S.E. degree requirement must be taken at a graduate-appropriate level. In the Department of Computer Science, this includes courses that are 600-level and above, as well as 400-level courses for students in the combined BS/MSE program who have not yet switched to graduate status.
Applications for admission to the Ph.D. program in Computer Science are reviewed by a faculty committee. Although the specific criteria are not rigid, all students admitted will exhibit exceptional intellectual achievements and promise. Applicants must submit letters of recommendation, GRE scores, and (for international applicants) TOEFL/IELTS scores. Visit grad.jhu.edu for more information on the application process.

In keeping with Hopkins’ traditions, program requirements are flexible, as described below. For more detailed policies regarding the PhD program, please visit the Advising Manual (http://www.cs.jhu.edu/graduate-studies/phd-requirements) on our departmental website.

**University Residency**

Two consecutive semesters of residence as a full-time graduate student are required.

**Seminar Attendance**

All Ph.D. degree candidates are required to enroll and maintain satisfactory attendance in Computer Science Seminar EN.601.801 each semester for the duration of their enrollment in the program. Although seminar attendance is required, the seminar may not be counted toward the qualifying course requirement.

**Responsible Conduct of Research and Academic Ethics**

All doctoral students are required to take AS.360.625 Responsible Conduct of Research. Students are expected to complete the course by the end of the first year but have until the start of the fourth semester to meet this requirement. Failure to do so may result in a loss of funding. Additional information regarding this requirement can be found here: http://eng.jhu.edu/wse/page/conduct-of-research-training. In addition, all doctoral students must complete the course Academic Ethics (EN.500.603).

**Qualifying Course Requirements**

The Department of Computer Science classifies its courses into three research areas: analysis, applications, and systems. All Ph.D. candidates must complete at least two courses (3 class hours each) from each of these areas. Each upper-level course description in this catalog includes its area for reference. A course in multiple areas may only be counted toward one requirement. A current listing of courses with area designators (http://cs.jhu.edu/courses/courseareas.pdf) is provided on the departmental website. While this listing includes a few highly relevant courses outside the Department of Computer Science, only one such course may be applied toward the area requirements. Ph.D. students must also complete an additional two elective graduate courses (chosen from any CS area or from closely related departments such as Electrical and Computer Engineering, Cognitive Science, Mathematics, or Applied Mathematics and Statistics) for a total of eight courses.

Computer Science graduate students may count 600-level and above courses toward the coursework requirements. Other than independent study courses, no courses with grades of P or S can be counted toward the coursework requirement. Courses with grades of P or S will not be included in the grade point average calculation. One of the courses required for the degree, but only one, may be replaced by 3 credits from comparable short courses. With approval of the student’s faculty advisor, up to two courses can be transferred from graduate programs of other institutions; more than two such courses can be transferred with approval of the department.

**Tuition Support**

M.S.E. students are not normally eligible for tuition waivers, but will be able to work on campus up to 19.99 hours per week for hourly rates if they find campus employment (see the Office of Student Employment for open positions). There are also course assistant positions available for qualified students who are seeking financial support. Those interested must apply at the start of each semester for specific courses in need.

**Requirements for the Ph.D. Degree**

The goal of the Doctor of Philosophy (Ph.D.) program in the Department of Computer Science is to prepare first-rate scholars in the analysis, systems, and applications areas of computer science. Successful graduates may assume significant positions in academia, research institutes, industry, or government laboratories.
It is the obligation of the student to provide all necessary data to the Department of Computer Science regarding the course(s) for which transfer credit is being requested. Students are expected to complete the course requirements by the end of their second year as a Ph.D. candidate.

Qualifying Project Requirements
A Ph.D. student must complete two projects, each under the supervision and with the written agreement of a different faculty member in the Department of Computer Science. Upon conclusion of each project, the student must write a “Project Report” describing the project in detail. This report will be a public document and will be kept on file in the department office. The supervising faculty member must approve the project report. Students are expected to complete the qualifying projects by the end of their third year as a Ph.D. candidate.

Upon completion of the Ph.D. qualifying course requirements and the first qualifying project, students are ordinarily eligible to receive a master of science in engineering degree. The degree will be awarded upon student request.

Graduate Board Oral Examination (GBO)
This examination is a university requirement, ideally taken in the student’s third year. The oral exam is administered by a panel consisting of the research sponsor, two faculty members from the Department of Computer Science, and two from outside the department. The exam seeks to establish the student’s readiness to conduct original research in the area of his or her “Preliminary Research Proposal,” which should be distributed to the examiners in advance and presented by the student at the start of the exam.

Part-Time Ph.D.
Two consecutive semesters of residence as a full-time graduate student are required by the university. Attempting to obtain a Ph.D. is a major commitment and involves close coordination with a faculty advisor in the department. Part-time students must be able to establish and maintain these close links, therefore part-time study is by advanced permission only.

Departmental Seminar
Ph.D. students must give an official departmental seminar on their research area. This is to be done after the GBO and prior to the dissertation defense, or as part of the dissertation defense.

Dissertation and Defense
Ph.D. students must write a dissertation consisting of original research in their chosen area. They must deliver a public presentation of the dissertation before a dissertation committee consisting of the faculty advisor, a second faculty member in the Department of Computer Science (who must have a primary tenure-track appointment in the Department if the advisor does not), and one or more other members with Ph.D. degrees. In conformity with University requirements, the members of the dissertation committee must submit a referee’s letter to the Graduate Board recommending that the dissertation be accepted. Completed dissertations will be formatted and submitted to the Milton S. Eisenhower Library for electronic publication (http://guides.library.jhu.edu/etd).

Teaching Requirement
All Ph.D. students are required to serve as a Teaching Assistant at least one semester during their program of study. As part of the requirement, the supervising course instructor must give the TA an opportunity to be in front of a group of students at least once during the course. Students are required to sign-up for the course EN.601.807 Teaching Practicum during the semester in which the requirement is being fulfilled, and at the end of the semester his/her performance will be evaluated by the course instructor.

Student Progress Review
Ph.D. students are reviewed annually by their advisor(s) and the department, and notified in writing as to their standing in the program. Students deemed to not be making satisfactory progress may be placed on probation.

Financial Aid
All full-time CS PhD students in good academic standing are fully-funded. Additional financial aid may be available for candidates of high promise. Fellowships provide a student with a stipend plus tuition. Research assistantships are available on sponsored research projects directed by members of the faculty. Teaching assistantships normally consist of tuition plus a stipend commensurate with the teaching or grading duties assigned. Students determined to have significant deficiency in spoken English may be required to take one or more semesters of English as a Second Language in order to qualify for employment as a teaching or research assistant.

For current faculty and contact information go to http://cs.jhu.edu/faculty/

Faculty
Chair
Randal Burns
Professor: storage systems, high performance computing, and data-intensive scientific computing.

Professors
Yair Amir
Distributed systems, resilient clouds and critical infrastructure, overlay networks, distributed algorithms.

Jason M. Eisner
Computational linguistics (syntax and phonology), natural language processing, statistical machine learning, programming language design.

Gregory D. Hager
Mandell Bellmore Professor; Director, Malone Center for Engineering in Healthcare: vision, robotics, human-machine systems, computer-integrated medicine.

Philipp Koehn
Statistical machine translation.

S. Rao Kosaraju
Edward J. Schaefer Professor in Engineering: design of algorithms, pattern matching, and derandomization.

Aviel Rubin
Technical Director, Information Security Institute: system and networking security, computer privacy, applied cryptography.

Steven Salzberg
Bloomberg Distinguished Professor: genomics, bioinformatics, genome assembly, gene finding, sequence analysis algorithms.

Scott F. Smith
Programming languages, type systems, security in language design, component programming languages.

Alexander Szalay
Bloomberg Distinguished Professor: data intensive computing, theoretical astrophysics, galaxy formation.

Russell H. Taylor
John C. Malone Professor; Director, LCSR & CISST ERC: medical robotics, computer-integrated interventional medicine, medical image analysis, human-machine robotic systems.

David Yarowsky
Natural language and speech processing, information retrieval, machine translation, and machine learning.

Alan Yuille
Bloomberg Distinguished Professor: computational models of vision, mathematical models of cognition, artificial intelligence, neural networks.

Associate Professors
Mark Dredze
John C. Malone Assistant Professor: machine learning, natural language processing, health informatics.

Michael Kazhdan
Computer graphics, surface reconstruction, image and geometry processing.

Michael Schatz
Bloomberg Distinguished Associate Professor: novel algorithms for comparative genomics, human genetics, and personalized medicine.

Assistant Professors
Raman Arora
Machine learning, statistical signal processing, stochastic approximation algorithms, applications to speech and language processing.

Vladimir Braverman
Algorithms, massive data sets, data streams, and database systems.

Michael Dinitz
Theoretical computer science, approximation algorithms, applications to networks and distributed computing.

Soudeh Ghorbani
Networked systems, high-performance infrastructure, cloud applications, system design.

Matthew Green
Applied cryptography, cryptographic protocol design, analysis of practical security systems, privacy-preserving storage and identification technologies.

Chien-Ming Huang
John C. Malone Assistant Professor: Human robot interaction, human computer interaction, artificial intelligence, robotics.

Ryan P. Huang
Operating systems, distributed systems, software engineering, programming languages.

Abhishek Jain
Cryptography, security, theoretical computer science.

Xin Jin
Computer networking, distributed systems, software-defined networking, cloud computing, big data.

Benjamin Langmead
Computational genomics, sequence alignment, text indexing, parallel and high performance computing.

Xin Li
Theory of computation, randomness, complexity theory, distributed computing, cryptography.

Suchi Saria
John C. Malone Assistant Professor: machine learning, computational medicine, health informatics, and applications of machine learning in natural language processing, activity recognition and human-machine systems.

Ilya Shpitser
John C. Malone Assistant Professor: causal inference and missing data, graphical models, longitudinal data analysis in medicine and epidemiology.

Benjamin Van Durme
Artificial intelligence, natural language processing (computational semantics), and streaming algorithms.

Research Professors
Peter Kazanzides
Medical robots, computer-assisted surgery, real-time systems.

Nassir Navab
Augmented reality, vision, medical image computing and computer assisted interventions.

Associate Research Professors
Philippe Burlina
Computer vision, visual analysis and communications, multi-modality image exploitation, enterprise software systems for content and e-process management.

Chris Callison-Burch
Statistical natural language processing, machine translation, paraphrasing, evaluation of human language technologies.

Susan Hohenberger-Waters
Cryptography, computer security, algorithms, and complexity theory.

James Mayfield
Information retrieval, cross-language retrieval, information extraction, natural language processing.

Assistant Research Professors
Haider Ali
Computer vision, medical robotics, activity analysis, statistically-based deep learning techniques.

Kevin Duh
Natural language processing, machine learning.

Will Gray Roncal
Computer vision, image analysis, big data analytics.

Simon Leonard
Visual servoing, hand-eye coordination.

Christine Piatko
Computational geometry, information visualization, information retrieval.

Austin Reiter
Application of computer vision to robotics, machine vision, 3D reconstruction, image registration, visual recognition.

I-Jeng Wang
Wireless networking, Bayesian networks, probabilistic models.

**Associate Teaching Professors**

Sara Miner More
Foundations of computing, computer science education, cryptography, information flow.

Joanne Selinski
Director of Undergraduate Studies: CS education, software engineering.

**Associate Research Scientist**

Anton Dahbura
Executive Director, Information Security Institute: Information security, fault-tolerant computing, distributed systems, testing.

**Assistant Research Scientist**

Matt Post
Machine translation, syntax, parsing and language modeling.

**Part-time Faculty**

Ayo Akinyele
Adjunct Associate Research Engineer: applied cryptography, crypto automation, computer security.

Phillip Graff
Lecturer: machine learning.

Harold Lehmann
Lecturer; Professor (Health Sciences Informatics): medical informatics.

Timothy Leschke
Lecturer: computer ethics.

Jared Markowitz
Lecturer: machine learning.

Seth Nielson
Adjunct Associate Research Scientist: network security.

Lanier Watkins
Adjunct Associate Research Scientist: critical infrastructure security, network security.

**Visiting Faculty**

Mitra Basu
Visiting Professor: computational biology, pattern recognition, neural networks, artificial intelligence.

Kevin Kornegay
Visiting Professor: IoT device security, reverse engineering, hardware assurance, secure embedded system design, side-channel analysis, differential fault analysis.

Yansheng Li
Visiting Assistant Professor: visual saliency modeling, deep feature learning, image retrieval and classification.

Wei Shen
Visiting Assistant Professor: computer vision, deep learning, object recognition and detection.

**Adjunct Faculty**

Gabor Fichtinger
Adjunct Professor: applied surgical robotics, surgical CAD/CAM systems, percutaneous therapies, stereotactic radiosurgery.

**Joint Appointments**

Amitabh Basu
Assistant Professor (Applied Mathematics and Statistics): optimization, discrete and combinatorial geometry, operations research, convex analysis.

Alexis Battle
Assistant Professor (Biomedical Engineering): genetics of complex traits, graphical models, transfer learning, structured regularization methods.

Muyinatu A. Lediju Bell
Assistant Professor (Electrical and Computer Engineering): ultrasound imaging, photoacoustic imaging, image quality improvements, advanced beamforming methods, light delivery systems, medical robotics, image-guided surgery, technology development, medical device design, clinical translation.

Emad Doctor
Assistant Professor (Radiology-Medical Imaging Physics): image-guided intervention, ultrasound imaging, elasticity, and thermal imaging.

Tamas Budavari
Assistant Professor (Applied Mathematics and Statistics): computational statistics, bayesian inference, low-dimensional embeddings, streaming and randomized algorithms.

Gregory Chirikjian
Professor (Mechanical Engineering): robotics, kinematics, dynamics, control, motion planning.

Noah Cowan
Professor (Mechanical Engineering): sensor-based control of locomotion and manipulation, and biologically inspired robotics.

Ralph Etienne-Cummings
Professor (Electrical and Computer Engineering): mixed-signal VLSI, computational sensors, robotics, neuromorphic engineering.

James Fill
Professor (Applied Mathematics and Statistics): probability, stochastic processes, random structures, and algorithms.

Liliana Florea
Assistant Professor (McKusick-Nathans Institute for Genetic Medicine): application of computation techniques towards modeling and solving problems in biology and genetic medicine.

Rachel Karchin
Associate Professor (Biomedical Engineering): computational molecular biology, bioinformatics, genetic variation.

Sanjeev Khudanpur
Associate Professor (Electrical and Computer Engineering): information theory, statistical language modeling for speech recognition and machine translation.

Enrique Mallada
Assistant Professor (Electrical and Computer Engineering): networked dynamics, distributed systems.

Michael I Miller
Professor (Biomedical Engineering): image understanding, computer vision, medical imaging, computational anatomy.

Mihaela Pertea
Assistant Professor (Medicine): computational tools for RNA-seq analysis, gene finding, splice site prediction, sequence motif finding.

Carey Priebe
Professor (Applied Mathematics and Statistics): computational statistics, kernel and mixture estimates, statistical pattern recognition, and statistical image analysis.

Jerry L. Prince
William B. Kouwenhoven Professor (Electrical and Computer Engineering): image processing, computer vision, medical imaging.

Rebecca Schulman
Assistant Professor (Chemical and Biomolecular Engineering): molecular programming, DNA nanotechnology, self-assembly (theory and experiment), theoretical and systems biology, smart materials, nanoscale robotics.

Ralph Semmel
Professor (Director, APL): artificial intelligence, database systems, software engineering.

Jeff Siewersden
John C. Malone Professor (Biomedical Engineering): imaging physics, diagnostic radiology, image-guided interventions.

James Taylor
Associate Professor (Biology): genome informatics.

Archana Venkataraman
John C. Malone Assistant Professor (Electrical and Computer Engineering): multimodal integration, network modeling, clinical neuroscience.

Rene Vidal
Professor (Biomedical Engineering): computer vision, machine learning, robotics, and control.

Joshua T. Vogelstein
Assistant Professor (Biomedical Engineering): big data science, connectomics, statistical neuroscience.

Louis Whitcomb
Professor (Mechanical Engineering): dynamics and control of mechanical systems.

Raimond L. Winslow
Professor (Biomedical Engineering): modeling of biological systems, nonlinear systems theory, grid computing and data management, biomedical ontologies.

For current course information and registration go to https://sis.jhu.edu/classes/

Courses

EN.601.104. Computer Ethics. 1.0 Credit.
Students will examine a variety of topics regarding policy, legal, and moral issues related to the computer science profession itself and to the proliferation of computers in all aspects of society, especially in the era of the Internet. The course will cover various general issues related to ethical frameworks and apply those frameworks more specifically to the use of computers and the Internet. The topics will include privacy issues, computer crime, intellectual property law -- specifically copyright and patent issues, globalization, and ethical responsibilities for computer science professionals. Work in the course will consist of weekly assignments on one or more of the readings and a final paper on a topic chosen by the student and approved by the instructor.
Instructor(s): T. Leschke
Area: Humanities.

EN.601.105. M & Ms: Freshman Experience. 1.0 Credit.
This course provides freshmen computer science majors with an introduction to the field and department. A variety of faculty members will provide a mix of historical context and current topics. Classes will be interactive, enabling students to think about and explore topics in a fun way, as well as get to know their classmates. CS non-freshmen and minors may enroll by permission only. Satisfactory/Unsatisfactory only.
Instructor(s): J. Selinski

EN.601.107. Introductory Programming in Java. 3.0 Credits.
This course introduces fundamental structured and object-oriented programming concepts and techniques, using Java, and is intended for all who plan to use computer programming in their studies and careers. Topics covered include variables, arithmetic operators, control structures, arrays, functions, recursion, dynamic memory allocation, files, class usage and class writing. Program design and testing are also covered, in addition to more advanced object oriented concepts including inheritance and exceptions as time permits. First-time programmers are strongly advised to take EN.601.108 concurrently in Fall/Spring semesters.
Prerequisites: Students may receive credit for only one of EN.600.107/EN.601.107, EN.600.112, or EN.580.200
Instructor(s): J. Selinski; S. More
Area: Engineering.

EN.601.108. Introduction to Programming Lab. 1.0 Credit.
This course is intended for novice programmers, and must be taken in conjunction with EN.601.107. The purpose of this course is to give first-time programmers extra hands-on practice with guided supervision. Students will work in pairs each week to develop working programs, with checkpoints for each development phase. Must have familiarity with computers. Satisfactory/Unsatisfactory only.
Corequisites: EN.600.107
Instructor(s): J. Selinski; P. Froehlich; S. More
Area: Engineering.

This course will give an introduction to the concepts and major elements of computer-integrated surgery (CIS) through clinical applications. Students will learn to ask questions and look for answers the way clinical engineers build and analyze CIS systems. Major topics will include medical imaging, image processing, surgical planning, surgical robotics, robot navigation, systems integration, and clinical validation. No computer programming will be necessary to complete the assignments.
Instructor(s): S. Leonard
Area: Engineering.
EN.601.220. Intermediate Programming. 4.0 Credits.
This course teaches intermediate to advanced programming, using C and C++. (Prior knowledge of these languages is not expected.) We will cover low-level programming techniques, as well as object-oriented class design, and the use of class libraries. Specific topics include pointers, dynamic memory allocation, polymorphism, overloading, inheritance, templates, collections, exceptions, and others as time permits. Students are expected to learn syntax and some feature specific languages independently. Course work involves significant programming projects in both languages.
Prerequisites: AP Computer Science, or C+ or better in EN.600.107/EN.601.120 OR EN.580.200 OR EN.600.112.
Instructor(s): J. Selinski; M. Darvish Darab; S. More
Area: Engineering.

EN.601.226. Data Structures. 4.0 Credits.
This course covers the design and implementation of data structures including arrays, stacks, queues, linked lists, binary trees, heaps, balanced trees (e.g. 2-3 trees, AVL-trees) and graphs. Other topics include sorting, hashing, memory allocation, and garbage collection. Course work involves both written homework and Java program assignments.
Prerequisites: EN.600.120 OR EN.601.220 OR EN.600.107 OR EN.601.107 or equivalent with C+ or better grades.
Instructor(s): M. Schatz
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.229. Computer System Fundamentals. 3.0 Credits.
We study the design and performance of a variety of computer systems from simple 8-bit micro-controllers through 32/64-bit RISC architectures all the way to ubiquitous x86 CISC architecture. We’ll start from logic gates and digital circuits before delving into arithmetic and logic units, registers, caches, memory, stacks and procedure calls, pipelined execution, superscalar architectures, memory management units, etc. Along the way we’ll study several typical instruction set architectures and review concepts such as interrupts, hardware and software exceptions, serial and other peripheral communications protocols, etc. A number of programming projects, frequently done in assembly language and using various processor simulators, round out the course.
Prerequisites: EN.600.120
Instructor(s): P. Froehlich
Area: Engineering.

EN.601.231. Automata & Computation Theory. 3.0 Credits.
This course is an introduction to the theory of computing. Topics include design of finite state automata, pushdown automata, linear bounded automata, Turing machines and phrase structure grammars; correspondence between automata and grammars; computable functions, decidable and undecidable problems, P and NP problems, NP-completeness, and randomization. Students may not receive credit for EN.601.231/EN.600.271 and EN.601.631/EN.600.471 for the same degree.
Prerequisites: EN.550.171
Instructor(s): X. Li
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.255. Introduction to Video Game Design. 3.0 Credits.
A broad survey course in game design (as opposed to mathematical game theory), covering artistic, technical, as well as sociological aspects of video games. Students will learn about the history of video games, archetypal game styles, computer graphics and programming, user interface and interaction design, graphical design, spatial and object design, character animation, basic game physics, plot and character development, as well as psychological and sociological impact of games. Students will design and implement an experimental video game in interdisciplinary teams of 3-4 students as part of a semester-long project. Section 1 requires technical skills, including at least one programming course (preferably 2 or more). Section 2 requires artistic skills, including at least one multimedia course (preferably 2 or more). Open to sophomores and above.
Corequisites: EN.601.256
Instructor(s): P. Froehlich
Area: Engineering.

EN.601.256. Introduction to Video Game Design Lab. 1.0 Credit.
A lab course in support of 601.255: Introduction to Video Game Design covering a variety of multi-media techniques and applications from image processing, through sound design, to 3D modeling and animation. See 601.255: Introduction to Video Game Design for details about enrolling.
Corequisites: EN.601.255
Instructor(s): P. Froehlich.

EN.601.290. User Interfaces and Mobile Applications. 3.0 Credits.
This course will provide students with a rich development experience, focused on the design and implementation of user interfaces and mobile applications. A brief overview of human computer interaction will provide context for designing, prototyping and evaluating user interfaces. Students will invent their own mobile applications and implement them using the Android SDK, which is JAVA based. An overview of the Android platform and available technologies will be provided, as well as XML for layouts, and general concepts for effective mobile development. Students will be expected to explore and experiment with outside resources in order to learn technical details independently. There will also be an emphasis on building teamwork skills, and on using modern development techniques and tools.
Prerequisites: EN.600.120 OR EN.601.220 OR EN.600.107 OR EN.601.107 or equivalent with C+ or better grades.
Instructor(s): J. Selinski
Area: Engineering.

EN.601.295. Developing Health IT Applications. 3.0 Credits.
This course is a project-based introduction to working on successful projects in health care. In the first half of the term, students perform reading and homework assignments designed to introduce: (1) the context of health care delivery and health IT, (2) techniques to overcome challenges to conducting health care data analyses, and (3) techniques to design meaningful applications around health care data. In the second half of the term, students work in small groups to solve a real-world problem of their choosing. Includes exercises in written and oral communication and team building.
Prerequisites: (EN.600.120 OR EN.601.220) AND (EN.600.226 OR EN.601.226)
Instructor(s): C. Overby Taylor; I. Shpitser
Area: Engineering.
EN.601.310. Software for Resilient Communities. 3.0 Credits.
This is a project-based course focusing on the design and implementation of practical software systems. Students will work in small teams to design and develop useful open-source software products that support their communities. Students will be paired with community partners and will aim to develop software that can be used after the course ends to solve real problems facing those partners today. Instructors will connect with the community partners and determine viable project areas prior to the course start. Students will meet with their community partners to analyze the challenges in their project area, agree on a concrete target project outcome, and gather requirements for their project. Based on these requirements, students will design and implement open-source software systems. [Oral]
**Prerequisites:** EN.600.120/EN.601.220 AND EN.600.226/EN.601.226
**Instructor(s):** A. Babay; Y. Amir
**Area:** Engineering.

EN.601.315. Databases. 3.0 Credits.
Introduction to database management systems and database design, focusing on the relational and object-oriented data models, query languages and query optimization, transaction processing, parallel and distributed databases, recovery and security issues, commercial systems and case studies, heterogeneous and multimedia databases, and data mining. [Systems] (www.cs.jhu.edu/~yarowsky/cs415.html)
**Prerequisites:** EN.600.226; Students may receive credit for only one of EN.600.315, EN.600.415, EN.601.315, EN.601.415, EN.601.615.
**Instructor(s):** D. Yarowsky
**Area:** Engineering.

EN.601.317. Distributed Systems. 3.0 Credits.
This course teaches how to design and implement protocols that enable processes to exchange information, cooperate, and coordinate efficiently in a consistent manner over a computer network. Topics include communication protocols, group communication, distributed databases, distributed operating systems, and security. [Systems]
**Students may receive credit for EN.601.317 or EN.601.417 but not both.**
**Prerequisites:** Students may receive credit for 600.337 or 600.437, but not both.
**Instructor(s):** Y. Amir
**Area:** Engineering.

EN.601.318. Operating Systems. 3.0 Credits.
This course covers fundamental topics related to operating systems theory and practice. Topics include processor management, storage management, concurrency control, multi-programming and processing, device drivers, operating system components (e.g., file system, kernel), modeling and performance measurement, protection and security, and recent innovations in operating system structure. Course work includes the implementation of operating systems techniques and routines, and critical parts of a small but functional operating system.
**Prerequisites:** EN.600.120 AND EN.600.226 AND EN.600.233; Students may receive credit for only one of EN.600.318, EN.600.418, EN.601.318, EN.601.418, EN.601.618.
**Instructor(s):** P. Huang
**Area:** Engineering.

EN.601.320. Parallel Programming. 3.0 Credits.
This course prepares the programmer to tackle the massive data sets and huge problem size of modern scientific and enterprise computing. Google and IBM have commented that undergraduate CS majors are unable to “break the single server mindset” (http://www.google.com/intl/en/press/pressrel/20071008_ibm_univ.html). Students taking this course will abandon the comfort of serial algorithmic thinking and learn to harness the power of cutting-edge software and hardware technologies. The issue of parallelism spans many architectural levels. Even “single server” systems must parallelize computation in order to exploit the inherent parallelism of recent multi-core processors. The course will examine different forms of parallelism in four sections. These are: (1) massive data-parallel computations with Hadoop; (2) programming compute clusters with MPI; (3) thread-level parallelism in Java; and, (4) GPGPU parallel programming with NVIDIA’s Cuda. Each section will be approximately 3 weeks and each section will involve a programming project. The course is also suitable for undergraduate and graduate students from other science and engineering disciplines that have prior programming experience. [Systems] **Prerequisite:** EN.600.233/EN.601.229 and EN.601.226
**Prerequisites:** EN.600.226 AND EN.600.233; Students may receive credit for only one of EN.600.320, EN.600.420, EN.601.320, EN.601.420, EN.601.620.
**Instructor(s):** R. Burns
**Area:** Engineering.

EN.601.325. Declarative Methods. 3.0 Credits.
Suppose you could simply write down a description of your problem, and let the computer figure out how to solve it. What notation could you use? What strategy should the computer then use? In this survey class, you’ll learn to recognize when your problem is an instance of satisfiability, constraint programming, logic programming, dynamic programming, or mathematical programming (e.g., integer linear programming). For each of these related paradigms, you’ll learn to reformulate hard problems in the required notation and apply off-the-shelf software that can solve any problem in that notation -- including NP-complete problems and many of the problems you’ll see in other courses and in the real world. You’ll also gain some understanding of the general-purpose algorithms that power the software. [Analysis] Students can only receive credit for EN.601.325 or EN.601.425, not both.
**Instructor(s):** J. Eisner
**Area:** Engineering.

EN.601.328. Compilers and Interpreters. 3.0 Credits.
Introduction to compiler design, including lexical analysis, parsing, syntax-directed translation, symbol tables, run-time environments, and code generation and optimization. Students are required to write a compiler as a course project. [Systems] Co-listed with EN.601.428
**Prerequisites:** EN.600.120 AND EN.600.226; Students may receive credit for only one of EN.600.328, EN.600.428, EN.601.328, EN.601.428, EN.601.628.
**Instructor(s):** P. Froehlich
**Area:** Engineering.
EN.601.350. Introduction to Genomic Research. 3.0 Credits.
This course will use a project-based approach to introduce undergraduates to research in computational biology and genomics. During the semester, students will take a series of large data sets, all derived from recent research, and learn all the computational steps required to convert raw data into a polished analysis. Data challenges might include the DNA sequences from a bacterial genome project, the RNA sequences from an experiment to measure gene expression, the DNA from a human microbiome sequencing experiment, and others. Topics may vary from year to year. In addition to computational data analysis, students will learn to do critical reading of the scientific literature by reading high-profile research papers that generated groundbreaking or controversial results. [Applications] Recommended Course Background: Knowledge of the Unix operating system and programming expertise in a language such as Perl or Python.
Instructor(s): S. Salzberg
Area: Engineering.

EN.601.355. Video Game Design Project. 3.0 Credits.
An intensive capstone design project experience in video game development. Students will work in groups of 4-8 on developing a complete video game of publishable quality. Teams will (hopefully) include programmers, visual artists, composers, and writers. Students will be mentored by experts from industry and academia. Aside from the project itself, project management and communication skills will be emphasized. Enrollment is limited to ensure parity between the various disciplines. [General] May involve travel to MICA. Junior or senior standing recommended.
Prerequisites: EN.600.255
Instructor(s): P. Froehlich
Area: Engineering.

EN.601.356. Seminar: Computer Integrated Surgery II. 1.0 Credit.
Students may receive credit for EN.601.456 or EN.601.356, but not both. Lecture only version of EN.601.456 (no project). Recommended Course Background: EN.601.455 or instructor permission required.
Instructor(s): R. Taylor
Area: Engineering.

EN.601.365. Knowledge Discovery from Text. 3.0 Credits.
The world is full of text: webpages, emails, newspaper articles, tweets, medical records, and so on. The purpose of text is for people to convey knowledge to other people. This course focuses on how computers analyze large, potentially streaming, text collections to automatically discover knowledge on their own (and to help people better find it themselves). Lectures and assignments will cover relevant topics in automatic classification (applied machine learning), linguistics, high-performance computing, and systems engineering, working with software systems for automatic question answering, populating knowledge bases, and aggregate analysis of social media such as Twitter. [Applications] 
Prerequisites: EN.600.120 AND EN.600.226
Instructor(s): B. Van Durme; T. Lippincott
Area: Engineering.

EN.601.382. Deep Learning Lab. 1.0 Credit.
This course is an optional hands-on lab supplement for a few courses in the curriculum. It will provide tutorial support and practical experience for developing deep ML systems using PyTorch and TensorFlow, and may provide exposure to some other frameworks. It will also go into detail on practical methods for scalable learning on large data sets, and other more practical issues in setting up deep learning systems. 
Corequisites: Students must also register for EN.601.482 OR EN.601.682 OR EN.601.765.
Instructor(s): G. Hager
Area: Engineering.

EN.601.402. Digital Health and Biomedical Informatics. 1.0 Credit.
Advances in technology are driving a change in medicine, from personalized medicine to population health. Computers and information technology will be critical to this transition. We shall discuss some of the coming changes in terms of computer technology, including computer-based patient records, clinical practice guidelines, and region-wide health information exchanges. We will discuss the underlying technologies driving these developments - databases and warehouses, controlled vocabularies, and decision support.
Instructor(s): H. Lehmann
Area: Engineering.

EN.601.411. Computer Science Innovation & Entrepreneurship II. 3.0 Credits.
This course is the second half of a two-course sequence and is a continuation of course EN.660.410.01, CS Innovation and Entrepreneurship, offered by the Center for Leadership Education (CLE). In this sequel course the student groups, directed by CS faculty, will implement the business idea which was developed in the first course and will present the implementations and business plans to an outside panel made up of practitioners, industry representatives, and venture capitalists. [General]
Prerequisites: EN.600.410
Instructor(s): A. Dahbura; L. Aronhime
Area: Engineering.

EN.601.414. Computer Networks. 4.0 Credits.
Topics covered will include application layer protocols (e.g. HTTP, FTP, SMTP), transport layer protocols (UDP, TCP), network layer protocols (e.g. IP, ICMP), link layer protocols (e.g. Ethernet) and wireless protocols (e.g. IEEE 802.11). The course will also cover routing protocols such as link state and distance vector, multicast routing, and path vector protocols (e.g. BGP). The class will examine security issues such as firewalls and denial of service attacks. We will also study DNS, NAT, Web caching and CDN's, peer to peer, and protocol tunneling. Finally, we will explore security protocols (e.g. TLS, SSH, IPsec), as well as some basic cryptography necessary to understand these. Grading will be based on hands-on programming assignments, homeworks and two exams.
[Systems]
Prerequisites: EN.600.226 AND EN.600.233; Students may receive credit for only one of EN.600.344, EN.600.444, EN.601.414, EN.601.614.
Instructor(s): M. Green; X. Jin
Area: Engineering.
EN.601.415. Databases. 3.0 Credits.
Similar material as EN.601.315 covered in more depth for advanced undergraduates. Introduction to database management systems and database design, focusing on the relational and object-oriented data models, query languages and query optimization, transaction processing, parallel and distributed databases, recovery and security issues, commercial systems and case studies, heterogeneous and multimedia databases, and data mining. [Systems] (www.cs.jhu.edu/~yarowsky/cs415.html)
Prerequisites: Students may receive credit for only one of EN.600.315, EN.600.415, EN.601.415, EN.601.615.;EN.600.226
Instructor(s): D. Yarowsky
Area: Engineering.

EN.601.417. Distributed Systems. 3.0 Credits.
Graduate version of 601.317 Systems. Students may receive credit for 601.317 or 601.417 but not both. Recommended Course Background: EN.601.220, EN.601.226
Instructor(s): Y. Amir
Area: Engineering.

EN.601.418. Operating Systems. 3.0 Credits.
Similar material as EN.601.318, covered in more depth. Intended for advanced undergraduate students. This course covers fundamental topics related to operating systems theory and practice. Topics include processor management, storage management, concurrency control, multi-programming and processing, device drivers, operating system components (e.g., file system, kernel), modeling and performance measurement, protection and security, and recent innovations in operating system structure. Course work includes the implementation of operating systems techniques and routines, and critical parts of a small but functional operating system.
Prerequisites: EN.600.120 AND EN.600.226 AND EN.600.233;Students may receive credit for only one of EN.600.318, EN.600.418, EN.601.318, EN.601.418, EN.601.618.
Instructor(s): P. Huang
Area: Engineering.

EN.601.420. Parallel Programming. 3.0 Credits.
More advanced version of EN.601.320. Students may receive credit for EN.601.320 or EN.601.420, but not both. Prerequisite: EN.601.226 and EN.601.229 Computer System Fundamentals.
Prerequisites: EN.600.226 AND EN.600.233;Students may receive credit for only one of EN.600.320, EN.600.420, EN.601.320, EN.601.420, EN.601.620.
Instructor(s): R. Burns
Area: Engineering.

EN.601.421. Object Oriented Software Engineering. 3.0 Credits.
This course covers object-oriented software construction methodologies and their application. The main component of the course is a large team project on a topic of your choosing. Course topics covered include object-oriented analysis and design, UML, design patterns, refactoring, program testing, code repositories, team programming, and code reviews. [Systems or Applications] [http://pl.cs.jhu.edu/oose/index.shtml]
Prerequisites: EN.600.120 AND EN.600.226;Students may receive credit for only one of EN.600.321, EN.600.421, EN.601.421, EN.601.621.
Instructor(s): S. Smith
Area: Engineering.

EN.601.425. Declarative Methods. 3.0 Credits.
Students can only receive credit for EN.601.325 or EN.601.425, not both. Graduate level version of EN.601.325. Recommended Course Background: EN.601.226, EN.601.231, AS.110.107/AS.110.109
Instructor(s): J. Eisner
Area: Engineering.

EN.601.426. Principles of Programming Languages. 3.0 Credits.
Functional, object-oriented, and other language features are studied independent of a particular programming language. Students become familiar with these features by implementing them. Most of the implementations are in the form of small language interpreters. Some type checkers and a small compiler will also be written. The total amount of code written will not be overly large, as the emphasis is on concepts. The ML programming language is the implementation language used. [Analysis] Prerequisites include EN.601.226. No Freshmen or Sophomores.
Prerequisites: EN.600.226
Instructor(s): S. Smith
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.427. Ontologies and Knowledge Representation. 3.0 Credits.
Knowledge representation (KR) deals with the possible structures by which the content of what is known can be formally represented in such a way that queries can be posed and inferences drawn. Ontology concerns the hierarchi- cal classification of entities from given domains of knowledge together with the relations between various classes or subclasses. We begin with KR, examining the standard variety of frameworks developed or implemented over the last twenty years, including 1st-order logic and automated theorem proving, networks, frames, and description logics. Then we move on to a study of the problems inherent in ontology development and examine the some of the currently prevalent environments, including Universal Modeling Language, OWL and Proteg‘, RDFS and semantic web applications. [Analysis] Recommended Course Background: EN.601.107
Instructor(s): R. Rynasiewicz
Area: Humanities, Quantitative and Mathematical Sciences.

EN.601.428. Compilers & Interpreters. 3.0 Credits.
Prerequisites: EN.600.120 AND EN.600.226 AND EN.600.233
Instructor(s): P. Froehlich
Area: Engineering.

EN.601.430. Combinatorics & Graph Theory in Computer Science. 3.0 Credits.
This is a graduate level course studying the applications of combinatorics and graph theory in computer science. We will start with some basic combinatorial techniques such as counting and pigeon hole principle, and then move to advanced techniques such as the probabilistic method, spectral graph theory and additive combinatorics. We shall see their applications in various areas in computer science, such as proving lower bounds in computational models, randomized algorithms, coding theory and pseudorandomness. [Analysis] Recommended Course Background: probability theory and linear algebra
Prerequisites: EN.550.171
Instructor(s): X. Li
Area: Engineering, Quantitative and Mathematical Sciences.
EN.601.433. Intro Algorithms. 3.0 Credits.
This course concentrates on the design of algorithms and the rigorous analysis of their efficiency. topics include the basic definitions of algorithmic complexity (worst case, average case); basic tools such as dynamic programming, sorting, searching, and selection; advanced data structures and their applications (such as union-find); graph algorithms and searching techniques such as minimum spanning trees, depth-first search, shortest paths, design of online algorithms and competitive analysis. [Analysis]
Prerequisites: EN.600.226 AND EN.550.171; Students may receive credit for only one of EN.600.363, EN.600.463, EN.601.433, EN.601.633.
Instructor(s): M. Dinitz
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.434. Randomized and Big Data Algorithms. 3.0 Credits.
The course emphasizes algorithmic design aspects, and how randomization can be a helpful tool. The topics covered include: tail inequalities, linear programming relaxation & randomized rounding, de-randomization, existence proofs, universal hashing, markov chains, metropolis and metropolis-hastings methods, mixing by coupling and by eigenvalues, counting problems, semi-definite programming and rounding, lower bound arguments, and applications of expanders. [Analysis] (www.cs.jhu.edu/~cs464) Recommended Course Background: Probability
Prerequisites: EN.600.363 AND (EN.550.420 OR EN.550.620 OR EN.550.310) or similar; Students may receive credit for only one of EN.600.464, EN.600.664, EN.601.434, EN.601.634.
Instructor(s): V. Braverman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.435. Approximation Algorithms. 3.0 Credits.
This course provides an introduction to approximation algorithms. Topics include vertex cover, TSP, Steiner trees, cuts, greedy approach, linear and semi-definite programming, primal-dual method, and randomization. Additional topics will be covered as time permits. There will be a final project. Students may receive credit for EN.601.435 or EN.601.635, but not both. [Analysis]
Instructor(s): M. Dinitz
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.436. Algorithmic Game Theory. 3.0 Credits.
This course provides an introduction to algorithmic game theory: the study of games from the perspective of algorithms and theoretical computer science. There will be a particular focus on games that arise naturally from economic interactions involving computer systems (such as economic interactions between large-scale networks, online advertising markets, etc.), but there will also be broad coverage of games and mechanisms of all sorts. Topics covered will include a) complexity of computing equilibria and algorithms for doing so, b) (in)equality of equilibria, and c) algorithmic mechanism design. [Analysis]
Prerequisites: EN.600.363 OR EN.600.463 OR EN.601.433 OR EN.601.633
Instructor(s): M. Dinitz
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.440. Web Security. 3.0 Credits.
This course begins with reviewing basic knowledge of the World Wide Web, and then exploring the central defense concepts behind Web security, such as same-origin policy, cross-origin resource sharing, and browser sandboxing. It will cover the most popular Web vulnerabilities, such as cross-site scripting (XSS) and SQL injection, as well as how to attack and penetrate software with such vulnerabilities. Students will learn how to detect, respond, and recover from security incidents. Newly proposed research techniques will also be discussed. [Systems]
Prerequisites: (EN.601.226 OR EN.600.226) AND (EN.601.229 OR EN.600.233)
Instructor(s): Y. Cao
Area: Engineering.

EN.601.441. Blockchains and Cryptocurrencies. 3.0 Credits.
This course will introduce students to cryptocurrencies and the main underlying technology of Blockchains. The course will start with the relevant background in cryptography and then proceed to cover the recent advances in the design and applications of blockchains. This course should primarily appeal to students who want to conduct research in this area or wish to build new applications on top of blockchains. It should also appeal to those who have a casual interest in this topic or are generally interested in cryptography. Students are expected to have mathematical maturity. [Analysis]
Prerequisites: Students may receive credit for only one of EN.600.451 OR EN.601.441 OR EN.601.641; EN.601.226 AND (EN.553.211 OR EN.553.310 OR EN.553.311 OR EN.560.348 OR EN.553.420)
Instructor(s): A. Jain
Area: Engineering.

EN.601.442. Modern Cryptography. 3.0 Credits.
Modern Cryptography includes seemingly paradoxical notions such as communicating privately without a shared secret, proving things without leaking knowledge, and computing on encrypted data. In this challenging but rewarding course we will start from the basics of private and public key cryptography and go all the way up to advanced notions such as zero-knowledge proofs, functional encryption and program obfuscation. The class will focus on rigorous proofs and require mathematical maturity. [Analysis]
Prerequisites: EN.600.271 AND (EN.553.420 or EN.553.310); Students may receive credit for only one of EN.600.442, EN.601.442, EN.601.642.
Instructor(s): A. Jain
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.443. Security & Privacy in Computing. 3.0 Credits.
Lecture topics will include computer security, network security, basic cryptography, system design methodology, and privacy. There will be a heavy work load, including written homework, programming assignments, exams and a comprehensive final. The class will also include a semester-long project that will be done in teams and will include a presentation by each group to the class. [Applications] Recommended Course Background: A basic course in operating systems and networking, or permission of instructor.
Prerequisites: (EN.600.318 OR EN.600.418) OR (EN.600.344 OR EN.600.444) AND (EN.600.233 OR EN.601.229); Students may receive credit for only one of EN.600.443, EN.601.443, EN.601.643.
Instructor(s): A. Rubin
Area: Engineering.
EN.601.444. Network Security. 3.0 Credits.
This course focuses on communication security in computer systems and networks. The course is intended to provide students with an introduction to the field of network security. The course covers network security services such as authentication and access control, integrity and confidentiality of data, firewalls and related technologies, Web security and privacy. Course work involves implementing various security techniques. A course project is required. [Systems]
Prerequisites: EN.600.120 AND EN.600.226 AND (EN.600.344 OR EN.600.444) or permission; Students may receive credit for only one of EN.600.424, EN.650.424, EN.601.444, EN.601.644.
Instructor(s): S. Nielsen
Area: Engineering.

EN.601.445. Practical Cryptographic Systems. 3.0 Credits.
This semester-long course will teach systems and cryptographic design principles by example: by studying and identifying flaws in widely-deployed cryptographic products and protocols. Our focus will be on the techniques used in practical security systems, the mistakes that lead to failure, and the approaches that have might have avoided the problem. We will place a particular emphasis on the techniques of provable security and the feasibility of reverse-engineering undocumented cryptographic systems. [Systems]
Prerequisites: EN.600.226 AND EN.600.233; Students may receive credit for only one of EN.600.454, EN.601.445, EN.601.645.
Instructor(s): M. Green
Area: Engineering.

EN.601.447. Computational Genomics: Sequences. 3.0 Credits.
Your genome is the blueprint for the molecules in your body. It’s also a string of letters (A, C, G and T) about 3 billion letters long. How does this string give rise to you? Your heart, your brain, your health? This, broadly speaking, is what genomics research is about. This course will familiarize you with a breadth of topics from the field of computational genomics. The emphasis is on current research problems, real-world genomics data, and efficient software implementations for analyzing data. Topics will include: string matching, sequence alignment and indexing, assembly, and sequence models. Course will involve significant programming projects. [Applications]
Prerequisites: EN.600.120 AND EN.600.226; Students may receive credit for only one of EN.600.439, EN.600.639, EN.601.447, EN.601.647.
Instructor(s): B. Langmead
Area: Engineering.

EN.601.448. Computational Genomics: Data Analysis. 3.0 Credits.
Genomic data has the potential to reveal causes of disease, novel drug targets, and relationships among genes and pathways in our cells. However, identifying meaningful patterns from high-dimensional genomic data has required development of new computational tools. This course will cover current approaches in computational analysis of genomic data with a focus on statistical methods and machine learning. Topics will include disease association, prediction tasks, clustering and dimensionality reduction, data integration, and network reconstruction. There will be some programming and a project component. [Applications]
Prerequisites: EN.601.226 or other programming experience, probability and statistics, linear algebra or calculus.
Prerequisites: Students may receive credit for EN.600.438 or EN.600.638, but not both.
Instructor(s): A. Battle
Area: Engineering.

EN.601.452. Computational Biomedical Research. 3.0 Credits.
[Co-listed with AS.020.415] This course for advanced undergraduates includes classroom instruction in interdisciplinary research approaches and lab work on an independent research project in the lab of a Bloomberg Distinguished Professor and other distinguished faculty. Lectures will focus on cross-cutting techniques such as data visualization, statistical inference, and scientific computing. In addition to two 50-minute classes per week, students will commit to working approximately 3 hours per week in the lab of one of the professors. The student and professor will work together to schedule the research project. Students will present their work at a symposium at the end of the semester.
Instructor(s): M. Schatz
Area: Engineering.

EN.601.454. Augmented Reality. 3.0 Credits.
Same as EN.601.654, for undergraduate students. This course introduces students to the field of Augmented Reality. It reviews its basic definitions, principles and applications. It then focuses on Medical Augmented Reality and its particular requirements. The course also discusses the main issues of calibration, tracking, multi-modal registration, advance visualization and display technologies. Homework in this course will relate to the mathematical methods used for calibration, tracking and visualization in medical augmented reality. Students may also be asked to read papers and implement various techniques within group projects. Recommended Course Background: EN.601.220, EN.601.226, and AS.110.201. [Applications]
Prerequisites: EN.600.120 AND EN.600.226 AND (AS.110.201 OR EN.550.291); Students may receive credit for only one of EN.600.484, EN.600.684, EN.601.454, EN.601.654.
Instructor(s): N. Navab
Area: Engineering.

EN.601.455. Computer Integrated Surgery I. 4.0 Credits.
This course focuses on computer-based techniques, systems, and applications exploiting quantitative information from medical images and sensors to assist clinicians in all phases of treatment from diagnosis to preoperative planning, execution, and follow-up. It emphasizes the relationship between problem definition, computer-based technology, and clinical application and includes a number of guest lectures given by surgeons and other experts on requirements and opportunities in particular clinical areas. Recommended Course Background: EN.601.220, EN.601.457, EN.601.461, image processing.
Prerequisites: EN.600.226 AND (AS.110.201 OR AS.110.212) or permission of the instructor; Students may receive credit for only one of EN.600.445, EN.600.645, EN.601.455, EN.601.655.
Instructor(s): R. Taylor
Area: Engineering.
EN.600.461. Computer Integrated Surgery II. 3.0 Credits.
This weekly lecture/seminar course addresses similar material to EN.601.445, but covers selected topics in greater depth. In addition to material covered in lectures/seminars by the instructor and other faculty, students are expected to read and provide critical analysis/presentations of selected papers in recitation sessions. Students taking this course are required to undertake and report on a significant term project under the supervision of the instructor and clinical end users. Typically, this project is an extension of the term project from EN.601.445, although it does not have to be. Grades are based on the project and on classroom recitations. Students wishing to attend the weekly lectures as a 1-credit seminar should sign up for EN.600.452. [Applications]
Prerequisites: EN.600.445 or EN.600.645 or permission; Students may receive credit for only one of EN.600.446, EN.600.646, EN.601.456, EN.601.656.
Instructor(s): R. Taylor
Area: Engineering.

EN.601.457. Computer Graphics. 3.0 Credits.
This course introduces computer graphics techniques and applications, including image processing, rendering, modeling and animation. [Applications]
Prerequisites: EN.600.120 AND EN.600.226, and linear algebra or permission of instructor; Students may receive credit for only one of EN.600.357, EN.600.457, EN.601.457, EN.601.657.
Instructor(s): M. Kazhdan
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.460. Information Retrieval and Web Agents. 3.0 Credits.
An in-depth, hands-on study of current information retrieval techniques and their application to developing intelligent WWW agents. Topics include a comprehensive study of current document retrieval models, mail/news routing and filtering, document clustering, automatic indexing, query expansion, relevance feedback, user modeling, information visualization and usage pattern analysis. In addition, the course explores the range of additional language processing steps useful for template filling and information extraction from retrieved documents, focusing on recent, primarily statistical methods. The course concludes with a study of current issues in information retrieval and data mining on the World Wide Web. Topics include web robots, spiders, agents and search engines, exploring both their practical implementation and the economic and legal issues surrounding their use. Recommended Course Background: EN.601.226
Prerequisites: EN.600.226
Instructor(s): D. Yarowsky
Area: Engineering.
EN.601.468. Machine Translation. 3.0 Credits.
Google translate can instantly translate between any pair of over fifty human languages (for instance, from French to English). How does it do that? Why does it make the errors that it does? And how can you build something better? Modern translation systems learn to translate by reading millions of words of already translated text, and this course will show you how they work. The course covers a diverse set of fundamental building blocks from linguistics, machine learning, algorithms, data structures, and formal language theory, along with their application to a real and difficult problem in artificial intelligence.
Prerequisites: EN.600.226 and prob/stat.; Students may receive credit for only one of EN.600.468, EN.601.468, EN.601.668.
Instructor(s): P. Koehn
Area: Engineering.

EN.601.475. Machine Learning. 3.0 Credits.
Machine learning is a subfield of computer science and artificial intelligence, whose goal is to develop computational systems, methods, and algorithms that can learn from data to improve their performance. This course introduces the foundational concepts of modern Machine Learning, including core principles, popular algorithms and modeling platforms. This will include both supervised learning, which includes popular algorithms like SVMs, logistic regression, boosting and deep learning, as well as unsupervised learning frameworks, which include Expectation Maximization and graphical models. Homework assignments include a heavy programming component, requiring students to implement several machine learning algorithms in a common learning framework. Additionally, analytical homework questions will explore various machine learning concepts, building on the pre-requisites that include probability, linear algebra, multi-variate calculus and basic optimization. Students in the course will develop a learning system for a final project. [Applications or Analysis] Required course background: multivariable calculus, probability, linear algebra.
Prerequisites: EN.600.107 OR EN.600.120 OR EN.601.220 OR EN.600.226/EN.601.226 OR EN.580.200 OR EN.500.200 OR AS.250.205 OR EN.601.107 OR EN.500.112 OR AP Computer Science; Students may receive credit for only one of EN.600.475, EN.601.475, EN.601.675.
Instructor(s): M. Dredze
Area: Engineering.

EN.601.476. Machine Learning: Data to Models. 3.0 Credits.
How can robots localize themselves in an environment when navigating? Can we predict which patients are at greatest-risk for complications in the hospital? Which movie should I recommend to this user given his history of likes? Many such big data questions can be answered using the paradigm of probabilistic models in machine learning. These are especially useful when common off-the-shelf algorithms such as support vector machines and k-means fail. You will learn methods for clustering, classification, structured prediction, recommendation and inference. We will use Murphy’s book, Machine Learning: a Probabilistic Perspective, as the text for this course. Assignments are solved in groups of size 1-3 students. The class will have 4 interactive sessions during which we brainstorm how to solve example open-ended real-world problems with the tools learnt in class. Students are also required to do a project of their choice within which they experiment with the ideas learnt in class. [Applications or Analysis] Prerequisites include Intro Prob/Stat, Linear Algebra and Intro Machine Learning as well as strong background in s.
Instructor(s): S. Saria
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.477. Causal Inference. 3.0 Credits.
"Big data" is not necessarily "high quality data." Systematically missing records, unobserved confounders, and selection effects present in many datasets make it harder than ever to answer scientifically meaningful questions. This course will teach mathematical tools to help you reason about causes, effects, and bias sources in data with confidence. We will use graphical causal models, and potential outcomes to formalize what causal effects mean, describe how to express these effects as functions of observed data, and use regression model techniques to estimate them. We will consider techniques for handling missing values, structure learning algorithms for inferring causal directionality from data, and connections between causal inference and reinforcement learning. [Analysis] Prerequisites: familiarity with the R programming language, multivariate calculus, basics of linear algebra and probability.
Prerequisites: EN.600.475 OR (EN.550.310 OR EN.550.420) AND AS.110.202 or permission of instructor.; Students may receive credit for only one of EN.600.477, EN.600.677, EN.601.477, EN.601.677.
Instructor(s): I. Shpitser
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.479. Representation Learning. 3.0 Credits.
Often the success of a machine learning project depends on the choice of features used. Machine learning has made great progress in training classification, regression and recognition systems when "good" representations, or features, of input data are available. However, much human effort is spent on designing good features which are usually knowledge-based and engineered by domain experts over years of trial and error. A natural question to ask then is "Can we automate the learning of useful features from raw data?" Representation learning algorithms such as principal component analysis aim at discovering better representations of inputs by learning transformations of data that disentangle factors of variation in data while retaining most of the information. The success of such data-driven approaches to feature learning depends not only on how much data we can process but also on how well the features that we learn correlate with the underlying unknown labels (semantic content in the data). This course will focus on scalable machine learning approaches for learning representations from large amounts of unlabeled, multi-modal, and heterogeneous data. We will cover topics including deep learning, multi-view learning, dimensionality reduction, similarity-based learning, and spectral learning. Students may receive credit for 601.479 or 601.679 but not both. [Applications or Analysis] Required course background: machine learning or basic probability and linear algebra.
Prerequisites: If you have completed EN.600.679 you may not enroll in EN.601.479.
Instructor(s): R. Arora
Area: Engineering.
EN.601.481. Machine Learning: Optimization. 3.0 Credits.
Optimization is at the heart of machine learning. Most machine learning problems can be posed as optimization problems. However, unlike mathematical optimization where the focus is on efficient algorithms for finding solutions with a high degree of accuracy as measured by optimality conditions, optimization for machine learning focuses on algorithms that are efficient and generalize well. In this course, we will focus on optimization for problems that arise in machine learning, design and analysis of algorithms for solving these problems, and the interplay of optimization and machine learning. The coursework will include homework assignments and a final project focusing on applying optimization algorithms to real world machine learning problems.
[Analysis or Applications]
Prerequisites: EN.601.475[ OR ( EN.553.310 OR ( EN.553.420 AND EN.553.430 ) AND AS.110.201 AND AS.110.202 );Students may receive credit for only one of EN.601.481/681.
Instructor(s): R. Arora
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.482. Machine Learning: Deep Learning. 3.0 Credits.
Deep learning (DL) has emerged as a powerful tool for solving data-intensive learning problems such as supervised learning for classification or regression, dimensionality reduction, and control. As such, it has a broad range of applications including speech and text understanding, computer vision, medical imaging, and perception-based robotics. The goal of this course is to introduce the basic concepts of deep learning (DL). The course will include a brief introduction to the basic theoretical and methodological underpinnings of machine learning, commonly used architectures for DL, DL optimization methods, DL programming systems, and specialized applications to computer vision, speech understanding, and robotics. Students will be expected to solve several DL problems on standardized data sets, and will be given the opportunity to pursue team projects on topics of their choice. [Applications] Students should also consider taking EN.601.382 Deep Learning Lab as a supplement. Students may choose to skip the lab course if they already have a strong programming background and are comfortable learning on their own using online resources and tutorials. Pre-req: (AS.110.201 or AS.110.212 or EN.553.291) and (EN.553.310 EN.553.311 or EN.553.420); Calc III and numerical optimization recommended.
Prerequisites: (AS.110.201 OR AS.110.212 OR EN.553.291) AND (EN.553.310 OR EN.553.311 OR EN.553.420 OR EN.560.348); Calc III and numerical optimization recommended.
Instructor(s): G. Hager
Area: Engineering.

EN.601.485. Probabilistic Models of the Visual Cortex. 3.0 Credits.
The course gives an introduction to computational models of the mammalian visual cortex. It covers topics in low-, mid-, and high-level vision. It briefly discusses the relevant evidence from anatomy, electrophysiology, imaging (e.g., fMRI), and psychophysics. It concentrates on mathematical modelling of these phenomena taking into account recent progress in probabilistic models of computer vision and developments in machine learning, such as deep networks. [Applications or Analysis]. Programming experience (Python preferred).
Prerequisites: AS.110.106 OR AS.110.108
Instructor(s): A. Yuille
Area: Quantitative and Mathematical Sciences.

EN.601.488. Foundations of Computational Biology & Bioinformatics II. 3.0 Credits.
This course will introduce probabilistic modeling and information theory applied to biological sequence analysis, focusing on statistical models of protein families, alignment algorithms, and models of evolution. Topics will include probability theory, score matrices, hidden Markov models, maximum likelihood, expectation maximization and dynamic programming algorithms. Homework assignments will require programming in Python. Foundations of Computational Biology I is not a preq. [Analysis] Co-listed with EN.580.488. Recommended Course Background: math through linear algebra and differential equations, at least one prob/stat course, EN.580.221 or equivalent, EN.601.226 or equivalent.
Instructor(s): R. Karchin
Area: Engineering, Natural Sciences.

EN.601.490. Introduction to Human-Computer Interaction. 3.0 Credits.
This course is designed to introduce undergraduate and graduate students to design techniques and practices in human-computer interaction (HCI), the study of interactions between humans and computing systems. Students will learn design techniques and evaluation methods, as well as current practices and exploratory approaches, in HCI through lectures, readings, and assignments. Students will practice various design techniques and evaluation methods through hands-on projects focusing on different computing technologies and application domains. This course is intended for undergraduate and graduate students in Computer Science/Cognitive Science/Psychology. Interested students from different disciplines should contact the instructor before enrolling in this course. [Applications] Recommended Background: Basic programming skills.
Prerequisites: Students can receive credit for either EN.601.490 or EN.601.690, but not both.
Instructor(s): C. Huang
Area: Engineering.

EN.601.501. Computer Science Workshop. 1.0 - 3.0 Credits.
An applications-oriented, computer science project done under the supervision and with the sponsorship of a faculty member in the Department of Computer Science. Computer Science Workshop provides a student with an opportunity to apply theory and concepts of computer science to a significant project of mutual interest to the student and a Computer Science faculty member. Permission to enroll in CSW is granted by the faculty sponsor after his/her approval of a project proposal from the student. Interested students are advised to consult with Computer Science faculty members before preparing a Computer Science Workshop project proposal.
Instructor(s): D. Yarowsky; J. Selinski; M. Darvish Darab; S. Smith.

EN.601.503. Independent Study. 1.0 - 3.0 Credits.
Individual guided study for undergraduate students under the direction of a faculty member in the department. The program of study, including the credit to be assigned, must be worked out in advance between the student and the faculty member involved. Permission required.
Instructor(s): Staff.

EN.601.507. Undergraduate Research. 1.0 - 3.0 Credits.
Individual research for undergraduates under the direction of a faculty member in the department. The program of research, including the credit to be assigned, must be worked out in advance between the student and the faculty member involved. Permission required.
Instructor(s): Staff.
EN.601.509. Computer Science Internship. 1.0 Credit.
Individual work in the field with a learning component, supervised by a faculty member in the department. The program of study and credit assigned must be worked out in advance between the student and the faculty member involved. Students may not receive credit for work that they are paid to do. As a rule of thumb, 40 hours of work is equivalent to one credit. Permission required.
Instructor(s): Staff.

EN.601.517. Group Undergraduate Research. 1.0 - 3.0 Credits.
Independent research for undergraduates under the direction of a faculty member in the department. This course has a weekly research group meeting that students are expected to attend. The program of research, including the credit to be assigned, must be worked out in advance between the student and the faculty member involved.
Instructor(s): Staff.

EN.601.519. Senior Honors Thesis. 3.0 Credits.
The student will undertake a substantial independent research project under the supervision of a faculty member, potentially leading to the notation "Departmental Honors with Thesis" on the final transcript. Students are expected to enroll in both semesters of this course during their senior year. Project proposals must be submitted and accepted in the preceding spring semester (junior year) before registration. Students will present their work publicly before April 1st of senior year. They will also submit a first draft of their project report (thesis document) at that time. Faculty will meet to decide if the thesis will be accepted for honors.
Computer science majors only. Students should have a 3.5 GPA in computer science courses at the end of their junior year and permission of faculty sponsor.
Instructor(s): Staff.

EN.601.520. Senior Honors Thesis. 0.0 - 3.0 Credits.
For computer science majors only, a continuation of EN.601.519. Recommended Course Background: EN.601.519
Instructor(s): Staff.

EN.601.556. Senior Thesis In CIS. 3.0 Credits.
Prerequisites: EN.600.445 or permission of instructor.
Instructor(s): R. Taylor.

EN.601.611. Computer Science Innovation & Entrepreneurship II. 3.0 Credits.
This course is the second half of a two-course sequence and is a continuation of course EN.660.410.01, CS Innovation and Entrepreneurship, offered by the Center for Leadership Education (CLE). In this sequel course the student groups, directed by CS faculty, will implement the business idea which was developed in the first course and will present the implementations and business plans to an outside panel made up of practitioners, industry representatives, and venture capitalists. [General]
Instructor(s): A. Dahbura; L. Aronhime
Area: Engineering.

EN.601.614. Computer Networks. 4.0 Credits.
This course considers intersystem communications issues. Topics covered include layered network architectures; the OSI model; bandwidth, data rates, modems, multiplexing, error detection/correction; switching; queuing models; circuit switching, packet switching; performance analysis of protocols, local area networks; and congestion control. Recommended Course Background: EN.601.220 and EN.601.229.
Students can only receive credit for EN.600.344 or EN.601.414, not both.
Instructor(s): X. Jin
Area: Engineering.

EN.601.615. Databases. 3.0 Credits.
Same material as 601.415, for graduate students. Introduction to database management systems and database design, focusing on the relational and object-oriented data models, query languages and query optimization, transaction processing, parallel and distributed databases, recovery and security issues, commercial systems and case studies, heterogeneous and multimedia databases, and data mining. [Systems] (www.cs.jhu.edu/~yarowsky/cs415.html) Recommended Course Background: EN.601.226
Prerequisites: Students may receive credit for only one of EN.600.315, EN.600.415, EN.601.315, EN.601.415, EN.601.615.
Instructor(s): D. Yarowsky
Area: Engineering.

EN.601.618. Operating Systems. 3.0 Credits.
Same material as 601.418, for graduate students. This course covers fundamental topics related to operating systems theory and practice. Topics include processor management, storage management, concurrency control, multi-programming and processing, device drivers, operating system components (e.g., file system, kernel), modeling and performance measurement, protection and security, and recent innovations in operating system structure. Course work includes the implementation of operating systems techniques and routines, and critical parts of a small but functional operating system. [Systems] Recommended Course Background: 601.226 and 601.229.
Prerequisites: Students may receive credit for only one of EN.600.318, EN.600.418, EN.601.318, EN.601.418, EN.601.618.
Instructor(s): P. Huang
Area: Engineering.

EN.601.620. Parallel Programming. 3.0 Credits.
Graduate level version of EN.601.420. Recommended Course Background: EN.601.220 AND EN.601.229.
Instructor(s): R. Burns
Area: Engineering.

EN.601.621. Obj Orient Software Eng. 3.0 Credits.
Same material as EN.601.421, for graduate students. This course covers object-oriented software construction methodologies and their application. The main component of the course is a large team project on a topic of your choosing. Course topics covered include object-oriented analysis and design, UML, design patterns, refactoring, program testing, code repositories, team programming, and code reviews. [Systems or Applications] (http://pl.cs.jhu.edu/oose/index.shtml) Recommended Course Background: EN.601.226 and EN.601.220
Prerequisites: Students may receive credit for only one of EN.600.321, EN.600.421, EN.601.421, EN.601.621.
Instructor(s): S. Smith
Area: Engineering.

EN.601.626. Principles of Programming Languages. 3.0 Credits.
Same material as EN.601.426, for graduate students. Functional, object-oriented, and other language features are studied independent of a particular programming language. Students become familiar with these features by implementing them. Most of the implementations are in the form of small language interpreters. Some type checkers and a small compiler will also be written. The total amount of code written will not be overly large, as the emphasis is on concepts. The ML programming language is the implementation language used. [Analysis] Students may receive credit for only one of EN.601.426/626. Required course background: EN.601.226.
Instructor(s): S. Smith
Area: Engineering, Quantitative and Mathematical Sciences.
EN.601.636. Algorithmic Game Theory. 3.0 Credits.
Same material as EN.601.436, for graduate students. This course provides an introduction to algorithmic game theory: the study of games from the perspective of algorithms and theoretical computer science. There will be a particular focus on games that arise naturally from economic interactions involving computer systems (such as economic interactions between large-scale networks, online advertising markets, etc.), but there will also be broad coverage of games and mechanisms of all sorts. Topics covered will include a) complexity of computing equilibria and algorithms for doing so, b) (in)efficiency of equilibria, and c) algorithmic mechanism design. [Analysis]
Instructor(s): M. Dinitz
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.640. Web Security. 3.0 Credits.
This course begins with reviewing basic knowledge of the World Wide Web, and then exploring the central defense concepts behind Web security, such as same-origin policy, cross-origin resource sharing, and browser sandboxing. It will cover the most popular Web vulnerabilities, such as cross-site scripting (XSS) and SQL injection, as well as how to attack and penetrate software with such vulnerabilities. Students will learn how to detect, respond, and recover from security incidents. Newly proposed research techniques will also be discussed. [Systems] Required background: data structures and computer system fundamentals.
Instructor(s): Y. Cao
Area: Engineering.

EN.601.641. Blockchains and Cryptocurrencies. 3.0 Credits.
Same as EN.601.441, for graduate students. This course will introduce students to cryptocurrencies and the main underlying technology of Blockchains. The course will start with the relevant background in cryptography and then proceed to cover the recent advances in the design and applications of blockchains. This course should primarily appeal to students who want to conduct research in this area or wish to build new applications on top of blockchains. It should also appeal to those who have a casual interest in this topic or are generally interested in cryptography. Students are expected to have mathematical maturity.
[Analysis]
Prerequisites: Students may receive credit for only one of EN.600.451 OR EN.601.451 OR EN.601.641; EN.601.426 AND (EN.553.310 OR EN.553.420)
Instructor(s): A. Jain
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.642. Modern Cryptography. 3.0 Credits.
Same material as 601.442, for graduate students. Modern Cryptography includes seemingly paradoxical notions such as communicating privately without a shared secret, proving things without leaking knowledge, and computing on encrypted data. In this challenging but rewarding course we will start from the basics of private and public key cryptography and go all the way up to advanced notions such as zero-knowledge proofs, functional encryption and program obfuscation. The class will focus on rigorous proofs and require mathematical maturity. [Analysis] Required course background: EN.601.231 or EN.601.631.
Prerequisites: Students may receive credit for only one of EN.600.442, EN.601.442, EN.601.642.
Instructor(s): A. Jain
Area: Engineering, Quantitative and Mathematical Sciences.
EN.601.443. Security & Privacy in Computing. 3.0 Credits.
Same material as 601.443, for graduate students. Lecture topics will include computer security, network security, basic cryptography, system design methodology, and privacy. There will be a heavy work load, including written homework, programming assignments, exams and a comprehensive final. The class will also include a semester-long project that will be done in teams and will include a presentation by each group to the class. [Applications] Recommended Course Background: A basic course in operating systems and networking, or permission of instructor.
Prerequisites: Students may receive credit for only one of EN.600.443, EN.601.443, EN.601.643.
Instructor(s): A. Rubin
Area: Engineering.

EN.601.444. Network Security. 3.0 Credits.
Same material as 601.444, for graduate students. This course focuses on communication security in computer systems and networks. The course is intended to provide students with an introduction to the field of network security. The course covers network security services such as authentication and access control, integrity and confidentiality of data, firewalls and related technologies, Web security and privacy. Course work involves implementing various security techniques. A course project is required. [Systems] Recommended. Course Background: EN.601.220, EN.601.226 or equivalent
Prerequisites: Students may receive credit for only one of EN.600.424, EN.650.424, EN.601.444, EN.601.644.
Instructor(s): S. Nielsen
Area: Engineering.

EN.601.457. Computer Graphics. 3.0 Credits.
Same material as 601.457, for graduate students. Lecture topics will include computer graphics techniques and applications, including image processing, rendering, modeling and animation. [Applications] Permission of instructor is required for students not satisfying a pre-requisite.
Prerequisites: Students may receive credit for only one of EN.600.457, EN.601.457, EN.601.657.
Instructor(s): R. Taylor
Area: Engineering.

EN.601.455. Computer Integrated Surgery I. 4.0 Credits.
Same material as 601.455, for graduate students. This course covers computer-based techniques, systems, and applications exploiting quantitative information from medical images and sensors to assist clinicians in all phases of treatment from diagnosis to preoperative planning, execution, and follow-up. It emphasizes the relationship between problem definition, computer-based technology, and clinical application and includes a number of guest lectures given by surgeons and other experts on requirements and opportunities in particular clinical areas. [Applications] Recommended Course Background: intermediate programming in C/C++, EN.601.457, EN.601.461, image processing.
Prerequisites: Students may receive credit for only one of EN.600.445, EN.600.645, EN.601.455, EN.601.655.
Instructor(s): N. Navab
Area: Engineering.

EN.601.645. Practical Cryptographic Systems. 3.0 Credits.
Same material as 601.445, for graduate students. This semester-long course will teach systems and cryptographic design principles by example: by studying and identifying flaws in widely-deployed cryptographic products and protocols. Our focus will be on the techniques used in practical security systems, the mistakes that lead to failure, and the approaches that might have avoided the problem. We will place a particular emphasis on the techniques of provable security and the feasibility of reverse-engineering undocumented cryptographic systems. [Systems] Recommended Course Background: EN.601.220, EN.601.226 or equivalent
Prerequisites: Students may receive credit for only one of EN.600.454, EN.650.454, EN.601.445, EN.601.645.
Instructor(s): M. Green
Area: Engineering.

EN.601.654. Augmented Reality. 3.0 Credits.
This course introduces students to the field of Augmented Reality. It reviews its basic definitions, principles and applications. It then focuses on Medical Augmented Reality and its particular requirements. The course also discusses the main issues of calibration, tracking, multi-modal registration, advance visualization and display technologies. Homework in this course will relate to the mathematical methods used for calibration, tracking and visualization in medical augmented reality. Students may also be asked to read papers and implement various techniques within group projects. Recommended Course Background: EN.601.220, EN.601.226, and AS.110.201. [Applications] Recommended Course Background: intermediate programming in C/C++, EN.601.457, EN.601.461, image processing.
Prerequisites: Students may receive credit for only one of EN.600.445, EN.600.645, EN.601.455, EN.601.655.
Instructor(s): L. Shi
Area: Engineering.
EN.601.658. Introduction to Geometry Processing. 2.0 Credits.
In this course we will look at fundamental techniques in geometry processing, including smoothing / sharpening, parameterization, and (if time allows) vector fields. The course will begin with a review of the discretization of the underlying concepts from differential geometry (e.g. normals, curvature, Laplacian) before proceeding to specific applications.
Prerequisites: EN.600.357 AND EN.600.457
Instructor(s): F. Prada Nino; M. Kazhdan.

EN.601.661. Computer Vision. 3.0 Credits.
Same material as 601.461, for graduate students. Students may receive credit for at most one of 601.461/661/761. This course gives an overview of fundamental methods in computer vision from a computational perspective. Methods studied include: camera systems and their modeling, computation of 3-D geometry from binocular stereo, motion, and photometric stereo; and object recognition. Edge detection and color perception are covered as well. Elements of machine vision and biological vision are also included. [Applications] Recommended Course Background: intro programming, linear algebra, prob/stat.
Prerequisites: Students may receive credit for only one of EN.600.361, EN.600.461, EN.600.661, EN.601.461, EN.601.661.
Instructor(s): H. Ali
Area: Engineering.

EN.601.663. Algorithms for Sensor-Based Robotics. 3.0 Credits.
Same material as EN.601.463, for graduate students. This course surveys the development of robotic systems for navigating in an environment from an algorithmic perspective. It will cover basic kinematics, configuration space concepts, motion planning, and localization and mapping. It will describe these concepts in the context of the ROS software system, and will present examples relevant to mobile platforms, manipulation, robotics surgery, and human-machine systems. [Analysis] Recommended Course Background: EN.600.226 and Linear Algebra and Probability.
Prerequisites: Students may receive credit for only one of EN.600.336, EN.600.436, EN.600.636, EN.601.463, EN.601.663.
Instructor(s): S. Leonard
Area: Engineering.

EN.601.664. Artificial Intelligence. 3.0 Credits.
Same material as EN.601.464, for graduate students. The class is recommended for all scientists and engineers with a genuine curiosity about the fundamental obstacles to getting machines to perform tasks such as learning, planning and prediction. Materials will be primarily based on the popular textbook, Artificial Intelligence: A Modern Approach. Strong programming skills are expected, as well as basic familiarity with probability. For students intending to also take courses in Machine Learning (e.g., EN.601.475/675, EN.601.476/676), they may find it beneficial to take this course first, or concurrently. [Applications] Prereq: EN.600.226; Recommended: linear algebra, prob/stat.
Prerequisites: Students may receive credit for only one of EN.600.335, EN.600.435, EN.601.464, EN.601.664.
Instructor(s): B. Van Durme
Area: Engineering.

EN.601.665. Natural Language Processing. 4.0 Credits.
Same material as 601.465, for graduate students. This course is an in-depth overview of techniques for processing human language. How should linguistic structure and meaning be represented? What algorithms can recover them from text? And crucially, how can we build statistical models to choose among the many legal answers? The course covers methods for trees (parsing and semantic interpretation), sequences (finite-state transduction such as morphology), and words (sense and phrase induction), with applications to practical engineering tasks such as information retrieval and extraction, text classification, part-of-speech tagging, speech recognition and machine translation. There are a number of structured but challenging programming assignments. [Applications] Recommended Course Background: EN.601.226.
Prerequisites: Students may receive credit for only one of EN.600.465, EN.601.465, EN.601.665.
Instructor(s): J. Eisner
Area: Engineering.

EN.601.666. Information Retrieval and Web Agents. 3.0 Credits.
Same material as EN.601.466, for graduate students. An in-depth, hands-on study of current information retrieval techniques and their application to developing intelligent WWW agents. Topics include a comprehensive study of current document retrieval models, mail/news routing and filtering, document clustering, automatic indexing, query expansion, relevance feedback, user modeling, information visualization and usage pattern analysis. In addition, the course explores the range of additional language processing steps useful for template filling and information extraction from retrieved documents, focusing on recent, primarily statistical methods. The course concludes with a study of current issues in information retrieval and data mining on the World Wide Web. Topics include web robots, spiders, agents and search engines, exploring both their practical implementation and the economic and legal issues surrounding their use. [Applications]
Instructor(s): D. Yarowsky
Area: Engineering.

EN.601.668. Machine Translation. 3.0 Credits.
Same material as 601.468, for graduate students. Google translate can instantly translate between any pair of over fifty human languages (for instance, from French to English). How does it do that? Why does it make the errors that it does? And how can you build something better? Modern translation systems learn to translate by reading millions of words of already translated text, and this course will show you how they work. The course covers a diverse set of fundamental building blocks from linguistics, machine learning, algorithms, data structures, and formal language theory, along with their application to a real and difficult problem in artificial intelligence. [Applications] Recommended Course Background: prob/stat, EN.601.226; EN.601.465.
Prerequisites: Students may receive credit for only one of EN.600.468, EN.601.468, EN.601.668.
Instructor(s): P. Koehn
Area: Engineering.
EN.601.675. Machine Learning. 3.0 Credits.
Same material as 601.475, for graduate students. Machine learning is a subfield of computer science and artificial intelligence, whose goal is to develop computational systems, methods, and algorithms that can learn from data to improve their performance. This course introduces the foundational concepts of modern Machine Learning, including core principles, popular algorithms and modeling platforms. This will include both supervised learning, which includes popular algorithms like SVMs, logistic regression, boosting and deep learning, as well as unsupervised learning frameworks, which include Expectation Maximization and graphical models. Homework assignments include a heavy programming component, requiring students to implement several machine learning algorithms in a common learning framework. Additionally, analytical homework questions will explore various machine learning concepts, building on the pre-requisites that include probability, linear algebra, multi-variate calculus and basic optimization. Students in the course will develop a learning system for a final project. [Applications or Analysis] Recommended Course Background: multivariable calculus, probability, linear algebra.
Prerequisites: Students may receive credit for only one of EN.600.475, EN.601.475, EN.601.675.
Instructor(s): M. Dredze
Area: Engineering.

EN.601.677. Causal Inference. 3.0 Credits.
"Big data" is not necessarily "high quality data." Systematically missing records, unobserved confounders, and selection effects present in many datasets make it harder than ever to answer scientifically meaningful questions. This course will teach mathematical tools to help you reason about causes, effects, and bias sources in data with confidence. We will use graphical causal models, and potential outcomes to formalize what causal effects mean, describe how to express these effects as functions of observed data, and use regression model techniques to estimate them. We will consider techniques for handling missing values, structure learning algorithms for inferring causal directionality from data, and connections between causal inference and reinforcement learning. [Analysis] Pre-requisites: familiarity with the R programming language, multivariate calculus, basics of linear algebra and probability.
Prerequisites: Students may receive credit for only one of EN.600.477, EN.600.677, EN.601.477, EN.601.677.
Instructor(s): I. Shpitser
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.679. Representation Learning. 3.0 Credits.
Graduate level version of 601.479. Students may receive credit for 601.479 or 601.679 but not both. [Analysis or Applications] Required course background: machine learning or basic probability and linear algebra. Co-listed with EN.601.479
Prerequisites: If you have completed EN.600.479 you may not enroll in EN.600.679.
Instructor(s): R. Arora.

EN.601.681. Machine Learning: Optimization. 3.0 Credits.
Same material as EN.601.481, for graduate students. Optimization is at the heart of machine learning. Most machine learning problems can be posed as optimization problems. However, unlike mathematical optimization where the focus is on efficient algorithms for finding solutions with a high degree of accuracy as measured by optimality conditions, optimization for machine learning focuses on algorithms that are efficient and generalize well. In this course, we will focus on optimization for problems that arise in machine learning, design and analysis of algorithms for solving these problems, and the interplay of optimization and machine learning. The course will include homework assignments and a final project focusing on applying optimization algorithms to real world machine learning problems. [Analysis or Applications] Recommended Course Background: EN.601.475 OR ( EN.553.310 OR EN.553.420 AND EN.553.430 ) AND AS.110.201 AND AS.110.202
Prerequisites: Students may receive credit for only one of EN.601.481/681
Instructor(s): R. Arora.

EN.601.682. Machine Learning: Deep Learning. 3.0 Credits.
Deep learning (DL) has emerged as a powerful tool for solving data-intensive learning problems such as supervised learning for classification or regression, dimensionality reduction, and control. As such, it has a broad range of applications including speech and text understanding, computer vision, medical imaging, and perception-based robotics. The goal of this course is to introduce the basic concepts of deep learning (DL). The course will include a brief introduction to the basic theoretical and methodological underpinnings of machine learning, commonly used architectures for DL, DL optimization methods, DL programming systems, and specialized applications to computer vision, speech understanding, and robotics. Students will be expected to solve several DL problems on standardized data sets, and will be given the opportunity to pursue team projects on topics of their choice. [Applications] Students should also consider taking EN.601.382 Deep Learning Lab as a supplement. Students may choose to skip the lab course if they already have a strong programming background and are comfortable learning on their own using online resources and tutorials. Recommended Course Background: (AS.110.201 or AS.110.212 or EN.553.291) and (EN.553.310 OR EN.553.430 OR EN.553.420); numerical optimization recommended.
Instructor(s): G. Hager
Area: Engineering.

EN.601.690. Introduction to Human-Computer Interaction. 3.0 Credits.
This course is designed to introduce undergraduate and graduate students to design techniques and practices in human-computer interaction (HCI), the study of interactions between humans and computing systems. Students will learn design techniques and evaluation methods, as well as current practices and exploratory approaches, in HCI through lectures, readings, and assignments. Students will practice various design techniques and evaluation methods through hands-on projects focusing on different computing technologies and application domains. This course is intended for undergraduate and graduate students in Computer Science/Cognitive Science/Psychology. Interested students from different disciplines should contact the instructor before enrolling in this course. [Applications] Recommended Background: Basic programming skills.
Prerequisites: Students can receive credit for either EN.601.490 or EN.601.690, but not both.
Instructor(s): C. Huang
Area: Engineering.
EN.601.418 OR EN.601.618
programming. [Systems]

students will work on a substantial project that integrates the principles, methods, and knowledge learned in this course. [Applications] Required course background: EN.601.220 and EN.601.226.

EN.601.714. Advanced Computer Networks. 3.0 Credits.

This is a graduate-level course on computer networks. It provides a comprehensive overview on advanced topics in network protocols and networked systems. The course will cover both classic papers on Internet protocols and recent research results. It will examine a wide range of topics, e.g., routing, congestion control, network architectures, datacenter networks, network virtualization, software-defined networking, and programmable networks, with an emphasis on core networking concepts and principles. The course will include lectures, paper discussions, programming assignments and a research project. Recommended Course Background: One undergraduate course in computer networks (e.g., EN.601.414/614 Computer Network Fundamentals or the equivalent), or permission of the instructor. The course assignments and projects assume students to be comfortable with programming. Instructor(s): S. Ghorbani Khaledi.

EN.601.717. Advanced Distributed Systems & Networks. 3.0 Credits.
The course explores the state of the art in distributed systems, networks and Internet research and practice, trying to see what it would take to push the envelop a step further. The course is conducted as a discussion group, where the professor and students brainstorm and pick interesting semester-long projects with high potential future impact. Example areas include robust scalable infrastructure (distributed datacenters, cloud networking, scada systems), real-time performance (remote surgery, trading systems), hybrid networks (mesh networks, 3G/4G/Wifi/Bluetooth). Students should feel free to bring their own topics of interest and ideas. Recommended Course Background: a systems course (distributed systems, operating systems, computer networks, parallel programming) or permission of instructor. Instructor(s): Y. Amir.

EN.601.718. Advanced Operating Systems. 3.0 Credits.

Students will study advanced operating system topics and be exposed to recent developments in operating systems research. This course involves readings on classic and new papers. Topics include virtual memory management, synchronization and communication, file systems, protection and security, operating system structure and extension techniques, fault tolerance, and history and experience of systems programming. [Systems] Prerequisites: EN.600.318 OR EN.600.418 OR EN.601.318 OR EN.601.418 OR EN.601.618 Instructor(s): P. Huang.

EN.601.723. Advanced Topics in Data-Intensive Computing. 3.0 Credits.
The advent of cloud computing has lead to an explosion of storage system and data analysis software, including NoSQL databases, bulk-synchronous processing, graph computing engines, and stream processing. This course will explore scale-out software architectures for data-processing tasks. It will examine the algorithms and data-structures that underlie scalable systems and look at how hardware and networking trends influence the design and deployment of cloud computing. Recommended Course Background: EN.601.320/420 or permission of instructor. [Systems] Prerequisites: EN.600.320 OR EN.600.420 OR EN.601.620

EN.601.730. Pseudorandomness and Combinatorial Constructions. 3.0 Credits.

Randomness is very useful in almost all areas of computer science, such as algorithms, distributed computing and cryptography. However, computers generally do not have access to truly uniform random bits. To deal with this, we rely on various pseudorandom objects to reduce either the quantity or the quality of the random bits needed. In this course, we will develop provably good pseudorandom objects for a variety of tasks. We will frequently require explicit combinatorial constructions. That is, we will want to efficiently and deterministically construct such objects. Along the way, we will also explore the close connections of such objects to many other areas in computer science and mathematics, such as graph theory, coding theory, complexity theory and arithmetic combinatorics. [Analysis] Recommended course background: EN.601.231 or EN.601.631, and probability. Instructor(s): X. Li.

EN.601.743. Advanced Topics in Computer Security. 3.0 Credits.

Topics will vary from year to year, but will focus mainly on network perimeter protection, host-level protection, authentication technologies, intellectual property protection, formal analysis techniques, intrusion detection and similarly advanced subjects. Emphasis in this course is on understanding how security issues impact real systems, while maintaining an appreciation for grounding the work in fundamental science. Students will study and present various advanced research papers to the class. There will be homework assignments and a course project. Instructor(s): A. Rubin.

EN.601.745. Advanced Topics in Applied Cryptography. 3.0 Credits.

This reading and project based course will explore the latest research in the area of applied cryptography and cryptographic engineering. Topics covered will include zero knowledge, efficient multiparty computation, cryptocurrencies, and trusted computing hardware. Readings will be drawn from the latest applied cryptography and security conferences. The course will include both reading, critical analysis, presentations and a course programming project. [Analysis or Applications] Prerequisites: EN.600.454 OR EN.601.445 OR EN.600.442 OR EN.601.442 OR EN.601.642

EN.601.748. Computational Genomics: Data Analysis. 3.0 Credits.

Graduate level version of EN.601.448. [Applications] Recommended Course Background: EN.601.226 or other programming experience, probability and statistics, linear algebra or calculus. Students may receive credit for EN.601.448 or EN.601.748 but not both. Prerequisites: Students may receive credit for EN.600.438 or EN.600.638, but not both. Instructor(s): A. Battle
Area: Engineering.
EN.601.749. Computational Genomics: Applied Comparative Genomics. 3.0 Credits.
The goal of this course is to study the leading computational and quantitative approaches for comparing and analyzing genomes starting from raw sequencing data. The course will focus on human genomics and human medical applications, but the techniques will be broadly applicable across the tree of life. The topics will include genome assembly & comparative genomics, variant identification & analysis, gene expression & regulation, personal genome analysis, and cancer genomics. The grading will be based on assignments, a midterm & final exam, class presentations, and a significant class project. [Applications] Expected course background: familiarity with UNIX scripting and/or programming.
Instructor(s): M. Schatz.

EN.601.750. Frontiers of Sequencing Data Analysis. 3.0 Credits.
Public archives now contain petabytes of valuable but hard-to-analyze DNA sequencing data. Analyzing even small datasets is complicated by sequencing errors, differences between individuals, and the fragmentary nature of the sequencing reads. In this course, we study recent algorithms and methods that seek to make sense of DNA sequencing datasets from small to very large. Topics covered will vary from year to year, but could include RNA sequencing data analysis, other functional genomics data analysis, metagenomics analysis, data compression, indexing, applications of streaming algorithms and sketch data structures, assembly, etc. There will be homework assignments and a course project. [Applications] Instructor(s): B. Langmead.

EN.601.751. Advanced Topics in Genomic Data Analysis. 3.0 Credits.
New Description: Genomic data is becoming available in large quantities, but understanding how genetics contributes to human disease and other traits remains a major challenge. Machine learning and statistical approaches allow us to automatically analyze and combine genomic data, build predictive models, and identify genetic elements important to disease and cellular processes. This course will cover current uses of statistical methods and machine learning in diverse genomic applications including new genomic technologies. Students will present and discuss current literature. Topics include personal genomics, integrating diverse genomic data types, new technologies such as single cell sequencing and CRISPR, and other topics guided by student interest. The course will include a project component with the opportunity to explore publicly available genomic data. [Applications] Recommended Course Background: coursework in data science or machine learning.
Instructor(s): A. Battle.

EN.601.760. FFT in Graphics & Vision. 3.0 Credits.
In this course, we will study the Fourier Transform from the perspective of representation theory. We will begin by considering the standard transform defined by the commutative group of rotations in 2D and translations in two- and three-dimensions, and will proceed to the Fourier Transform of the non-commutative group of 3D rotations. Subjects covered will include correlation of images, shape matching, computation of invariances, and symmetry detection. Recommended Course Background: AS.110.201 and comfort with mathematical derivations.
Instructor(s): M. Kazhdan.

EN.601.761. Advanced Computer Vision. 3.0 Credits.
Similar material as 601.461/661, covered in more depth. [Applications] Recommended Course Background: intro programming, linear algebra, prob/stat.
Prerequisites: Students may receive credit for only one of the following:
EN.600.461/EN.601.461, EN.600.661/EN.601.661, or EN.601.761.
Instructor(s): A. Reiter
Area: Engineering.

EN.601.763. Algorithms for Sensor-Based Robotics. 3.0 Credits.
Similar material as EN.601.463 and EN.601.663, covered in more depth. [Applications] Recommended course background: EN.601.226, AS.110.106, probability and statistics.
Prerequisites: Students may only earn credit for one of the following:
EN.600.336, EN.600.436/EN.601.463, EN.600.663, or EN.600.636/EN.601.763.
Instructor(s): S. Leonard.

EN.601.765. Machine Learning: Linguistic & Sequence Modeling. 3.0 Credits.
This course surveys formal ingredients that are used to build structured models of character and word sequences. We will unpack recent deep learning architectures that consider various kinds of latent structure, and see how they draw on earlier work in structured prediction, dimensionality reduction, Bayesian nonparametrics, multi-task learning, etc. We will also examine a range of strategies used for inference and learning in these models. Students will be expected to read recent papers and carry out a research project. [Applications or Analysis]
Prerequisites: EN.600.465/EN.601.465 or EN.601.665
Instructor(s): J. Eisner; R. Cotterell.

EN.601.766. Information Extraction. 3.0 Credits.
Introduction to statistical methods of speech recognition (automatic transcription of speech) and understanding. The course is a natural continuation of EN.601.465 but is independent of it. Topics include elementary information theory, hidden Markov models, the Baum and Viterbi algorithms, efficient hypothesis search methods, statistical decision trees, the estimation-maximization (EM) algorithm, maximum entropy estimation and estimation of discrete probabilities from sparse data for acoustic and language modeling. Weekly assignments and several programming projects. Co-listed as EN.520.666. Recommended Course Background: EN.601.220 and EN.553.310 or equivalent, expertise in C or C++ programming.
Instructor(s): S. Khudanpur.

EN.601.769. Events Semantics in Theory and Practice. 3.0 Credits.
This course explores selected topics in the nature of event representations from the perspective of cognitive science, computer science, linguistics, and philosophy. These fields have developed a rich array of scientific theories about the representation of events, and how humans make inferences about them – we investigate how (and if) such theories could be applied to current research topics and tasks in computational semantics such as inference from text, automated summarization, veridicality assessment, and so on. In addition to classic articles dealing with formal semantic theories, the course considers available machine-readable corpora, ontologies, and related resources that bear on event structure, such as WordNet, PropBank, FrameNet, etc.. The course is aimed to marry theory with practice: students with either a computational or linguistic background are encouraged to participate. [Applications]
Instructor(s): B. Van Durme; K. Rawlins.
EN.601.775. Statistical Machine Learning. 3.0 Credits.
This is a second graduate level course in machine learning. It will provide a formal and an in-depth coverage of topics at the interface of statistical theory and computational sciences. We will revisit popular machine learning algorithms and understand their performance in terms of the size of the data (sample complexity), memory needed (space complexity), as well as the overall computational runtime (computation or iteration complexity). We will cover topics including nonparametric methods, kernel methods, online learning and reinforcement learning, as well as introduce students to current topics in large-scale machine-learning and randomized projections. Topics will vary from year-to-year but the general focus would be on combining methodology with theoretical and computational foundations. [Analysis or Applications] Instructor(s): R. Arora.

EN.601.776. Machine Learning: Data to Models. 3.0 Credits.
Students in the class will be asked to do assignments in Matlab. Matlab is typically easy to pick up if one is already familiar with a different programming language. Students are expected to be mathematically mature. One should have taken at least an introductory course in probability theory and linear algebra. Though not required, exposure to optimization or machine learning is recommended. Proficiency in at least one programming language is expected. When in doubt, send the instructor a copy of your transcript to see if the class is appropriate for you. Also, sit through the first few sessions and first homework to get a sense of fit. Requisites include Intro Prob/Stat, Linear Algebra and Intro Machine Learning as well as strong background in s.
Instructor(s): S. Saria.

EN.601.777. Advanced Topics in Causal Inference. 3.0 Credits.
This course will cover advanced topics on all areas of causal inference, including learning causal effects, path-specific effects, and optimal policies from data featuring biases induced by missing data, confounders, selection, and measurement error, techniques for generalizing findings to different populations, complex probabilistic models relevant for causal inference applications, learning causal structure from data, and inference under interference and network effects. The course will feature a final project which would involve either an applied data analysis problem (with a causal inference flavor), a literature review, or theoretical work. [Analysis] Pre-requisite: EN.600.477/677 or permission.
Prerequisites: EN.600.477 OR EN.600.677
Instructor(s): I. Shpitser.

EN.601.779. Machine Learning: Advanced Topics. 3.0 Credits.
This course will focus on recent advances in machine learning. Topics will vary from year to year. The course will be project focused and involve presenting and discussing recent research papers.
Prerequisites: EN.600.475/EN.601.475 or EN.600.675/EN.601.675 or EN.600.775/EN.601.775 or EN.600.479/EN.601.479 or EN.600.679/EN.601.679 or EN.600.476/EN.601.476 or EN.600.676/EN.601.676 or permission.
Instructor(s): R. Arora.

EN.601.780. Unsupervised Learning: From Big Data to Low-Dimensional Representations. 3.0 Credits.
In the era of data deluge, the development of methods for discovering structure in high-dimensional data is becoming increasingly important. This course will cover state-of-the-art methods from algebraic geometry, sparse and low-rank representations, and statistical learning for modeling and clustering high-dimensional data. The first part of the course will cover methods for modeling data with a single low-dimensional subspace, such as PCA, Robust PCA, Kernel PCA, and manifold learning techniques. The second part of the course will cover methods for modeling data with multiple subspaces, such as algebraic, statistical, sparse and low-rank subspace clustering techniques. The third part of the course will cover applications of these methods in image processing, computer vision, and biomedical imaging. Requisites include Linear Algebra, Optimization, and prior exposure to Machine I.
Instructor(s): R. Vidal.

EN.601.782. Deep Learning for Image Understanding. 3.0 Credits.
This course discusses advanced topics on the recent progresses using deep learning, specifically deep convolutional neural networks in computer vision and medical image analysis. Topics will be selected from most recent papers from CVPR/ICCV/ArXiv/NIPS/MICCAI, with the core focus on object/scene recognition, object detection, domain transfer learning and computer-aided diagnosis. This course is targeted toward graduate students who are interested in mastering the understanding of the recent massive amount of literature and applying the skills to a course project (with lectures, paper reading, in-class presentation & discussion and a final research project). [Applications]
Prerequisites: Prereq: EN.600.461 OR EN.600.661
Instructor(s): L. Lu.

EN.601.783. Vision as Bayesian Inference. 3.0 Credits.
This is an advanced course on computer vision from a probabilistic and machine learning perspective. It covers techniques such as linear and non-linear filtering, geometry, energy function methods, markov random fields, conditional random fields, graphical models, probabilistic grammars, and deep neural networks. These are illustrated on a set of vision problems ranging from image segmentation, semantic segmentation, depth estimation, object recognition, object parsing, scene parsing, action recognition, and text captioning. [Analysis or Applications] Required course background: calculus, linear algebra (AS.110.201 or equiv.), probability and statistics (AS.553.311 or equiv.), and the ability to program in Python and C++.
In the era of data deluge, the development of methods for discovering structure in high-dimensional data is becoming increasingly important. This course will cover state-of-the-art methods from algebraic geometry, sparse and low-rank representations, and statistical learning for modeling and clustering high-dimensional data. The first part of the course will cover methods for modeling data with a single low-dimensional subspace, such as PCA, Robust PCA, Kernel PCA, and manifold learning techniques. The second part of the course will cover methods for modeling data with multiple subspaces, such as algebraic, statistical, sparse and low-rank subspace clustering techniques. The third part of the course will cover applications of these methods in image processing, computer vision, and biomedical imaging. Requisites include Linear Algebra, Optimization, and prior exposure to Machine I.
Instructor(s): R. Vidal.

EN.601.801. Computer Science Seminar. 1.0 Credit.
Required for all full-time CS PhD students. Recommended for MSE students.
Instructor(s): S. Smith.

EN.601.803. Masters Research. 3.0 - 10.0 Credits.
Permission required. Independent research for masters or pre-dissertation PhD students.
Instructor(s): Staff.

EN.601.805. Graduate Independent Study. 1.0 - 3.0 Credits.
Permission required. Individual study in an area of mutual interest to a graduate student and a faculty member in the department.
Instructor(s): Staff.
Instructor(s): B. Langmead.

**EN.601.807. Teaching Practicum. 1.0 Credit.**

PhD students will gain valuable teaching experience, working closely with their assigned faculty supervisor. Successful completion of this course fulfills the PhD teaching requirement. (Grad students) Permission req'd. Instructor(s): J. Selinski; M. Schatz; S. Smith.

**EN.601.808. Selected Topics in CS Education.**

This course will explore current issues and research in computer science education. Topics will be drawn from literature, news items, and participant experience. Current faculty and students with interests in academic careers are encouraged to attend.

Instructor(s): J. Selinski.

**EN.601.809. PhD Research. 3.0 - 20.0 Credits.**

Instructor(s): Staff.

**EN.601.817. Selected Topics in Systems Research. 1.0 Credit.**

This course covers latest advances in the research of computer systems including operating systems, distributed system, mobile and cloud computing. Students will read and discuss recent research papers in top systems conferences. Each week, one student will present the paper and lead the discussion for the week. The focus topics covered in the papers vary semester to semester. Example topics include fault-tolerance, reliability, verification, energy efficiency, and virtualization.

Instructor(s): P. Huang.

**EN.601.826. Selected Topics in Programming Languages. 1.0 Credit.**

This seminar course covers recent developments in the foundations of programming language design and implementation. Topics covered include type theory, process algebra, higher-order program analysis, and constraint systems. Students will be expected to present papers orally.

Instructor(s): S. Smith.

**EN.601.831. CS Theory Seminar. 1.0 Credit.**

Seminar series in theoretical computer science. Topics include algorithms, complexity theory, and related areas of TCS. Speakers will be a mix of internal and external researchers, mostly presenting recently published research papers.

Instructor(s): M. Dinitz; X. Li.

**EN.601.833. Seminar in Algorithms. 1.0 Credit.**

This course will explore algorithms and theoretical computer science with a focus on algorithms for massive data. Examples of topics include streaming algorithms, approximation algorithms, online algorithms. Students will be encouraged to select a paper and lead a discussion. External speakers will be invited to present current work as well. This course is a good opportunity for motivated students to learn modern algorithmic methods. Recommended Course Background: EN.601.433 or equivalent.

Instructor(s): V. Braverman
Area: Engineering.

**EN.601.845. Selected Topics in Applied Cryptography. 1.0 Credit.**

In this course students will read, discuss and present current research papers in applied cryptography. Topic coverage will vary each semester. Instructor approval required.

Instructor(s): M. Green.

**EN.601.850. Selected Topics in Computational Genomics. 1.0 Credit.**

This course will survey current areas where computer science approaches have been applied to genomics research. Chiefly, the course focuses on DNA sequencing data analysis, including sequence alignment, de novo assembly, error correction, and DNA data compression. Subject matter will be partially guided by student interests. Students will present papers orally.

Instructor(s): B. Langmead.

**EN.601.856. Seminar: Medical Image Analysis. 1.0 Credit.**

This weekly seminar will focus on research issues in medical image analysis, including image segmentation, registration, statistical modeling, and applications. It will also include selected topics relating to medical image acquisition, especially where they relate to analysis. The purpose of the course is to provide the participants with a thorough background in current research in these areas, as well as to promote greater awareness and interaction between multiple research groups within the University. The format of the course is informal. Students will read selected papers. All students will be assumed to have read these papers by the time the paper is scheduled for discussion. But individual students will be assigned on a rotating basis to lead the discussion on particular papers or sections of papers. Co-listed with En.520.746.

Instructor(s): J. Prince; R. Taylor.

**EN.601.857. Selected Topics in Computer Graphics. 1.0 Credit.**

In this course we will review current research in computer graphics. We will meet for an hour once a week and one of the participants will lead the discussion for the week.

Instructor(s): M. Kazhdan.

**EN.601.865. Selected Topics in Natural Language Processing. 1.0 Credit.**

A reading group exploring important current research in the field and potentially relevant material from related fields. Enrolled students are expected to present papers and lead discussion.

Prerequisites: EN.600.465 OR EN.601.665 or permission of instructor

Instructor(s): J. Eisner.

**EN.601.866. Selected Topics in Computational Semantics. 1.0 Credit.**

This weekly reading group will review current research and survey articles on the topics of computational semantics, statistical machine translation, and natural language generation. Enrolled students will present papers and lead discussions.

Instructor(s): B. Van Durme.

**EN.601.868. Selected Topics in Machine Translation. 1.0 Credit.**

Students in this course will review, present, and discuss current research in machine translation. Permission of instructor.

Instructor(s): P. Koehn.

**EN.601.875. Selected Topics in Machine Learning. 1.0 Credit.**

This seminar is recommended for all students interested in data intensive computing research areas (e.g., machine learning, computer vision, natural language processing, speech, computational social science). The meeting format is participatory. Papers that discuss best practices and the state-of-the-art across application areas of machine learning and data intensive computing will be read. Student volunteers lead individual meetings. Faculty and external speakers present from time-to-time.

Recommended Course Background: machine learning or permission of the instructor.

Instructor(s): R. Arora.

**Cross Listed Courses**

**Cognitive Science**

**AS.050.375. Probabilistic Models of the Visual Cortex. 3.0 Credits.**

The course gives an introduction to computational models of the mammalian visual cortex. It covers topics in low-, mid-, and high-level vision. It briefly discusses the relevant evidence from anatomy, electrophysiology, imaging (e.g., fMRI), and psychophysics. It concentrates on mathematical modeling of these phenomena taking into account recent progress in probabilistic models of computer vision and developments in machine learning, such as deep networks.

Prerequisites: AS.110.106 OR AS.110.108

Instructor(s): A. Yuille

Area: Quantitative and Mathematical Sciences.
The course gives an introduction to computational models of the mammalian visual cortex. It covers topics in low-, mid-, and high-level vision. It briefly discusses the relevant evidence from anatomy, electrophysiology, imaging (e.g., fMRI), and psychophysics. It concentrates on mathematical modelling of these phenomena taking into account recent progress in probabilistic models of computer vision and developments in machine learning, such as deep networks. Also offered as AS.050.375. Co-listed with Computer Science as EN.601.485.
Instructor(s): A. Yuille.

AS.050.814. Research Seminar in Computer Vision.
This course covers advanced topics in computational vision. It discusses and reviews recent progress and technical advances in visual topics such as object recognition, scene understanding, and image parsing.
Instructor(s): A. Yuille.

Physics Astronomy
AS.171.205. Introduction to Practical Data Science: Beautiful Data. 3.0 Credits.
The class will provide an overview of data science, with an introduction to basic statistical principles, databases, fundamentals of algorithms and data structures, followed by practical problems in data analytics. Recommended Course Background: Familiarity with principles of computing.
Instructor(s): S. Szalay
Area: Natural Sciences, Quantitative and Mathematical Sciences.

Psychological Brain Sciences
AS.200.313. Models of Mind and Brain. 3.0 Credits.
This is a seminar surveying computational approaches to understanding mental and neural processes, including sensory and conceptual representation, categorization, learning and memory. The course will also develop familiarity with computational tools such as numerical simulation, linear transformation and data visualization. Enrollment limited to Juniors and Seniors. Recommended Course Background: AS.110.106 / Calculus I OR AS.110.108 Calculus I, AS.050.101 / Cognition OR AS.200.211 / Sensation & Perception OR AS.080.105 / Introduction to Neuroscience OR other introductory coursework in cognitive & neural sciences.
Instructor(s): C. Honey
Area: Quantitative and Mathematical Sciences, Social and Behavioral Sciences.

General Engineering
EN.500.112. Gateway Computing. 3.0 Credits.
This course introduces fundamental programming concepts and techniques, and is intended for all who plan to develop computational artifacts or intelligently deploy computational tools in their studies and careers. Topics covered include the design and implementation of algorithms using variables, control structures, arrays, functions, files, testing, debugging, and structured program design. Elements of object-oriented programming, algorithmic efficiency and data visualization are also introduced. Students deply programming to develop working solutions that address problems in engineering, science and other areas of contemporary interest that vary from section to section. Course homework involves significant programming. Attendance and participation in class sessions are expected.
Instructor(s): I. Sekyonda; J. Selinski; M. Darvish Darab
Area: Engineering, Natural Sciences.

EN.500.745. Seminar in Computational Sensing and Robotics. 1.0 Credit.
Seminar series in robotics. Topics include: Medical robotics, including computer-integrated surgical systems and image-guided intervention. Sensor based robotics, including computer vision and biomedical image analysis. Algorithmic robotics, robot control and machine learning. Autonomous robotics for monitoring, exploration and manipulation with applications in home, environmental (land, sea, space), and defense areas. Biorobotics and neuromechanics, including devices, algorithms and approaches to robotics inspired by principles in biomechanics and neuroscience. Human-machine systems, including haptic and visual feedback, human perception, cognition and decision making, and human-machine collaborative systems. Cross-listed Mechanical Engineering, Computer Science, Electrical and Computer Engineering, and Biomedical Engineering.
Instructor(s): L. Whitcomb; P. Kazanzides.

Electrical Computer Engineering
EN.520.434. Modern Biomedical Imaging Instrumentation and Techniques. 3.0 Credits.
An intermediate biomedical imaging course covering modern biomedical imaging instrumentation and techniques as applied to diagnostic radiology and other biomedical applications. It includes recent advances in various biomedical imaging modalities, multi-modality imaging and molecular imaging. The course is team taught by experts in the respective fields and provides a broad based knowledge of modern biomedical imaging to prepare students for graduate studies and research in biomedical imaging. Also, the course will offer tours and practical experience with modern biomedical imaging equipments in clinical and research settings. Co-listed with EN.580.473
Prerequisites: Students may not have taken EN.520.634
Instructor(s): B. Tsui.

EN.520.447. Information Theory. 3.0 Credits.
This course will address some basic scientific questions about systems that store or communicate information. Mathematical models will be developed for (1) the process of error-free data compression leading to the notion of entropy, (2) data (e.g. image) compression with slightly degraded reproduction leading to rate-distortion theory and (3) error-free communication of information over noisy channels leading to the notion of channel capacity. It will be shown how these quantitative measures of information have fundamental connections with statistical physics (thermodynamics), computer science (string complexity), economics (optimal portfolios), probability theory (large deviations), and statistics (Fisher information, hypothesis testing).
Instructor(s): S. Khudanpur
Area: Engineering, Quantitative and Mathematical Sciences.

EN.520.701. Current Topics in Language and Speech Processing. 1.0 Credit.
This biweekly seminar will cover a broad range of current research topics in human language technology, including automatic speech recognition, natural language processing and machine translation. The Tuesday seminars will feature distinguished invited speakers, while the Friday seminars will be given by participating students. A minimum of 75% attendance and active participation will be required to earn a passing grade. Grading will be S/U.
Instructor(s): J. Trmal.
EN.520.702. Current Topics in Language and Speech Processing. 1.0 Credit.
This biweekly seminar will cover a broad range of current research topics in human language technology, including automatic speech recognition, natural language processing and machine translation. The Tuesday seminars will feature distinguished invited speakers, while the Friday seminars will be given by participating students. A minimum of 75% attendance and active participation will be required to earn a passing grade. Cross-listed with Computer Science. Grading will be S/U.
Instructor(s): J. Vogelstein
Area: Engineering.

Mechanical Engineering
EN.530.707. Robot System Programming. 4.0 Credits.
This course seeks to introduce students to open-source software tools that are available today for building complex experimental and fieldable robotic systems. The course is grouped into sections, each of which building on the previous in increasing complexity and specificity: tools and frameworks supporting robotics research, robotics-specific software frameworks, integrating complete robotic systems, and culminates with an independent project of the student's own design using small mobile robots or other robots in the lab. Students will need to provide a computer (with at least a few GB of memory and a several tens of GB of disc space) running Ubuntu (https://www.ubuntu.com or one of its variants such as Xubuntu) and ROS (http://ros.org/). Students should have an understanding of intermediate programming in C/C++ (including data structures and object-oriented programming). Familiarity with Linux programming. Familiarity with software version control systems such as Git, and linear algebra. Students should see the course homepage http://dscl.lcsr.jhu.edu/ME530707_2018 for more information and to get started with the course. Required Course Prerequisite/Corequisite: EN.530.646 and EN.600.436. Registration only by permission of the instructor. Please contact Prof. Louis Whitcomb at llw@jhu.edu. Please put '530.707 Robot System Programming' in the subject line of your email.
Instructor(s): L. Whitcomb.

Biomedical Engineering
EN.580.468. The Art of Data Science. 3.0 Credits.
In this course, we will cover the fundamentals of doing data science research, explaining "best practices" for each step, that collectively comprise an upward spiral. These steps include: (i) asking an interesting question, (ii) determining the degree to which the answer is known, (iii) assessing there currently exists data to likely obtain a satisfactory answer, (iv) exploring the data set, (v) cleaning up the dataset, (vi) formalizing a statistical inquiry, (vii) positing a statistical model which we hope will yield satisfactory answers, (viii) devising a test to assess the answer, (ix) building an estimator to assess the model, (x) checking the model, (xi) reporting the results, (xii) suggesting the next experiment to perform or question to answer to further enhance the model. Note that this course will largely be project based; each student will be expected to complete each of the above steps on some real data of interest to the student. Lectures will be minimal, giving introductory explanations one day, hopefully only part of the time. The rest of the time, we will work independently or in small groups to complete the weekly portion of the overall project. Please come ready to do science! If you don't have questions that you want answered, you can work in small groups, but each student will need to write the code and reports on their own. Recommended course background: No courses are formally required, though students will need to write numerical code (in R, Python, or Julia), and make reports using LaTeX, knitr, or Jupyter notebooks or similar.
Instructor(s): J. Vogelstein
Area: Engineering.

EN.580.473. Modern Biomedical Imaging Instrumentation and Techniques. 3.0 Credits.
An intermediate biomedical imaging course covering modern biomedical imaging instrumentation and techniques as applied to diagnostic radiology and other biomedical applications. It includes recent advances in various biomedical imaging modalities, multi-modality imaging and molecular imaging. The course is team taught by experts in the respective fields and provides a broad based knowledge of modern biomedical imaging to prepare students for graduate studies and research in biomedical imaging. Also, the course will offer tours and practical experience with modern biomedical imaging equipment in clinical and research settings. Co-listed with EN.520.434 Recommended course background: EN.520.432 or EN.580.472
Prerequisites: Students may not have taken EN.580.773.
Instructor(s): B. Tsui
Area: Engineering, Natural Sciences.

EN.580.668. The Art of Data Science. 3.0 Credits.
In this course, we will cover the fundamentals of doing data science research, explaining "best practices" for each step, that collectively comprise an upward spiral. These steps include: (i) asking an interesting question, (ii) determining the degree to which the answer is known, (iii) assessing there currently exists data to likely obtain a satisfactory answer, (iv) exploring the data set, (v) cleaning up the dataset, (vi) formalizing a statistical inquiry, (vii) positing a statistical model which we hope will yield satisfactory answers, (viii) devising a test to assess the answer, (ix) building an estimator to assess the model, (x) checking the model, (xi) reporting the results, (xii) suggesting the next experiment to perform or question to answer to further enhance the model. Note that this course will largely be project based; each student will be expected to complete each of the above steps on some real data of interest to the student. Lectures will be minimal, giving introductory explanations one day, hopefully only part of the time. The rest of the time, we will work independently or in small groups to complete the weekly portion of the overall project. Please come ready to do science! If you don't have questions that you want answered, you can work in small groups, but each student will need to write the code and reports on their own. Recommended course background: No courses are formally required, though students will need to write numerical code (in R, Python, or Julia), and make reports using LaTeX, knitr, or Jupyter notebooks or similar.
Instructor(s): J. Vogelstein
Area: Engineering.

EN.580.688. Foundations of Computational Biology & Bioinformatics II. 3.0 Credits.
This course will introduce probabilistic modeling and information theory applied to biological sequence analysis, focusing on statistical models of protein families, alignment algorithms, and models of evolution. Topics will include probability theory, score matrices, hidden Markov models, maximum likelihood, expectation maximization and dynamic programming algorithms. Homework assignments will require programming in Python. Recommended Course Background: Math through linear algebra and differential equations, EN.580.221 or equivalent, EN.601.225 or equivalent.
Instructor(s): R. Karchin.
EN.580.689. Computational Personal Genomics. 3.0 Credits.
What can we learn from the genome sequence of an individual? Genomic technology now makes it possible to generate huge amounts of DNA sequence data for a single individual at a relatively low cost. To make sense of this data, we need to employ sophisticated computational methods to identify genetic variations that influence an individual’s health. In this course, we will first review the state of the art in sequencing technology, and discuss how this technology is being applied to study human biology and disease. We will then explore the computational methods used to turn raw sequence data into knowledge. Topics will include genetic variant detection; discovery of chromosomal rearrangements and fusions; methods to measure gene expression from RNA; and measurements of the microbiome living inside our bodies. Recommended Course Background: EN.601.447/639, EN.600.363/463, EN.600.688, EN.580.688 (any one is sufficient), or permission of the instructor. Course is also open to undergraduate students.
Instructor(s): S. Salzberg
Area: Engineering.

EN.580.694. Statistical Connectomics. 3.0 Credits.
This course will cover the basics of an exciting emerging field of statistical connectomics (aka, brain-graphs). It is so new, that we are going to make some of it up in this class! The first week will be introductory lectures that I give. The rest of the semester will be run like a seminar; each week will focus on a different topic. On Tuesdays we will hear about a statistical method that operates on graphs, and on Thursdays we will read about some neuroscience data upon which one could apply these techniques. The final project will consist of implementing a statistical method devised for graphs on a brain-graph problem. Recommended background: coursework in probability, linear algebra, and numerical programming (eg, R, Python, Matlab).
Instructor(s): J. Vogelstein
Area: Engineering.

EN.580.745. Mathematics of Deep Learning. 1.5 Credits.
The past few years have seen a dramatic increase in the performance of recognition systems thanks to the introduction of deep networks for representation learning. However, the mathematical reasons for this success remain elusive. For example, a key issue is that the training problem is nonconvex, hence optimization algorithms are not guaranteed to return a global minima. Another key issue is that while the size of deep networks is very large relative to the number of training examples, deep networks appear to generalize very well to unseen examples and new tasks. This course will overview recent work on the theory of deep learning that aims to understand the interplay between architecture design, regularization, generalization, and optimality properties of deep networks.
Instructor(s): R. Vidal.