Electrical & Computer Engineering

2019-2020 M.S. Catalog/Handbook

CMKL University

 This handbook is posted to CMKL web page prior to the start of each academic year and is updated as needed. This handbook is effective August 1, 2019 through July 31, 2020.

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WELCOME TO ELECTRICAL AND COMPUTER ENGINEERING

Welcome to Electrical and Computer Engineering at CMKL University and Carnegie Mellon University Thailand. Our institution was established as a collaboration between Carnegie Mellon University and King Mongkut's Institute of Technology Ladkrabang (KMITL). Our education and research programs offer a unique experience for our students who will be able to benefit from best-in-class Carnegie Mellon education. In addition, you will also be well-equipped with industrial experience by participating in real-world engineering research and projects that Carnegie Mellon and CMKL University has been working with our partners and our communities.

Our program brings about the best of engineering and entrepreneurial minds to tackle challenges that will drive future development of Thailand and Southeast Asia. Our research and teaching cover a spectrum of technical areas including software systems, architecture, artificial intelligence, machine learning, and distributed systems, among others. With our hands-on approach, we believe our graduates will have the required technical strength, professional excellence and entrepreneurial mindset that will transform the industries while making impact to our ever-changing society.

I hope you will browse through this catalog/handbook to learn more about our programs. Please feel free to reach out if you have any questions or comments.

Sincerely,

Akkarit Sangpetch
Carnegie Mellon-KMITL Program Director
CMKL University

BRIEF OVERVIEW OF PROGRAM

Carnegie Mellon ECE Program has been a leader in both research and education for years; it is known for its innovative qualities, boldness of ideas, and unbridled enthusiasm.

We value scientific truth, creativity, quality, innovation, and engineering solutions, all within a diverse and inclusive community guided by respect and joy of doing. Our core values form the foundation for what we do; we hold them to be intrinsically true. We believe in solving problems that have large societal impact; we also believe that to be successful, we must work within an environment of enthusiasm and openness, respect and integrity, and freedom to express and explore a variety of ideas.

Vision

To be a creative driving force within the university and worldwide of highest scholarly and entrepreneurial quality.

Mission and Objectives

To inspire, educate, and produce electrical and computer engineers capable of tackling fundamental scientific problems and important societal challenges, and to do so with the highest commitment to quality, integrity, and respect for others.

We aim to be the best at what we do, to apply all our skills and knowledge to execute our vision. We educate young people to become engineers sought after by industry and academia alike; we do so in an environment imbued by enthusiasm and love for what we do, with respect and willingness to listen to each other, with freedom to express our ideas and look at challenges from different points of view. We strive to be the program of choice for those who are willing to step off the beaten path, for the visionaries and dreamers.

INTRODUCTION

Degrees Offered

Graduates of the program will earn dual-degrees from Carnegie Mellon University and CMKL University. Students in M.S. in ECE program are provided with a thorough background in the fundamentals of electrical or computer engineering, as well as the opportunity for in-depth specialization in some particular aspect of these fields. Upon enrollment in the program, students are given the opportunity, with the help of an academic advisor and faculty mentor, to choose an educational program that is consistent with their background and is best suited to their own academic goals.

Graduate Student Handbook

This catalog/handbook is intended to set guidelines and expectations for new and current Master's students in Electrical and Computer Engineering at CMKL University. This catalog/handbook is not exhaustive and is subject to revision at any time by the program.

It is the responsibility of each student to read and understand the contents of this catalog/handbook.
This catalog/handbook, along with any revisions, will be posted and announced annually to the university website.

CMKL UNIVERSITY STATEMENT OF ASSURANCE

CMKL University does not discriminate in admission, employment, or administration of its programs or activities on the basis of race, color, national origin, sex, handicap or disability, age, sexual orientation, gender identity, religion, creed, ancestry, belief, veteran status, or genetic information. Furthermore, CMKL University does not discriminate and is required not to discriminate in violation of national laws or executive orders.

Inquiries concerning the application of and compliance with this statement should be directed to the vice president for campus affairs, CMKL University,1 Soi Chalongkrung 1, Ladkrabang, Bangkok 10520, Thailand. Obtain general information about CMKL University by calling +66 65 878 5000.

FACULTY INFORMATION

University Personnel

Throughout your time in the M.S. program, you will encounter a variety of faculty and staff who will help you on your way to completing your degree. You may view a list of faculty and a list of staff affiliated with ECE online. Below is a list of faculty and staff whom you are likely to encounter during your time in the M.S. program.

- Chair of Executive Committee: Prof. Dr. Suchatvee Suwansawat
- President of CMKL University: Dr. Supan Tungjitkusolmun
- Vice President of CMKL University: Dr. Orathai Sangpetch
- Program Director, Carnegie Mellon University Thailand: Professor Hyong Kim
- Program Director, Carnegie Mellon – KMITL: Dr. Akkarit Sangpetch

Course Instructors

Our courses are taught by world-renowned educators and researchers.

- Anupam Datta
Professor, ECE, Carnegie Mellon University
Adjunct Faculty, CMKL University
Ph.D., Computer Science, Stanford University

- Hyong Kim
Drew D. Perkins Professor, ECE, Carnegie Mellon University
Adjunct Faculty, CMKL University
Ph.D., Electrical Engineering, University of Toronto

- José Moura
Phillip L. and Marsha Dowd University Professor, ECE, Carnegie Mellon University
Adjunct Faculty, CMKL University
DSc, Electrical Engineering and Computer Science, Massachusetts Institute of Technology

- Raj Rajkumar
  George Westinghouse Professor, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Anthony Rowe
  Professor, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Marios Savvides
  Bossa Nova Robotics Professor of Artificial Intelligence, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Suchatvee Suwansawat
  Professor, King Mongkut's Institute of Technology Ladkrabang
  Special Faculty, CMKL University
  Ph.D., Civil and Environmental Engineering, Massachusetts Institute of Technology

- Soummya Kar
  Associate Professor, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Hae Young Noh
  Associate Professor, Civil and Environmental Engineering, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Civil and Environmental Engineering, Stanford University

- Sooksan Panichpapiboon
  Associate Professor, King Mongkut's Institute of Technology Ladkrabang
  Special Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Osman Yağan
  Associate Research Professor, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, University of Maryland

- Pei Zhang
  Associate Research Professor, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Computer Engineering, Princeton University

- Javad Mohammadi
  Special Faculty, ECE, Carnegie Mellon University
  Adjunct Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Charnchai Pluempittiwiriyawej
  Assistant Professor, Chulalongkorn University
  Special Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Akkarit Sangpetch
  Adjunct Faculty, ECE, Carnegie Mellon University
  Assistant Professor, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Orathai Sangpetch
  Assistant Professor, King Mongkut's Institute of Technology Ladkrabang
  Adjunct Faculty, ECE, Carnegie Mellon University
  Assistant Professor, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Supan Tungjitkusolmun
  Assistant Professor, King Mongkut's Institute of Technology Ladkrabang
  Assistant Professor, CMKL University
  Ph.D., Electrical Engineering, University of Wisconsin

- Rachata Aussavarungnirun
  Lecturer, TGGS, King Mongkut's University of Technology North Bangkok
  Special Faculty, CMKL University
  Ph.D., Electrical and Computer Engineering, Carnegie Mellon University

- Suporn Pongnumkul
  Senior Researcher, National Electronics and Computer Technology Center
  Special Faculty, CMKL University
  Ph.D., Computer Science and Engineering, University of Washington

- Pongsin Poosankam
  Data Innovation, Krungthai Bank
  Special Faculty, Special Faculty, CMKL University
  Ph.D., Computer Science, Carnegie Mellon University

PRE-MATRICULATION

Admissions Policies

Admission criteria for the ECE/Thailand M.S. Program are identical to current ECE M.S. admission standards. For information about ECE's admission policies, including application requirements, application deadlines, and a link to apply, please visit these webpages:
https://www.cmkl.ac.th/cmkm
https://www.ece.cmu.edu/admissions/graduate-application-deadlines.html
https://www.ece.cmu.edu/admissions/graduate-faq.html

TOEFL Requirements and Language Proficiency

Admission to CMKL University graduate programs requires demonstration of completed, relevant undergraduate degree programs, as demonstrated by an original transcript from the degreegranting institution during the admission process.

The TOEFL test is required of all international applicants whose native language is not English. Native language is defined as first language, or language spoken from birth. The TOEFL is not required if the applicant has graduated from a U.S. university, or if the applicant is a CMU student or alum.

The Admissions Committee prefers the TOEFL to the IELTS. While you are encouraged to take the TOEFL, if you are unable to do so, we look for a minimum overall score of 7 on the IELTS, with minimum sub-scores of Reading-6.5, Listening-6.5, Speaking-6, and Writing-6.

ECE generally does not allow admission deferrals because admission decisions are based on the current applicant pool. Therefore, students are admitted into the program for a particular semester only. If a student wishes to attend in a future semester, the student must reapply to the ECE program.

Final Undergraduate Transcripts

Applicants admitted to any ECE program must submit final official transcripts, properly sealed, upon completion of their undergraduate program from the institution conferring their degree as a condition of enrollment at CMKL University. Certificates of graduation and/or degree certificates should also be submitted if provided by the institution. Failure to provide such documents that confirm the completion of undergraduate requirements by the end of the first semester of study at CMKL University may prevent the M.S. degree from being certified.

ENROLLMENT AND REGISTRATION

Overview

After matriculating into ECE, students should create an academic plan and register for courses. Students should actively engage in their process by reviewing degree requirements on the website, connecting with their academic advisor, and conferring with a faculty mentor. Once plans are firm, students can proceed by accessing Student Information Online (SIO).

SIO is an important online tool to use during the registration process, as well as throughout graduate school. Students can access SIO with their Student ID.
Within SIO, there is a Course Planning module that allows students to view and modify their proposed schedule before registering for courses. Once a schedule is developed, it is the student's responsibility to register for courses using their SIO. Students must be registered for every course that they plan to take for the semester, even if it is not taken for credit (e.g., audited courses).
After the first semester, a student's assigned registration time is determined by the number of completed units and cannot be changed. If a student's tuition balance and/or fees are greater than THB 0.00, the student will not be able to register until the balance is cleared.

Degree Progress and Planning Student Responsibility

It is the sole responsibility of the student to manage the academic progression of their program. Students are expected to ensure that they are taking the necessary prerequisites and courses to complete degree requirements on time. Students have the ability to add courses, drop courses, and select units for variable unit courses through SIO. It is the students' responsibility to be aware of all academic deadlines, including the add deadline, the drop deadline, the pass/fail deadline, and the audit deadline. Academic deadline information can be found within Academic Calendar. If a student is not progressing as expected, they are expected to seek advice and counsel from their academic advisor. If the student is concerned that they may be unable to complete degree requirements, they should contact their academic advisor for assistance.

Degree Requirements Timeframe

The duration of the ECE program is **four full-time semesters**. In order to have full-time status, students must enroll in at least 36 units each semester. In order to complete program requirements, students may need to enroll in more than 36 units per semester. The maximum number of units allowed in a semester is 48 units. Students are responsible for completing their enrollment each semester. Students who are not enrolled by the tenth day of class will be withdrawn from the university.

Students must be physically present and attend class at the start of the semester. If extenuating circumstances exist that prevent a student from attending class, a student must notify the academic advisor and instructors immediately. Not attending class from the start of the semester will have a detrimental effect on a student's progress in the program. ECE will make an effort to verify all students have arrived to begin their program and will consider a student as "withdrawn from the university" if he or she is not here by the tenth day of class as defined by the academic calendar.

International students who started the first year in Thailand, will be given Non-immigrant (ED) visa during the academic year which can be extended to a maximum of 12 months.

International students who started the first year in Pittsburg will be given a 16 month I-20 or DS-2019. International students must consult with CMU's Office of International Education (OIE) for questions on extension of their visa documents or if they complete their degree requirements in less than three semesters. Please see details and relevant forms on OIE's website under Maintaining Legal Status.

Full time Requirements

The M.S. degree program is a full-time program in which students complete **four full-time (36 units) semesters**. In addition to the regular course, the student must also enroll in M.S. graduate projects or research course and participate in ongoing university-partner project during their time in Thailand.

In extenuating circumstances, students may find that they may need to take a reduced course load. Extenuating circumstances that will be considered include medical reasons, initial academic difficulty due to problems with English language, or being placed in an improper course level. These students must submit an Authorization for a Reduced Course Load form to their academic advisor.

Statute of Limitations

ECE adheres to CMU CIT's policy on M.S. completion timelines. The CIT policy is as follows: "All units required for a master's degree in the College of Engineering, whether earned in residence or transferred from another institution, must be recorded on the transcript within six years of the date on which the student enrolled in the program." Former ECE students who did not fulfill graduation requirements and would like to return to complete a degree should refer to the statute of limitations in CIT's graduate student policies for more information.

Degree Timeline and Campus Location

The ECE/Thailand M.S. is a two-year program with one year on the Carnegie Mellon campus and one year on the CMKL campus in Thailand.

Students enrolled in the ECE master's program at CMKL University are subject to change residence to another campus (Thailand/Pittsburg) after completing one semester of full-time study. Eligibility is determined by the details included in the student's admission offer and is explicitly stated in the admission offer letter.

Courses Outside of Degree Requirements

Courses that do not satisfy degree requirements include StuCo courses (98), Physical Education course (69), audited courses, and pass/fail courses. Similar to courses taken for degree requirements, students must register for these other courses, and the units will count towards their course load for the semester. For a complete list of course restrictions, see the ECE website: https://www.ece.cmu.edu/academics/ms-ece/requirements.html.

Double Counting Courses

ECE follows CMU CIT Policy on double counting courses. Students are required to notify the Graduate Affairs Office prior to declaring a degree outside of ECE as this may have repercussions for your units and coursework to date.

The same course taken two separate times will not count towards the ECE M.S. If a student takes the same course twice, the course with the higher grade will be counted towards the ECE M.S. course requirements.

Maximum Units Allowed

No more than 168 units maximum should be taken while pursuing your degree. These units include courses taken for audit, pass/no pass, and withdrawal. Please refer to CMU CIT policy on M.S. degree units for additional information.
If it becomes clear that a student will exceed the maximum units and not be able to maintain the required 3.0 average, the student may be dropped from the M.S. ECE.

Maximum Units Allowed Outside CIT

Effective fall 2019, M.S. ECE students at all campuses may take no more than 48 units outside the College of Engineering, even if a student has already completed all M.S. ECE requirements. Please see the M.S. ECE Requirements pages on our website for details on which students this rule affects.

M.S. Concentrations

Four concentrations are available for M.S. students to choose from, allowing for focused study in a specific area of electrical and computer engineering. Students completing one or more of these concentrations should refer to their degree as a Master of Science in Electrical and Computer Engineering with a concentration in <name of concentration>. Students satisfying the requirements for more than one concentration may acknowledge all for which they fulfill the requirements.

- All concentrations require a minimum of four ECE courses, distributed across categories as described below. M.S. ECE students are not required to complete a concentration in order to graduate.
- Cyber-Physical Systems (CPS)
- Computer Security (CSec)
- Data and Network Science (DNS)
- Wireless Systems (WS)

For a list of approved courses within each concentration and faculty points of contact for each concentration, visit the website: https://www.ece.cmu.edu/academics/ms- ece/concentrations.html

Retaking Courses

If students do not pass a course, they should take a different course that will fulfill the requirement. Retaking a course is not recommended. Students may retake a prerequisite course in which they did not receive the minimum grade required.
All grades are recorded on the transcript and factored into the cumulative QPA; however, only the best 97 units that fulfill degree requirements are factored into the required 3.0 graduation QPA.

Auditing Courses

Auditing a course is being present in a classroom without receiving academic credit or a letter grade. An audited course will appear on a student's transcript. Students who are present in a classroom and who are not receiving academic credit or a letter grade must audit the class to continue to attend regularly.

A student who wants to audit a course is required to: Register for the course in SIO.
Obtain permission from the instructor and ask the instructor to sign the course audit approval form.
Submit the form to their academic advisor for approval.
If approved, the academic advisor will send the form for processing.

Once a course audit approval form is submitted, a letter grade ('A'-'R') will not be assigned for the course and the declaration cannot be reversed. You can find the deadline for submitting this form on the Academic Calendar. After the deadline, students will not be able to request the option to audit a course.

The extent of the student's participation must be arranged and approved by the course instructor. Typically, auditors are expected to attend class as though they are regular class members. Those who do not attend the class regularly or prepare themselves for class will receive a blank grade. Otherwise, the student receives the grade 'O', indicating an audit.

The units of audited courses count toward the maximum course load units, but do not count toward the degree requirements. Any student may audit a course. For billing, an audited course is considered the same as the traditional courses under the tuition charges. If a part-time student audits a course, he/she will be charged part-time tuition based on the per-unit tuition rate for the course.

Pass/No Pass Courses

Students who want to take a course pass/fail are required to register for the course and submit the pass/no pass approval form to their academic advisor for approval. If approved, the academic advisor will send the form for processing.

Once a Pass/Fail Audit Approval form is submitted, a letter grade ('A'-'R') will not be assigned for the course and the declaration cannot be reversed. Passing work (letter grade 'A'- 'C-') is recorded as 'P' (passing grade) or 'S' (satisfactory) on the student's academic record, with both grades meaning the same; work with a grade at or lower than 'D+' will not receive credit and will be recorded as 'N' (not passing grade) on the student's academic record. No quality points will be assigned to 'P'/'S' or 'N' grades; the units of 'P'/'S' or 'N' grades will not be factored into the student's QPA.

The units of pass/no pass courses count toward the maximum course load units, but do not count toward the degree requirements. You can find the deadline for submitting this form on the Academic Calendar. After the deadline, students will not be able to request the option to pass/fail a course.

Any student may take a course pass/fail. For billing, the pass/fail course is considered the same as the traditional courses under the tuition charges. If a part-time student takes a course pass/fail, he/she will be charged part-time tuition based on the per-unit tuition rate for the course.

Petition Process

Petitions to the GSC may include program or transfers, increase in units, course substitutions, and any other changes that are outside of the policies stated in the student handbook. Petitions are approved by the GSC. Students are advised to discuss their petitions with their academic advisors. The petitions process is as follows:

- Student completes the appropriate petition form (M.S. ECE GSC Petition form) and submits it to their academic advisor in the Graduate Affairs Office no later than 5pm ET on the Friday before the GSC meeting.
- The academic advisor presents the petition to the GSC.
- Students are notified of the outcome of their petition via an email from the M.S. Academic Advisor after the GSC has met. Generally, all GSC decisions are final. Due to time constraints, some petitions may be tabled until the following GSC meeting. When this occurs, students will be notified via email.
- The academic advisor saves a finalized version of the petition in the student's academic file.

Course Transfer Request Policy and Process

Only one graduate-level course, or the equivalent of 12 units, can be transferred from another university as credit toward the M.S. degree. As a guideline, three-credit courses from other universities equate to 9-unit CMU courses; a four-credit course equates to a 12-unit CMU course.

The course being transferred in must:

- Fulfill an ECE degree course requirement and is equivalent to a CMU course
- Be considered a graduate level course at the university where it was taken (unless requesting transfer credit for the one allowed undergraduate course)
- Have not been used to fulfill requirements for any previously earned degree

A grade of ‘B’ or better must be earned for the course to be transferred. The transfer credits will appear on the student’s transcript and will not be factored into the QPA.

Transfer credit is not granted prior to admission and must be approved by the Graduate Studies Committee and CIT Dean’s Office. Courses can only be requested for transfer after the student has successfully completed 36 units of coursework at Carnegie Mellon. After matriculating to Carnegie Mellon, ECE students should consult with their academic advisor before taking a course at another university.

Transfer courses will be reviewed for academic rigor and alignment with courses offered in ECE. The course description and syllabus, learning outcomes, delivery mode, and institutional accreditation will be considered when evaluating the course for transfer.
The process for requesting to transfer a course is as follows:

- Meet with academic advisor to discuss the course transfer
- Complete and collect the following mandatory documents:
  - Appropriate petition form (M.S. ECE GSC Petition form)
  - Official transcript from previous institution
  - Detailed course description/syllabus (should include grading scale, assignments required, mandatory books, and time required in class) of the course you wish to transfer
  - Letter from the previous institution’s registrar or academic advisor stating the course intended for transfer was not used towards a degree
  - E-mail endorsement from the instructor of the CMU course you believe your transfer course is most equivalent to
  - CIT Graduate Transfer Credit Request form
- Submit the completed packet to the academic advisor

The academic advisor will present the transfer request to the CIT Dean’s office and notify the student of the result.

Once the petition is approved, the Graduate Affairs Office will work with the student to complete the transfer request.

ECE has not entered into an articulation or transfer agreement with any specific college or university. The transfer of credits from any college or university must follow the above policy and process. Additionally, ECE does not award credit for prior experiential learning.

Research for Credit

**This option is only applicable when students are spending their semester at Carnegie Mellon in United States.*
Students can apply up to 15 units of research credit towards their M.S. degree requirements by registering for the 18-980, M.S. Research Project course. The number of units registered for should equal the number of hours you complete each week. For example, 12 units of research means the student should complete 12 hours of research each week. Alternative accommodations should be worked out with the supervising faculty member. Students are encouraged to wait until

their second semester to pursue research or teaching opportunities.

MS Research Approval Process:

- As an ECE student, you are able to view and apply for available research projects through Student Project Tracker - SPT (https://www.ece.cmu.edu/apps/spt/) electronically. New students will have access to the system on the first day of classes.
- You can view the details of the research projects listed and click the apply button to submit an application.
- Your application will be reviewed by the research instructor. You will be contacted by the research instructor (or someone from their research lab) if there is an interest in your application.
- The research instructor will inform your advisor through the SPT system if your application is approved and your advisor will register you for the appropriate research units. You will be registered for 18-980 based on the units reflected in the SPT system.
- If you already have a research project set up with a faculty member, the project still needs to be created in this portal. You must apply and get accepted through the system.
- If you are planning on conducting research with a non-ECE faculty member, the project must still be posted in SPT. You and/or your research instructor must find an ECE faculty member who will be a co-research instructor in the project.

Project & Research Innovation Requirements

During the student's time in Thailand. At least 48 units of research, entrepreneurship and innovations are required. This requirement offers students the opportunities to participate in ongoing real-world projects with university partners and preparing the students for future academic and industrial careers.

REGISTERING FOR COURSES ACADEMIC CALENDAR

ECE adheres to the official CMKL and CMU Academic Calendar. The Heinz College and the Tepper School follow their own calendars with dates that may differ from the University's calendar for the add, drop and pass/fail/audit deadlines. ECE students must adhere to the deadlines of the courses they are taking if the courses are in Heinz or Tepper.

Course Load

Due to the rigor of these programs, students are advised to take 37 units of courses in their first semester and 36 units of courses each semester thereafter. However, we recognize that our student body is diverse, and that includes how each student handles their course load. While students may register for maximum units each semester, we strongly recommend students take no more than 36 units each semester. Students unsure of whether they should take 48 units should schedule an appointment with their academic advisor to discuss their reason for overloading and prepare a plan for how to handle the additional load.

Adding Courses

Students have the option of adding courses to their schedule starting at their assigned registration time until the add/drop deadline through SIO. If a student wishes to be added to a course after the add/drop deadline, the Course Add Request Form must be completed and signed by the course instructor. Then, the student must submit the form to their academic advisor for approval. If approved, the academic advisor will send the form for processing.

In the event that an ECE course (18-XXX) is cross-listed with a course from another department, ECE students must register for the ECE course number.
Courses in the Tepper School of Business may be taken and can be registered for through a site outside the SIO. Tepper will publish a list of available MBA courses, and in order to register for Tepper courses, students should visit the Tepper registration site.

Course Locations

Courses will take place at various buildings and room locations across **CMKL University** as assigned in each academic semester. Each course location is tied to a section and has a final assignment that is linked to the final grade. It could be in the form of a final exam, final project, or research as stated in the syllabus on the first day of classes. Students should register for sections of their courses according to their physical campus location. Please refer to the schedule of classes available on your campus.

Dropping Courses

Students have the option of dropping courses from their schedule starting at their assigned registration time until the add/drop deadline through SIO. When a course is dropped before the drop deadline, it does not appear on the transcript. As a courtesy to others, students should drop a course as soon as they decide not to take it. This will allow a waitlisted student to be enrolled and will limit the disruption to any team-based projects.

Withdrawing from Courses

Students should remove themselves from a course before the drop deadline each semester. If a student chooses to withdraw from a course after the drop deadline, the student must officially withdraw from the course and should consult with their advisor to discuss the withdrawal. Withdrawals take place after the drop deadline but before the last day of the semester. Students must complete and submit the Course Withdrawal Request form with their academic advisor in order to withdraw from a course. Withdrawals receive a “W” grade for the course on a transcript; this “W” grade is not factored into the QPA but the course does count towards the maximum units.

Courses with Time Conflicts

Students are not permitted to register for two courses that conflict in time. Registration may be possible with consent from an instructor, allowing the conflict or attendance at an alternate time. Students should forward permissions from instructors to their academic advisor in order to register for conflicting courses.

Prerequisites

While SIO may allow you to register for courses without the published prerequisite, it is the student’s responsibility to have adequate background knowledge to be successful in the subsequent course. This background knowledge may come in the form of an introductory course taken at Carnegie Mellon, your undergraduate institution, or other work/research experience. You should consult with the instructor because it is up to their discretion whether or not a prerequisite course can be waived.

For ECE courses that require 18-613/15-213/15-513/18-213 as a prerequisite, students will not be permitted to enroll in the subsequent course without credit for 18-613/15-513. 18-613 and 15-513 are the only courses available to graduate students that satisfy the prerequisite requirement.

Some of the graduate courses that require 18-613/15-213/15-513/18-213 anywhere in their prerequisite tree include:

- 18-648 – Embedded Real-Time Systems
- 18-649 – Distributed Embedded Systems
- 18-656 – Data Intensive Workflow Development for Software Engineers
- 18-725 – Advanced Digital Integrated Circuit Design
- 18-740 – Computer Architecture
- 18-742 – Parallel Computer Architecture
- 18-745 – Rapid Prototyping of Computer Systems
- 18-746 – Advanced Storage Systems
- 18-748 – Wireless Sensor Networks
- 18-756 – Packet Switching and Computer Networks
- 18-759 – Wireless Networks
- 18-842 – Distributed Systems
- 18-845 – Internet Services
- 18-848 – Special Topics in Embedded Systems

Final Exams

All ECE students must attend final exams as scheduled by the university and individual course instructors. If a student believes that a final exam presents a scheduling conflict, he or she must discuss the issue with the course instructor. The ECE administration does not have control over the university exam schedule. Please keep this in mind when arranging travel at the end of a semester; having purchased airline tickets is not a proper excuse for missing a final exam.

Research Assistant & Teaching Assistant Positions

Students are encouraged to wait until their second semester to pursue research or teaching opportunities.

Research for Assistant for Credit

See the section titled “Research for Credit” for more information about receiving academic credit for research.

Research for Assistant for Pay

Students are permitted to pursue research opportunities for pay in any department/program. Students should contact faculty members individually to inquire about opportunities available and provide information on their background. The supervising faculty can provide further information about payroll procedures.

Teaching Assistant Positions

There are several levels of teaching assistant opportunities available for ECE students. For complete information please visit CMKL website.

Enrollment Verifications

The HUB is the primary contact for students or alumni who would like to request a transcript, enrollment verification, or other information related to their time in ECE.

ECE may verify some limited information in the form of a letter, which may be suitable for some purposes, such as the verification of skills students acquired through the ECE programs. Please contact your academic advisor for more information. ECE may verify some limited information in the form of a letter, which may be suitable for some purposes, such as the verification of skills students acquired through the ECE programs. Please note that the ECE program is only able to verify information on ECE courses.

Leave of Absence

Occasionally, students must pause their degree program due to personal, professional, or academic reasons. A student who is considering a leave of absence should speak to his or her academic advisor prior to taking a leave of absence in order to ensure his or her understanding of the leave of absence policy and its ramifications.

Leaves of absences are capped at two calendar years' total throughout the M.S. program. In extreme cases, a student may request additional leave time via a petition to the GSC. If they do not return within two academic years, they will be administratively withdrawn from the graduate program. Questions can be addressed to the M.S. Academic Program Advisor.

Once a student decides to take a leave of absence, he or she should complete the Leave of Absence form and bring it to their academic advisor for additional processing. Please note that the student's advisor must sign the leave of absence form.

Returning from a Leave of Absence

A student intending to return from leave must submit the Petition to Return from Leave of Absence form to their academic advisor at least 30 days prior to the start of the semester in which he/she plans to return. A student's return must coincide with the start of a new semester (fall, spring, or summer). Students cannot return from a leave of absence in mid-semester, with the exception of summers.

Per university policy on student leaves, "Students on leave are not permitted to live in university housing, attend classes or maintain employment as students at **CMKL** while their leave is in effect."

More information about the University's Leave of Absence and Withdrawal policies can be found in the University Policies section of this handbook.

Degree Certification Process & Commencement

A student must satisfy all degree requirements and achieve a minimum of 3.0 QPA in the courses being applied towards the required 145 units to be eligible for degree certification. In addition, students must have provided a final copy of their undergraduate transcript(s) and must have a tuition balance of THB 0.00 to receive a diploma.

CMKL Commencement only occurs once a year. ECE holds a diploma ceremony at the same time as the university. Students who are certified after the annual ceremony will be invited to attend the next commencement ceremony.
Before graduation, students should update their contact information, such as mailing address and e-mail address, within SIO. Also, students should review a proxy of their diploma in SIO to verify the information displayed there, such as the spelling of their name.

The title of the degree students receive is Master of Science in Electrical and Computer Engineering.

ACADEMIC STANDARDS

Grades

Below are the policies surrounding grades for students in Electrical and Computer Engineering programs.

University Policy on Grades

The university policy on grading offers details concerning university grading principles for students taking courses and covers the specifics of assigning and changing grades, grading options, drop/withdrawals and course repeats. It also defines the undergraduate and graduate grading standards.

Grading Policy

ECE follows the following letter grade scale. The letter grade scale is ‘A’ (highest for CIT students), ‘A-‘, ‘B+’, ‘B’, ‘B-‘, ‘C+’, ‘C’, ‘C-‘, ‘D+’, ‘D’, and ‘R’ (lowest). CIT students cannot receive an ‘A+’ grade on their transcript, even if a course is taken from another college where ‘A+’ is given. Grades lower than ‘C’, meaning C- or below, are considered failure in CIT and will not count toward degree requirements.

Incomplete Grade

Incomplete grades will be assigned at the discretion of the course instructor, per the university grading policy.

Withdrawal Grade/Withdrawing from Courses

Students can withdraw from a course after the add/drop deadline until the last day of classes. This will result in a ‘W’ on the transcript, which is not factored into the QPA. To withdraw, the course withdrawal request form must be completed and submitted to the academic advisor for approval. If approved, the academic advisor will send the form for processing.

Academic Performance Quality Point Average

In order to graduate, each student must have a Quality Point Average (QPA) of at least 3.0 in the courses being used towards the required 145 units. Coursework or graduate project units with a grade lower than ‘C’ will not be considered toward graduate degree requirements; however, they will be calculated into the student’s cumulative QPA.

Probation

In the event that a student's semester or cumulative QPA falls below a 3.0, that student is on academic probation and will receive a letter from the program alerting them. While on probation, students must meet with their academic advisor and comply with their recommendations. Once a student's semester and cumulative QPA increase above 3.0, the student is automatically removed from probation.

Academic Integrity

Students at CMKL are engaged in preparation for professional activity of the highest standards. Each profession constrains its members with both ethical responsibilities and disciplinary limits. To assure the validity of the learning experience a university establishes clear standards for student work.

In any presentation, creative, artistic, or research, it is the ethical responsibility of each student to identify the conceptual sources of the work submitted. Failure to do so is dishonest and is the basis for a charge of cheating or plagiarism, which is subject to disciplinary action.

ECE adheres to CMKL and Carnegie Mellon's policy on academic integrity and all students are expected to review the policies prior to their arrival at CMKL.

Penalties for Violating Academic Integrity

Instructors are responsible for defining academic integrity for students in their courses, including student performance expectations and attendance requirements. Students are responsible for understanding and abiding by the instructor's academic integrity policies. Policies may vary from instructor to instructor and students should seek further guidance from a faculty member if they have specific questions about a course's academic integrity policy.

Should an instructor believe that an academic integrity violation has occurred, he or she may consult with the Office of the Dean of Student Affairs, who will assist the faculty member in handling a possible academic integrity violation and, if a student is found responsible for violating academic integrity policies, determining possible sanctions. In accordance with the university's policy, a student who violates the academic integrity policy will not be permitted to drop the course in which the offense occurred in order to avoid penalty. If the student attempts to drop the course, he/she will be reenrolled.

If a student is found to have violated the academic integrity policy for a second time, the student will be dropped from the Electrical and Computer Engineering program effective at the end of the semester in which the infraction has occurred. Students have the right to appeal an academic integrity decision.

M.S. DEGREE REQUIREMENTS

This section outlines the degree requirements for the Master's of Science in Electrical & Computer Engineering at CMKL University. ECE course list and course descriptions are available on the ECE course website: https://www.cmkl.ac.th/cmkm

MS in Electrical & Computer Engineering

Each MS in ECE candidate must complete 145 units (1 unit=1 hour of work) of coursework. All incoming MS ECE students must take the one-unit Introduction to Graduate Studies course (18-

989) in the Carnegie-Mellon Pittsburgh campus. These units are made up of the following degree requirements (A, B, C, and D below):

A. ECE Core Graduate Coursework: 60 units
   The ECE program requires 60 units of core coursework that may not be waived or substituted. These courses should be courses in the Computer Science Department (15) at the 700-level or above (exceptions include 15-749, 15-862, 15-894) or in the ECE Department/program (18) at the 600-level or above (exceptions include 18-601, 18-603, 18-605, 18-606, 18-700, 18-703).

   Courses outside of ECE and Computer Science department that have been approved to be counted towards the 60 units of ECE Core Graduate Coursework include: 08-766, 08-781, 08769 ,10-701, 11-752,16-711, 16-720, 16-722, 16-741, 16-745, 16-811,16-822, 16-843, 16850 ,19-714 ,21-801, 24-751,33-755, 33-758, 33-761, 33-762, 36-783, 42-744, 96-714, 96-736, 96-839, 96-840, 96-842

B. Restricted Electives: 24 units
   Students have the opportunity to pursue a wide range of electives in which they have a special interest. These courses can be taken from the following departments:
   • Any ECE (18) course at the 500-level or above
   • Any course at the 600-level or higher from one of the following colleges or programs (with restrictions noted below)

   - Carnegie Institute of Technology (CIT) (39)
   - Biomedical Engineering (42)
   - Chemical Engineering (06)
   - Civil & Environmental Engineering (12)
   - Engineering & Public Policy (19) (restrictions include 19-602, 19-655)
   - Information Network Institute (14)
   - Integrated Innovation Institute (49)
   - Materials Science & Engineering (27)
   - Mechanical Engineering (24) (restrictions include 24-792)
   - CMU Rwanda (04) (restrictions include 04-601, 04-602, 04-605, 04-900, 04980)
   - CMU Silicon Valley (96) (restrictions include 96-705)
   - Dietrich College of Humanities and Social Sciences Statistics (36)
   - Center for the Neural Basis of Cognition (86)
   - Heinz School of Information Systems (95)
   - Heinz College-Wide Courses (94)
   - Mellon College of Science (MCS)
   - Biological Sciences (03)
   - Chemistry (09)
   - Mathematical Sciences (21)
   - Physics (33)
   - School of Computer Science (SCS)
   - Computational Biology (02) (restrictions include 02-713, 02-613)
   - Computer Science (15) (restrictions include 15-602, 15-603, 15-604, 15649,15-669,15-689, 15-697, 15-698, 15-749)
   - Entertainment Technology Center (53)
   - Institute for Software Research (08)
   - Robotics Institute (16) (restrictions include 16-861, 16-865)
   - Human-Computer Interaction Institute (05)
   - Language Technologies Institute (11)
   - Machine Learning (10)
   - Software Engineering (17) (restrictions include 17-643)

- Tepper School of Business (45)
- Statistics (36)

Courses outside these departments that have been approved to be counted towards the 24 units of Restricted Electives include: 36-725, 46-926, 46-929, 47-830, 47-834, 51-882, 90-756, 93-711.

C. Less-Restricted Elective: 12 units
The remaining 12 units must be 300 level or greater from the same colleges, departments and programs listed above. Courses numbered as xx-299 or lower will not be counted toward the MS degree. Three units of internship (18-994 Internship for Electrical and Computer Engineering Graduate Students) or professional development (39-699 CIT Professional Development Course) coursework may count towards the Less-Restricted Elective.

D. Research and Innovation: 48 units
At least 48 units of research, entrepreneurship and innovations are required. This unique requirement offers students the opportunities to participate in ongoing real-world projects with university partners and preparing the students for future academic and industrial careers.

Requirements:

1. Research, Entrepreneurship and Innovation (18-900): 12 units
2. Research and Development (18-910): 36 units
   *It is optional for students to complete their required Research and Development units via the following options:
   a. 24 units at CMKL; 12 units at CMU Pittsburgh
   OR
   b. 12 units at CMKL; 24 units at CMU Pittsburgh
   OR
   c. 36 units at CMKL

*Units completed to fulfill Research and Development requirements at CMU Pittsburgh will be conducted under the following course name: M.S. Graduate Project (18-980)

Courses where more than 50% of the course grade is based on a group project or more than 20% is based on attendance cannot be used towards the required 96 units in Category A-C

Petitions for exceptions to these criteria may be considered by the Graduate Studies Committee. Please see your academic advisor for more information.

Internship Course Option

ECE students may wish to participate in paid internships at off-campus organizations during the summer months.
ECE will enroll all students who are pursuing an internship for a 3-unit credit bearing internship course (18-994 Internship for Electrical and Computer Engineering Graduate Students), which can be taken once throughout the student’s ECE M.S. degree program of study, and is offered only during the summer. This internship will appear on a student’s transcript and tuition will charged for 3 units. Please see details for CIT cost of attendance on HUB's website. The work for the internship must be appropriate to the goals of the academic program and units can be applied to the less restricted elective requirement.

Eligible international students who are interested in pursuing off-campus internships must meet with program and OIE representatives. For additional information, please refer to OIE's website on Employment Options for international students. Academic and OIE advisors will provide students with information about CPT during the spring semester.

POST-MATRICULATION GUIDELINES

Return of University Property

ECE students must return all borrowed ECE and university materials—such as software, manuals, library books/materials, or any other CMKL/Carnegie Mellon University property—prior to their departure from the program.

Career Services Employment Outcomes

ECE students are asked to complete and return a survey for Career Services updating CMU/CMKL on their employment outcomes after graduation. Information about the survey is communicated in the students' final semester.

"Grandfather" Clause

When policies are changed, it is because the program believes the new rules offer an improvement; any such changes will be communicated to students. In case degree requirements are changed and certain courses are no longer offered, the program will try to find some compromise that allows those students to satisfy the original requirements.

TUITION AND FEES

As indicated in your admission offer letter, ECE does not offer financial assistance for our master's students. Unless otherwise arranged and approved in advance, ECE students are full-time and will be charged full-time ECE tuition. Total charges for a period of attendance and estimated schedule of total charges for entire educational program can be found at the following website: https://www.cmkl.ac.th/tuition-and-fees

Estimated charges for ECE M.S. degree:

12 Month Minimum Expenses* for Academic Year 2019-2020

Tuition	THB 1,580,000
Graduate Student Fees	THB 28,200
Living and Miscellaneous Expenses	THB 250,000
Books and Supplies	THB 50,000
Health Insurance (individual plan, estimate)*	THB 66,000
TOTAL*	THB 1,974,200

*Estimate only based on 2018-2019 expenses. Actual cost may vary.

Tuition Billing & Payments

The tuition rate for students entering ECE programs is set in the spring for the class entering in the following fall semester. Tuition for a student's second fall semester will likely increase in accordance with the tuition increase for the new academic year. The tuition will increase approximately 3% per year.

Students will be charged tuition per semester for each semester in which they are enrolled. The tuition billing and payment process for all ECE students is handled centrally by CMKL University.

University Financial Aid

Graduate Students should consult the graduate student financial aid information. Students will find the Graduate Financial Aid Guide, information about funding options, how to apply for financial aid and other helpful links.Graduate students who find themselves in need of immediate funds for emergency situation should contact the Office of the Dean of Student Affairs to inquire about an Emergency Situation Loan.

APPENDIX A: LIST OF PROGRAM COURSES

Courses offered at CMKL University and Carnegie Mellon University

The following courses are offered in Thailand at CMKL as well as in US at CMU (additional courses may be added later). Students can either take the courses at CMKL or CMU to satisfy the program requirements;

Foundations of Computer Systems (18-613) – 12 Units

This course provides a programmer's view of how computer systems execute programs, store information, and communicate. It enables students to become more effective programmers, especially in dealing with issues of performance, portability and robustness. It also serves as a foundation for courses on compilers, networks, operating systems, and computer architecture, where a deeper understanding of systems-level issues is required. Topics covered include: machine-level code and its generation by optimizing compilers, performance evaluation and optimization, computer arithmetic, processor architecture, memory organization and management, networking technology and protocols, and supporting concurrent computation. This course is modeled after 15-213/18-213/15-513, and is intended for ECE MS students with expanded course contents presented at the graduate level. It prepares students for other graduate level computer systems courses as well as working in the industry. Anti-requisites: 15213, 18213, 15513

Software Requirements and Interaction Design (18-658) – 12 Units

Good software systems should be engineered with user experience in mind. How can we design software systems that are at once useful, usable, and enjoyable to use?
This course addresses these challenges by integrating two disciplines: requirements engineering and interaction design. Students learn to combine user research, design-based ideation and validation, and requirements definition, within an agile software development process.
Students apply this knowledge during a semester-long project. Their goal is to envision and implement the first version of an innovative software system that could make a unique contribution to society. The system should address a real problem, satisfy real stakeholders' needs, and provide a superior user experience. Students collaborate closely with their stakeholders throughout the project for needs elicitation, design concepts validation, and usability testing.
This course is intended for ECE master students with a concentration in Software Engineering. It is a core course of the MS-SE program satisfying the "Software Engineering and Design" course area requirement.

Introduction to Machine Learning for Engineers (18-661) – 12 Units

This course provides an introduction to machine learning with a special focus on engineering applications. The course starts with a mathematical background required for machine learning and covers approaches for supervised learning (linear models, kernel methods, decision trees, neural networks) and unsupervised learning (clustering, dimensionality reduction), as well as theoretical foundations of machine learning (learning theory, optimization). Evaluation will consist of mathematical problem sets and programming projects targeting real-world engineering applications.

Advanced Cloud Computing (18-709) – 12 Units

Computing in the cloud has emerged as a leading paradigm for cost-effective, scalable, well-managed computing. Users pay for services provided in a broadly shared, power-efficient datacenter, enabling dynamic computing needs to be met without paying for more than needed. Actual machines may be virtualized into machine-like services, abstract programming platforms, or application-specific services, with the cloud infrastructure managing sharing, scheduling, reliability, availability, elasticity, privacy, provisioning and geo-replication.

This course will survey the aspects of cloud computing through about 30 papers and articles, executing cloud computing tasks on a state-of-the-art cloud computing service, and implementing a change or feature in a state-of-the-art cloud computing framework. There will be no final exam, but there will be one or two in-class exams. Grades will be about 50% project work and about 50% examination results.

Introduction to Computer Security (18-730) – 12 Units

This course provides a principled introduction to techniques for defending against hostile adversaries in modern computer systems and computer networks. Topics covered in the course include operating system security; network security, including cryptography and cryptographic protocols, firewalls, and network denial-of-service attacks and defenses; user authentication technologies; security for network servers; web security; and security for mobile code technologies, such as Java and JavaScript. More advanced topics will additionally be covered as time permits, such as: intrusion detection; techniques to provide privacy in Internet applications; and protecting digital content (music, video, software) from unintended use. Anti-requisites: 18-631 and 18-487

Secure Software Systems (18-732) – 12 Units

Poor software design and engineering are the root causes of most security vulnerabilities in deployed systems today. Moreover, with code mobility now commonplace--particularly in the context of web technologies and digital rights management--system designers are increasingly faced with protecting hosts from foreign software and protecting software from foreign hosts running it. This class takes a close look at software as a mechanism for attack, as a tool for protecting resources, and as a resource to be defended. Topics covered include the software design process; choices of programming languages, operating systems, databases and distributed object platforms for building secure systems; common software vulnerabilities, such as buffer overflows and race conditions; auditing software; proving properties of software; software and data watermarking; code obfuscation; tamper resistant software; and the benefits of open and closed source development. Senior or graduate standing required.

Computer Architecture – (18-740) – 12 Units

The Internet has transformed our everyday lives, bringing people closer together and powering multi-billion-dollar industries. The mobile revolution has brought Internet connectivity to the last-mile, connecting billions of users worldwide. But how does the Internet work? What do oft repeated acronyms like "LTE", "TCP", "WWW" or a "HTTP" actually mean and how do they work? This course introduces fundamental concepts of computer networks that form the building blocks of the Internet. We trace the journey of messages sent over the Internet from bits in a computer or phone to packets and eventually signals over the air or wires. We describe concepts that are common to and differentiate traditional wired computer networks from wireless and mobile networks. Finally, we build up to exciting new trends in computer networks such as the Internet of Things, 5-G and software defined networking. Topics include: physical layer and coding (CDMA, OFDM, etc.); data link protocol; flow control, congestion control, routing; local area networks (Ethernet, Wi-Fi, etc.); transport layer; and introduction to cellular (LTE) and 5-G networks. A final project asks you to a build a HTTP video server of your own. This course is cross-listed with 18-441 - both editions will share Lectures and Recitations. However, students in the two courses will receive different exams and will have a different project. The students in the two versions of the course will be graded on a separate curve.

Computer Architecture and Systems (18-742) – 12 Units

Historically, the performance and efficiency of computers has scaled favorably (according to "Moore's Law") with improvements at the transistor level that followed a steady trend (so-called "Dennard scaling"). Unfortunately, device scaling has hit a limit on performance and power improvements dictated by physical device properties. To continue to make systems capable, fast, energy efficient, programmable, and reliable in this "post-Dennard" era, computer architects must be creative and innovate across the layers of the system stack. This course begins with a recap of conventional, sequential computer architecture concepts. We will then discuss the end of convention, brought about by the end of Dennard Scaling and Moore's Law, and several trends that these changes precipitated. The first trend is the wholesale shift to parallel computer architectures and systems, covering parallel hardware and software execution models, cache coherence, memory consistency, synchronization, transactional memory, and architecture support for programming, debugging, and failure avoidance. The second trend is the shift to incorporating specialized, heterogeneous components into parallel computer architectures. Topics will include reconfigurable architectures, FPGAs in the datacenter, ASIC accelerators, GPGPU architectures, and the changes to the system stack that these components demand. The third trend is the emergence of newly capable hardware and software systems and new models of computation. Topics will include approximate and neuromorphic computing, intermittent computing, emerging non-volatile memory and logic technologies, and analog and asynchronous architectures, and may include future emerging topics.

Packet Switching and Computer Networks (18-756) – 12 Units

This course is designed to provide graduate students an understanding of the fundamental concepts in computer networks of the present and the future. In the past, the scarce and expensive resource in communication networks has been the bandwidth of transmission facilities. Accordingly, the techniques used for networking and switching have been chosen to optimize the efficient use of this resource. These techniques have differed according to the type of information carried: circuit switching for voice and packet switching for data. It is expected that elements of circuit and packet switching will be used in the integrated networks. This course focuses on packet switching for computer networks and protocol design. Topics in the course include: computer networks over-view; OSI layers, queuing theory; data link protocol; flow control; congestion control; routing; local area networks; transport layer. The current networks and applications will be introduced through the student seminars in the last weeks of the course. Prerequisites: 18-345 and senior or graduate standing.

Network Management and Control (18-757) – 12 Units

This course provides an understanding of the principles of broadband networks. The broadband networks differ from currently existing communication networks in many aspects and these issues will be dealt with in the course. Broadband networks are designed to support many different services, ranging from low bandwidth (telemetry) to high bandwidth applications (digitized video). The course will cover the underlying concepts of the broadband networks, and expose the research problems in next generation networks. Many concepts (ATM, SONET, MPLS, high-speed switching architecture, high-speed network control, unified control plane (GMPLS), and optical networks) will be discussed. The course project will explore latest network technologies, design networking systems, and evaluate via simulation techniques. Prerequisites: A course in probability; 18-756 and senior or graduate standing.

Applied Stochastic Processes (18-751) – 12 Units

Basic probability concepts: Probability space, simple and compound events, statistical independence, and Bayes Rule. Total Probability Concept; Bernoulli trials; Poisson Law. De Moivre-Laplace Theorem. Definition of a Random Variable (RV); Probability distribution of an RV: cumulative distribution function (CDF) and probability density function (PDF). Two Random Variables; several Random Variables. Functions of RV?s; conditional distributions; conditional expectations; joint distributions. Moments, generating functions, and characteristic functions of RVs. Chebyshev inequality. Estimation; linear estimation; minimum mean square estimation; and orthogonality principle. Limit theorems; Central Limit Theorem; Law of Large Numbers (both strong LLN and Weak LLN). Definition of a Random Process (RP). Different notions of stationarity. Poisson and Gaussian processes. Autocorrelation and Power Spectral Density (PSD) of an RP. Processing of random (stochastic) processes by linear systems. Ergodicity. Spectral analysis. Matched Filtering. Selected applications from telecommunications, data networking (queuing), Kalman filtering.

Wireless Networks (18-759) – 12 Units

In this course, we will do a quick review of wireless communications and networking principles which will be the basis of more advanced work and research. The emphasis will be on understanding the impact of mobility and connectivity that can be provided or supported by different wireless networks. To this end, wireless communications standards such as GSM (2G), 3G, 4G, and the ongoing work on 5G in addition to key wireless technologies such as Bluetooth, WiFi, Zigbee, RFID, and WiMax will be reviewed. Then, we will study the key papers in the following hot topics in wireless networking: 1) Ad Hoc Wireless Networks and Sensor Networks; 2) Self-organizing networks and adaptive complex networks; 3) Cognitive Networks; 4) Vehicular Ad Hoc Networks; 5) Social Networks; 6) The challenges of 5G wireless networks; 7) Internet of Things (IoT); 8) Role of Artificial Interference (AI) and Machine Learning (ML) in wireless networks.

Data, Inference, and Applied Machine Learning (18-785) – 12 Units

This course will provide the methods and skills required to utilize data and quantitative models to automate predictive analytics and make improved decisions. From descriptive statistics to data analysis to machine learning the course will demonstrate the process of collecting, cleaning, interpreting, transforming, exploring, analyzing and modeling data with the goal of extracting information, communicating insights and supporting decision-making. The advantages and disadvantages of linear, nonlinear, parametric, nonparametric and ensemble methods will be discussed while exploring the challenges of both supervised and unsupervised learning. The importance of quantifying uncertainty, statistical hypothesis testing and communicating confidence in model results will be emphasized. The advantages of using visualization techniques to explore the data and communicate the outcomes will be highlighted throughout. Applications will include visualization, clustering, ranking, pattern recognition, anomaly detection, data mining, classification, regression, forecasting and risk analysis. Participants will obtain hands-on experience during project assignments that utilize publicly available datasets and address practical challenges.

Image and Video Processing (18-793) – 12 Units

This course covers signal processing techniques specialized for handling 2D (images) and 3D (videos) signals. It builds upon 1D signal processing techniques developed in 18-290 and 18-491 and specializes them for the case of images and videos. In this class, you will learn fundamental tools and techniques for processing images and videos, and will learn to apply them to a range of practical applications. This course provides the fundamentals for studying images and videos. We will develop signal models specific to images and videos, develop associated optimization techniques for solving restoration problems like denoising, inpainting, study specialized compression algorithms. Specific focus will be on transform-domain, PDE and sparsity-based models and associated optimization techniques. These formal techniques will be enriched via applications in mobile devices, medical image processing, and compressive sensing.

Research, Entrepreneurship and Innovation requirement

The following courses satisfy research, entrepreneurship and innovation requirement for ECE/Thailand Program. Students must take at least 48 credits in this category during their time in Thailand.

Research, Entrepreneurship and Innovation (18-900) – 12 Units

This unique course for CMU Thailand program introduces students to explore the connections between research, entrepreneurship and innovation. Students will be introduced to industries and tech communities. Students will participate in exploratory projects which introduce research methodologies while also learning how to apply engineering techniques to solve challenging real-world problems.

Research and Development (18-910) – 36 Units

Students in ECE/Thailand programs will have the opportunity to participate in real-world supervised research and development projects. Students are encouraged to participate in existing projects with the university partners to gain professional experience in R&D.
*Minimum 12 units must be completed at CMKL

Courses offered at Carnegie Mellon University

The following courses are currently offered at Carnegie Mellon University and can be counted toward degree requirements for CMKL. The course descriptions listed here are for reference only.

Entrepreneurship and Innovation in Technology (18-601) – 12 Units

Have an idea you want to bring to the world? Ever want to start a company? Do you wonder what it takes to be an entrepreneur? Then this is the class for you. Entrepreneurship and Innovation in Technology is an introductory course in entrepreneurship for graduate students. The course targets non-business students and assumes no background in business. Students are exposed to fundamental concepts and issues around innovation and entrepreneurship. The course provides a foundation for starting a new venture and innovating new technologies and products within existing organizations. Topics covered include: identifying a business opportunity, acquiring customers, building a team, developing a business model, understanding investment, managing risk, and achieving differentiation. Emphasis will be on team projects, including developing an investor pitch for an original idea.

Neural Technology: Sensing and Stimulation (18-612) – 12 Units

This course gives engineering insight into the operation of excitable cells, as well as circuitry for sensing and stimulation nerves. Initial background topics include diffusion, osmosis, drift, and mediated transport, culminating in the Nernst equation of cell potential. We will then explore models of the nerve, including electrical circuit models and the Hodgkin-Huxley mathematical model. Finally, we will explore aspects of inducing a nerve to fire artificially, and cover circuit topologies for sensing action potentials and for stimulating nerves. If time allows, we will discuss other aspects of medical device design. Students will complete a neural stimulator or sensor design project. Although students in 18-612 will share lectures and recitations with students in 18-412, students in 18-612 will receive distinct homework assignments, distinct design problems, and distinct exams from the ones given to students in 18-412 and will be graded on a separate curve from students taking 18-412.

Microelectromechanical Systems (18-614) – 12 Units

This course introduces fabrication and design fundamentals for Microelectromechanical Systems (MEMS): on-chip sensor and actuator systems having micron-scale dimensions. Basic principles covered include microstructure fabrication, mechanics of silicon and thin-film materials, electrostatic force, capacitive motion detection, fluidic damping, piezoelectricity, piezoresistivity, and thermal micromechanics. Applications covered include pressure sensors, micromirror displays, accelerometers, and gas microsensors. Grades are based on exams and homework assignments. 4 hrs. lec.

Micro and Nano Systems Fabrication (18-615) – 12 Units
This is a new course intended to introduce students to the process flow and design methodology for integrated systems fabrication. The course will present this material through two paths. Lectures will be presented on the basic unit processes of micro and nanosystems fabrication: deposition, patterning, and etching. Lectures will draw on examples from: Semiconductor device fabrication; Microelectromechanical systems (MEMS) fabrication; Magnetic device fabrication; and Optical device fabrication. Problem sets will be given based on this lecture material to allow students to quantitatively analyze certain process steps in detail. The second path for material presentation will be through a series of labs that allow students to design, fabricate and test an integrated device. These laboratories will be scheduled at regular meeting times, and will use research facilities within the ECE department. This is a PhD level course. MS or senior students must obtain permission from the instructor to be registered.

Nano-Bio-Photonics (18-616) – 12 Units
Light can penetrate biological tissues non-invasively. Most of the available bio-optic tools are bulky. With the advent of novel nanotechnologies, building on-chip integrated photonic devices for applications such as sensing, imaging, neural stimulation, and monitoring is now a possibility. These devices can be embedded in portable electronic devices such as cell phones for point of care diagnostics. This course is designed to convey the concepts of nano-bio-photonics in a practical way to prepare students to engage in emerging photonic technologies. The course starts with a review of electrodynamics of lightwaves. The appropriate choice of wavelength and material platform is the next topic. Then optical waveguides and resonators are discussed. Resonance-based sensing is introduced followed by a discussion of the Figure of Merits (FOMs) used to design on-chip sensors. Silicon photonics is introduced as an example of a CMOS- compatible platform. On-chip spectroscopy is the next topic. The second part covers nano- plasmonics for bio-detection and therapy. The design methods are discussed, followed by an overview of nanofabrication and chemical synthesis, and then a discussion of applications. The last part of this course will be dedicated to a review of recent applications such as Optogenetic neural stimulation, Calcium imaging, Cancer Imaging and Therapy. Senior or graduate standing required. This course is cross-listed with 18416. Although students in 18-616 and 18-416 will share the same lectures and recitations, students in 18-616 will receive distinct course projects. Students in 18-416 and 18-616 will be graded on separate curves.

Smart Grids and Future Electric Energy Systems (18-618) – 12 Units
The course offers an advanced presentation of modern electric power systems, starting from a brief review of their structure and their physical components, through modeling, analysis, computation, sensing and control concepts. Great care is taken to avoid presenting "practical" techniques built on dubious theoretical foundations and also to avoid building elaborate "mathematical" models whose physical validity and relevance may be questionable. Mastering both principles and relevant models is important for those who wish to seriously understand how today's electric power grids work and their challenging technical issues. This prepares students for working on applying many novel information processing concepts for designing and operating more reliable, secure, and efficient electric energy systems. Students interested in both applied physics and signals and systems should consider taking this subject. Once the fundamentals of today's power systems are understood, it becomes possible to consider the role of smart electric power grids in enabling evolution of future electric energy systems. Integration of intermittent energy resources into the existing grid by deploying distributed sensors and actuators at the key locations throughout the system (network, energy sources, consumers) and changes in today's

Supervisory Control and Data Acquisition (SCADA) for better performance become well-posed problems of modeling, sensing and controlling complex dynamic systems. This opens opportunities to many innovations toward advanced sensing and actuation for enabling better physical performance. Modeling, sensing and control fundamentals for possible next generation SCADA in support of highly distributed operations and design are presented. Prior knowledge in 18-418 or 18-771 is highly recommended.

Digital Integrated Circuit Design (18-622) – 12 Units

This course covers the design and implementation of digital circuits in a modern VLSI process technology. Topics will include logic gate design, functional unit design, latch/flip-flop design, system clocking, memory design, clock distribution, power supply distribution, design for test, and design for manufacturing. The lab component of the course will focus on using modern computer aided design (CAD) software to design, simulate, and lay out digital circuits. The final project for the course involves the design and implementation to the layout level of a small microprocessor. 18-240 and 18-320 or equivalent background material with permission of the instructor. Although students in 18-422 and 18-622 will share lectures, labs, and recitations, students in 18-422 and 18-622 will receive different homework assignments, design projects, and exams, and in some cases 18-622 students will also have different or additional lab sessions.

Analog Integrated Circuit Design (18-623) – 12 Units

Some form of analog circuit design is a critical step in the creation of every modern IC. First and foremost, analog circuits act as the interface between digital systems and the real world. They act to amplify and filter analog signals, and to convert signals from analog to digital and back again. In addition, high performance digital cell design (either high speed or low power) also invokes significant analog circuit design issues. The goal of this course is to teach students some of the methods used in the design and analysis of analog integrated circuits, to illustrate how one approaches design problems in general, and to expose students to a broad cross-section of important analog circuit topologies. The course will focus on learning design through carrying out design projects. Design and implementation details of wide-band amplifiers, operational amplifiers, filters and basic data converters will be covered. Example topics to be covered include transistor large- and small-signal device models, small-signal characteristics of transistor-based amplifiers, large-signal amplifier characteristics and nonidealities, operational amplifier design, basic feedback amplifier stability analysis and compensation, and comparator design. The course will focus primarily on analog CMOS, but some aspects of BJT design will be discussed. 18-290 and 18-320 or equivalent background material with permission of the instructor. Although students in 18-623 will share Lectures and Recitations with students in 18-421, students in 18- 623 will receive distinct homework assignments, distinct design problems, and distinct exams from the ones given to students in 18-421 and will be graded on a separate curve from students taking 18-421.

ULSI Mobile Platform and Server Product Design (18-625) – 12 Units

The objective of this class is to design an ULSI (Ultra Large Scale Integrated) mobile platform and a server product in two scenarios: System on Chip (SoC) and System in Package (SiP). State-of-the-art 2016 technology nodes (28nm, 20nm or 14nm) will be assumed for the SoC scenario and full 3-D integration with Through Silicon Vias (TSV) will be pursued for the 2020 SiP scenario.

Students will be given all the necessary technology data (device performance, interconnect parasitics, wafer and TSV/packaging costs, and also the expected yield data). The design objective is to deliver a product competitive to the leading products available on the market or anticipated in 5 years. The complete product design will be carried out focusing on the processor cores, graphics and the embedded memories (including new generation memories in the 2020 scenarios). System performance and power will be estimated using provided simulators for specified benchmarks. The goal is to minimize the product cost by maximizing the number of good die per wafer while achieving competitive product performance and power objectives.
Prerequisites: 18664 or instructor permission

Introduction to Information Security (18-631) – 12 Units

Our growing reliance on information systems for daily activities, ranging from remote communications to financial exchanges, has made information security a central issue of our critical infrastructure. The course introduces the technical and policy foundations of information security. The main objective of the course is to enable students to reason about information systems from a security engineering perspective, taking into account technical, economic and policy factors. Topics covered in the course include elementary cryptography; access control; common software vulnerabilities; common network vulnerabilities; policy and export control laws, in the U.S., Japan, and elsewhere; privacy; management and assurance; economics of security; and special topics in information security. Prerequisites: The course assumes a basic working knowledge of computers, networks, C and UNIX programming, as well as an elementary mathematics background, but does not assume any prior exposure to topics in computer or communications security. Students lacking technical background (e.g., students without any prior exposure to programming) are expected to catch up through self-study.

Introduction to Hardware Security (18-632) – 12 Units

This course covers basic concepts in the security of hardware systems. Topics covered include active and passive attacks, reverse engineering, counterfeiting, and design of hardware security primitives (e.g., random number generators, physical unclonable functions, crypto-processors). Lab sessions will give students hands on experience with performing attacks, developing countermeasures, and implementing secure hardware building blocks. Students are expected to have basic knowledge of digital logic and Register-Transfer Level (RTL) design, but no specific background in security/cryptography is necessary.

Browser Security (18-636) – 12 Units

The Web continues to grow in popularity as platform for retail transactions, financial services, and rapidly evolving forms of communication. It is becoming an increasingly attractive target for attackers who wish to compromise users' systems or steal data from other sites. Browser vendors must stay ahead of these attacks by providing features that support secure web applications. This course will study vulnerabilities in existing web browsers and the applications they render, as well as new technologies that enable web applications that were never before possible. The material will be largely based on current research problems, and students will be expected to criticize and improve existing defenses. Topics of study include (but are not limited to) browser encryption, JavaScript security, plug-in security, sandboxing, web mashups, and authentication.

The course will involve an intensive group research project focusing on protocols/algorithms, vulnerabilities, and attacks as well as several individual homework and programming tasks. Groups will perform a sequence of cumulative tasks (literature review, analysis, simulation, design, implementation) to address aspects of their chosen topic, occasionally reporting their results to the class through brief presentations, leading to a final report.

Wireless Security (18-637) – 12 Units

With the surge of mobile device use, embedded system deployment, and development of always-connected devices, the underlying wireless communication and network systems are becoming more critical for everyday use. Even though security and privacy have emerged as important focus areas for modern technology, the wireless links that connect our pervasive devices are still less understood from the perspectives of security and privacy than other system aspects. This course will focus on the challenges in providing secure communication and network services in a variety of wireless systems and current and past approaches to manage these challenges. Topic coverage will include vulnerabilities, attacks, security mechanisms, and trade-offs at various layers of the network protocol stack, from aspects of physical communication to application and service security issues; examples include jamming, MAC-layer misbehavior, selective packet dropping, decentralized trust and reputation, and cross-layer holistic attacks. Systems of interest include (but are not limited to) personal devices, connected vehicles, embedded and IoT systems, wireless infrastructure, and ad hoc networks. Class material will be largely based on recent and current research. In addition to individual homework assignments, students will participate in an intensive group project involving significant research, development, and experimentation. Graduate standing is required to register for this course.

Mobile and IoT Security (18-638) – 12 Units

For many people, mobile and embedded devices have become an essential part of life and work. As such devices represent many and varied combinations of technologies, they have unique security and privacy issues that potentially impact users, developers, service providers, manufacturers, and regulators. This course will focus on various aspects of security and privacy that are faced by mobile and Internet of Things devices, including aspects of wireless communication and networking, mobile computing, data analytics, security, and privacy. The course will include studies of security and privacy aspects of networking (including telecom, enterprise, personal, etc.), applications, and data analytics as relevant to mobile and embedded/IoT devices. One of the main goals of the course is to improve knowledge and awareness of security issues faced by mobile application developers, embedded system builders, and smart system designers. Material will cover standards, best practices, and research challenges in both deployed and emerging systems. Topics of study include (but are not limited to) telecom protocols and vulnerabilities; mobile/IoT network security; security and privacy in edge computing; mobile application security; and location and activity privacy. In addition to individual homework assignments, students will participate in an intensive group project involving significant research, development, and experimentation. Graduate standing is required to register for this course.

Policies of the Internet (18-639) – 12 Units

This course will address public policy issues related to the Internet. This may include policy issues such as network neutrality and the open Internet, Internet governance and the domain name system (and the role of the United Nations), copyright protection of online content, regulation of indecency and pornography, universal access to Internet and Internet as a "human right," government surveillance of the Internet, Internet privacy and security, and taxation of electronic commerce. It will also teach some fundamentals of Internet technology. Because these are inherently interdisciplinary issues, the course will include detailed discussions of technology, economics, and law, with no prerequisites in any of these areas. Senior or graduate standing required.

Hardware Arithmetic for Machine Learning (18-640) – 12 Units

In this course, students explore the techniques for designing high-performance digital circuits for computation along with methods for evaluating their characteristics. We begin by reviewing number systems and digital arithmetic along with basic arithmetic circuits such as ripple-carry adders. From there, we move to more complex adders (carry-look-ahead, carry-skip, carry-bypass, etc.), multipliers, dividers, and floating-point units. For each circuit introduced, we will develop techniques and present theory for evaluating their functionality and speed. Other methods will be described for analyzing a circuit's power consumption, testability, silicon area requirements, correctness, and cost. In addition, we will utilize various CAD tools to evaluate the circuits described. Finally, advanced timing and clocking concepts will be investigated. For example, the notion of clock skew will be introduced and its impact on clock period for sequential circuits will be analyzed. We will also learn how to analyze and design asynchronous circuits, a class of sequential circuits that do not utilize a clock signal. Course projects focus on key arithmetic aspects of various machine learning algorithms including: K-nearest neighbors, neural networks, decision trees, and support vector machines.

*Note: Although students in 18-340 and 18-640 will share lectures, labs, and recitations, students in 18-340 and 18-640 will receive different homework assignments, design projects, and exams. In some cases 18-640 students will also have different or additional lab sessions. The homework assignments, design projects, and exams that are given to the students registered for 18-640 will be more challenging than those given to the students registered for 18-340 in that they will have more complex designs, involve additional theoretical analysis, and have more stringent specifications (e.g., in area, power, performance, and robustness).

Design Patterns for Smartphone Development (18-641) – 12 Units

This course provides an intensive exploration of computer programming by reviewing the basics of Object-Orientated programming and moving quickly to advanced programming using design patterns and a multi-tiered architecture. As part of the course work, students will learn smartphone development and how to apply the learned programming techniques to create extensible, reusable and quality software. It is intended for master's students who have had some prior, but perhaps limited, programming experience in Java or another object-oriented programming language; it is not intended as a first course in programming.

Embedded System Software Engineering (18-642) – 12 Units

In a very real sense, embedded software is what makes our everyday world function. From self-driving cars to chemical processing plant equipment, and from medical devices to the electric grid, embedded software is everywhere. You already know how to write code for a microcontroller. Now, learn software quality, safety, and security skills that are required to make embedded systems that can handle the messiness of the real world. This course provides in- depth coverage of the topics that are essential to the success of embedded software projects based on case studies of industry project teams that have suffered or failed. Students will learn about a variety of topics including: lightweight but high quality embedded software processes, technical best practices for embedded software, effective testing and validation, causes of software system failures, software for safety-critical systems, and embedded-specific aspects of software security. The material will generally be broken up into a set of four related topics each week, with one assignment per topic weekly, involving a combination of programming assignments, tool use experiences, and research questions to get hands-on experience at dealing with the types of problems that are encountered in industry embedded projects. We assume you already know how to code in C and understand the basics of microcontrollers. This course is about getting you ready to build industry-strength embedded projects. Undergraduate students are required to take 18349 prior to enrolling in this course. Graduate students are strongly encouraged to take 18-600/15-213/15-513/18-213 before or concurrently with this course.

Reconfigurable Logic: Technology, Architecture and Applications (18-643) – 12 Units

Three decades since its original inception as a lower-cost compromise to ASIC, modern Field Programmable Gate Arrays (FPGAs) are versatile and powerful systems-on-a-chip for many applications that need both hardware level efficiency and the flexibility of reprogrammability. More recently, FPGAs have also emerged as a formidable computing substrate with applications ranging from data centers and mobile devices. This course offers a comprehensive coverage of modern FPGAs in terms of technology, architecture and applications. The coverage will also extend into on-going research investigations of future directions. Students will take part in a substantial design projects applying the latest FPGA platforms to compute acceleration. Register-Transfer Level (RTL) hardware design experience is required.

Special Topics in Computer Systems (18-644) – 12 Units

This course covers applications of mobile hardware systems and the hardware associated with these systems. The course enables students 1) to analyze the implications of mobile hardware capabilities and restrictions in order to plan and develop mobile applications, 2) to propose and justify new ideas in the mobile space, and 3) to expose students to a range of mobile systems. Students will be able to devise and interface simple hardware additions to enable new applications. The course covers the elements of embedded systems development, such as hardware fundamentals, system development, as well mobile topics such as power management, machine-to-machine communication, and applications. Student teams will undertake small HW/SW interfacing projects on Arduino to sharpen their experience, and shape and build a novel application with the faculty. Unlike a conventional hardware course, the course would instead focus on the system and software implications, rather than the hardware components (i.e. CPU and radio). Prerequisites: Some understanding of basic electrical terminology; Java programming and C programming desired

How to Write Fast Code (18-645) – 12 Units

The fast evolution and increasing complexity of computing platforms pose a major challenge for developers of high performance software for engineering, science, and consumer applications: it becomes increasingly harder to harness the available computing power. Straightforward implementations may lose as much as one or two orders of magnitude in performance. On the other hand, creating optimal implementations requires the developer to have an understanding of algorithms, capabilities and limitations of compilers, and the target platform's architecture and microarchitecture. This interdisciplinary course introduces the student to the foundations and state-of-the-art techniques in high performance software development using important functionality such as linear algebra kernels, transforms, filters, and others as examples. The course will explain how to optimize for the memory hierarchy, take advantage of special instruction sets, and how to write parallel code for multicore, manycore, and cluster platforms, based on state-of-the-art research. Further, a general strategy for performance analysis and optimization is introduced that the students will apply in group projects that accompany the course. Finally, the course will introduce the students to the recent field of automatic performance tuning. Prerequiste: Senior ECE or CS undergraduate student or higher, solid C programming skills.

Low-Power System-on-Chip Architecture (18-646) – 12 Units

This course provides the architectural foundations for low-power systems out of which sensors, low power embedded systems, internet of things devices and the like are created. It includes microarchitecture, energy-aware programming, energy harvesting, energy management, and real-time measurement and abstraction of energy usage at runtime. As a part of the course, we will naturally build embedded systems at a level where energy usage can be measured and controlled.

Embedded Real-Time Systems (18-648) – 12 Units

Real-time embedded systems pervade many aspects of modern life ranging from household appliances, transportation and motion control systems, medical systems and devices, robotics, multimedia and mobile communications, video-games, energy generation/distribution/management, to aerospace and defense systems. This course has three complementary goals. One, it will cover the core concepts and principles underlying these systems, including resource management, scheduling, dependability and safety. Implications to multi-core platforms, SoCs, networks and communication buses will also be discussed. Mathematical models and analysis techniques will be presented. Two, the course will offer hands-on experience with implementing real-time embedded systems on realistic platforms. This will be facilitated by detailed discussions of hardware-software interfaces, concurrency and communications. Finally, application-level concepts such as signal processing, image processing, computer vision, sensor fusion and feedback control will complete an overview of the breadth and depth of real-time embedded systems. Knowledge of the C programming language, basic computer architecture and an assembly language will be assumed.

Distributed Embedded Systems (18-649) – 12 Units

Embedded computers seem to be everywhere, and are increasingly used in applications as diverse as transportation, medical equipment, industrial controls, and consumer products. This course covers how to design and analyze distributed embedded systems, which typically consist of multiple processors on a local area network performing real time control tasks. The topics covered will include issues such as communication protocols, synchronization, real-time operation, fault tolerance, distributed I/O, design validation, and industrial implementation concerns. The emphasis will be on areas that are specific to embedded distributed systems as opposed to general-purpose networked workstation applications. This course assumes that students already know fundamental topics such as interrupts, basic I/O, and uniprocessor scheduling that are commonly taught in introduction-level embedded system courses such as 18- 348 and 18-349. Any graduate student who has not taken one of the pre-requ isites is responsible for understanding relevant material necessary for this course. Additionally, all students are responsible for knowing or learning on their own intermediate-level programming in Java. Prerequisites: 18348 or 18349 and senior or graduate standing.

Policies of Wireless Systems (18-650) – 12 Units

This course will address public policy issues related to wireless systems. It investigates policies related to a wide variety of emerging wireless systems and technologies, including current and next-generation cellular systems, wifi and white space devices, emerging methods of accessing spectrum, communications systems for emergency responders (firefighters, police, emergency medical services), current and next-generation television, and satellite communications. This can include the government role in facilitating the creation of infrastructure, in advancing competition among broadcasters and communications service providers, in using scarce spectrum efficiently, in promoting public safety and homeland security, and in protecting privacy and security. Because these are inherently interdisciplinary issues, the course will include detailed discussions of technology, economics, and law, with no prerequisites in any of these areas. This course is cross-listed as 18-650, 19-403, 19-713, and 95-824. Senior or graduate standing required.

Networked Cyber-Physical Systems (18-651) – 12 Units

Cyber-physical systems (CPS) represent a new class of systems that bring together sensing, computation, communication, control and actuation to enable continuous interactions with physical processes. This integration of networked devices, people, and physical systems provides huge opportunities and countless applications in biology and healthcare, automotive and transportation, power grids and smart buildings, social and financial markets, etc. Hence, CPS need to provide real-time efficiency, adaptability, optimality, security and robustness to natural disasters or targeted attacks. While the focus on embedded systems relies on building computational models for specific applications, CPS need a multidisciplinary approach and a more general computational paradigm such that more-direct interactions between the system and physical world become possible. This course is primarily an in-depth introduction to networked CPS with an emphasis on methods for modeling, design, and optimization. Focus is on the dominant design paradigms like low-power and communication-centric design. Topics to be covered include: physical processes, models of concurrency, sensing and workload modeling, human behavior modeling, data-driven modeling, networking at micro- and macro-scale, system-wide resources management, programming, validation and integration. From a practical standpoint, students will directly experiment with hardware prototypes and software tools to explore concrete CPS examples. By structure and contents, this class is primarily targeted to ECE students; it can also provide a valuable basis for interdisciplinary research to students in CS and related disciplines.

Foundations of Software Engineering (18-652) – 12 Units

In this course, you will learn about software engineering paradigms that have shaped the software industry over the past few decades. You will be exposed to fundamental disciplines of software engineering as well as engineering practices that crosscut system, project, and user perspectives. You will learn to iteratively define requirements, and architect, design, implement, integrate, test, and deploy a solution. You will work on self-organizing teams and manage the work collaboratively. You will also learn to solve a real problem subject to multiple constraints while keeping the stakeholders involved throughout the lifecycle and balancing the underlying engineering tradeoffs. The topics are applied in the context of a semester-long group project. Please note that this course is intended for ECE master students with a concentration in Software Engineering and will satisfy the "Software Engineering and Design" course area requirement.

Prerequisites: Basic software development experience with proficiency in at least one modern programming language and modern programming concepts. Prior to admission, students must successful complete a programming assignment to demonstrate familiarity with required software technologies. Students who have successfully completed 18-652, Foundations in Software Engineering, are not eligible to take this course.

Software Architecture and Design (18-653) – 12 Units

Software Architecture and Design is a one-semester course, aiming to train our graduate students from software engineers toward becoming a Software Architect, who is the Technical Lead¿ of a software project team. The primary objective of the course is to help students develop skills in designing, developing, and justifying reasonable software architecture for enterprise-scale software-intensive systems, considering both functional and non-functional requirements as well as contextual system environments. Core topics include: overview of software architecture, micro architectural patterns (so-called design patterns) and macro architectural patterns (i.e., modern patterns), service oriented architecture, architectural modeling, viewpoints and perspectives, architectural analysis techniques, architectural tactics (QoS), agile architecture, and some advanced topics. Literature survey and study of state-of-the-art technologies, as well as both individual and group project work, are essential ingredients of this class. Research and practical projects build upon one another. Please note that this course is intended for ECE master students with a concentration in Software Engineering and will satisfy the Software Engineering and Design requirement. Anti-requisites: 17-655 from CS Dept. Pre-requisites: 18-652

Software Verification and Testing (18-654) – 12 Units

Verification and testing (V&T) support software engineers and development teams in their endeavor to build dependable systems. These interrelated activities form the backbone of a high-quality software solution that performs its function as intended. V&T is no longer considered an exclusively backend phase undertaken by a separate quality assurance unit, vulnerable to availability of discretionary resources near project end. Rather, V&T is a cross-functional discipline applied throughout the software lifecycle from beginning to end. As such V&T is an integral and essential part of any sensible software development process. This course introduces the students to concepts, principles, theory, types, tools, and techniques of V&T with exposure to both modern, widely-applicable approaches and traditional, formal techniques. Students will acquire sufficient depth and breadth in V&T through a balanced coverage of topics. The course syllabus spans fundamentals such as V&T principles, systematic testing, input space analysis, and test coverage; practical strategies such as test-driven development, unit testing, and test design; and formal approaches such as abstraction, model checking, static analysis, and symbolic execution. Please note that this course is intended for ECE master students with a concentration in Software Engineering and will satisfy the ¿Analysis¿ area core course requirement. Please note that this course is intended for ECE master students with a concentration in Software Engineering and will satisfy the Analysis area core course requirement.

Service Oriented Computing (18-655) – 12 Units

Service Oriented Computing (SOC) is a one-semester course that introduces how to build and leverage software systems as a service to facilitate reusability, scalability, availability, and interoperability, in a networked environment. SOC has been significantly changing the way how software systems and applications are analyzed, architected, designed, implemented, tested, evaluated, delivered, consumed, maintained and evolved. Its comprising techniques have enabled the emergence of the contemporary third-generation software engineering: Service Oriented Software Engineering (SOSE). In this course, key concepts and standards, core enabling technologies and innovative consulting methods, as well as major solution patterns, are captured in the whole lifecycle of SOSE. Research and practical projects build upon one another. Please note that this course is intended for ECE master students with a concentration in Software Engineering and will satisfy the "Software Engineering and Design" area requirement. Prerequisites: Proficiency with either Java or Python programming language and in modern software development concepts.

Data Intensive Workflow Development for Software Engineers (18-656) – 12 Units
Many software systems nowadays have become increasingly data intensive and data centered applications. Manipulating comprehensive datasets and heterogeneous data sources typically requires composing and executing a series of computational or data manipulation steps, called a workflow. A data-oriented workflow is a formal way of defining, automating, repeating and adapting multi-step computational procedures driven by data events. The primary objective of the course is to help students develop skills in engineering data-oriented workflows, in the context of service-oriented software engineering, big data, cloud computing, Internet of Things, social networking, and mobile computing. Core topics include: data-oriented workflow theory, models, languages, techniques, architectures, systems, tools; workflow discovery, reuse, recommendation, orchestrations and choreographies; workflow properties and data dependencies; data provenance capture, storage, retrieval, and mining; workflow execution, allocation, and optimization on cloud; workflow as a service, as well as collaborative data analytics on the Internet. Literature survey and study of state-of-the-art technologies, as well as both individual and group project work, are essential ingredients of this class. Research and practical projects build upon one another. Please note that this course is intended for ECE master students with a concentration in Software Engineering and will satisfy the Systems area requirement.

Decision Analysis and Engineering Economics for Software Engineers (18-657) – 12 Units
Engineering software systems entails continuously making resource and technical decisions at multiple levels subject to different sources of uncertainty, cost-benefit tradeoffs, historical data, and flexibility demands. This course will develop quantitative and modeling skills for economics- based and decision-theoretic reasoning in software engineering through a repertoire of techniques from several fields. Special consideration will be given to reasoning under uncertainty and empirical approaches to tackle a variety of software engineering decision-making problems, including technology, architecture, design, product, and process decisions. The analysis techniques covered will be illustrated through domain-specific examples. Analysis techniques that will be covered include Monte Carlo Simulation, Net Present Value, Expected Value of Information, Decision Tree Analysis, Real Options Theory, Utility Theory, and Analytic Hierarchy Process. Basic data analysis concepts, including descriptives, linear regression, correlation, and hypothesis testing will be explained and used. Examples and fully-developed case studies will illustrate how these techniques can be combined to best leverage their strengths. The course has a practical focus, but includes coverage of the necessary background theories. Orientation is distinctly quantitative. Knowledge of basic probability is required. Pre-requisites: 18-652 (can be taken concurrently)

Software Engineering Methods (18-659) – 12 Units
There has been a rapid evolution of software engineering development methods over the past decades. From Waterfall to Iterative and Incremental, to Agile and Lean, we have witnessed waves of new methods, each adding significant value to the field. However, the plethora of available methods poses a challenge for software practitioners: Which method should be adopted on a specific software project? Software Engineering Methods addresses this challenge by introducing students to emerging approaches for developing software-intensive systems. Given the vast spectrum of software development endeavors, these approaches aim at defining custom hybrid methods by focusing on software development principles and practices together with their applicability to specific project contexts. Students learn to analyze the context of a software project and recommend a custom hybrid development method that satisfies the project's specific needs. Students apply this knowledge in the context of a semester-long project where the entire class works together as a team of teams. They define the optimal software development method for their project aimed at evolving an existing software system. They build new system increments by adopting their own method. They monitor their progress and reflect on the effectiveness of their approach and the need for continuous improvement. This course is intended for ECE master

students with a concentration in Software Engineering and will satisfy the "Systems" course area requirement. Prerequisites: 18652 or instructor permission

Optimization (18-660) – 12 Units

Many design problems in engineering (e.g., machine learning, finance, circuit design, etc.) involve minimizing (or maximizing) a cost (or reward) function. However, solving these problems analytically is often challenging. Optimization is the study of algorithms and theory for numerically solving such problems, and it underpins many of the technologies we use today. This course is an introduction to optimization. Students will: (1) learn about common classes of optimization problems, (2) study (and implement) algorithms for solving them, and (3) gain hands-on experience with standard optimization tools. We will focus on convex optimization problems, but will also discuss the growing role of non-convex optimization, as well as some more general numerical methods. The course will emphasize connections to real-world applications including machine learning, networking, and finance. The course will involve lectures, homework, exams, and a project.

This course is crosslisted with 18460. Although students in 18460 will share lectures with students in 18660, students in 18460 will receive distinct homework assignments, distinct design problems, and distinct exams from the ones given to students in 18660. Specifically, the homework assignments, design problems and exams that are given to the 18660 students will be more challenging than those given to the 18460 students.

Hardware Architectures for Machine Learning (18-663) – 12 Units

Machine learning is poised to change the landscape of computing in more ways than its broad societal applications. Indeed, hardware architectures that can efficiently run machine learning face increasing challenges due to power consumption or run time constraints that technology, platforms, or users impose. This course provides an overview of current advances in hardware architectures that can enable fast and energy efficient machine learning applications from the edge to the cloud. Topics include hardware accelerators, hardware-software co-design, and general or application specific system design and resource management for machine learning applications.

ULSI Technology Status and Roadmap for System on Chips and System in Package (18-664) – 12 Units

This course provides the necessary background for the state-of-the art technologies utilized by the leading edge products covering full spectrum of market drivers from mobile platforms, microprocessors, game chips to the highest performance systems for enterprise solutions computing. We will present all key components of such systems, i.e., logic, analog/RF and embedded memories. Then we present the technology roadmap for the upcoming generations in terms of device architecture options for logic devices (FinFET, Nanowire and Tunnel FET) and memories (Phase Change Memory, Resistive RAM and Magnetic RAM/Spin-Transfer Torque RAM) from the device level all the way to the system level specifications. The last part of the class will be devoted to the system integration issues, namely 3-dimensional integration approaches. This course is designed for MS and PhD students from diverse areas: System/Hardware Design, Circuits and Devices/Nanofabrication and is aimed at bridging the gap among these areas.

Analytical Performance Modeling & Design of Computer Systems (18-687) – 12 Units

In designing computer systems one is usually constrained by certain performance requirements. For example, certain response times or throughput might be required of the system. On the other hand, one often has many choices: One fast disk, or two slow ones? What speed CPU will suffice? Should we invest our money in more buffer space, or a faster processor? Which migration policy will work best? Which task assignment policy will work best? How can we redesign the scheduling policy to improve the system performance? Often answers to these questions are counter-intuitive. Ideally, one would like to have answers to these questions before investing the time and money to build a system. This class will introduce students to analytic stochastic modeling with the aim of answering questions such as those above. Topics covered include Operational Laws, Markov Chain Theory, Queuing Theory, Modeling Empirical Loads, Simulations, and Management of Server Farms.

Introduction to Neuroscience for Engineers (18-690) – 12 Units
The first half of the course will introduce engineers to the neurosciences from the cellular level to the structure and function of the central nervous system (CNS) vis-à-vis the peripheral nervous system (PNS) and include a study of basic neurophysiology; the second half of the course will review neuroengineering methods and technologies that enable study of and therapeutic solutions for diseases or damage to the CNS. A goal of this course is to provide a taxonomy of neuroengineering technologies for research or clinical application in the neurosciences. This course is cross listed with 42-630

Statistical Discovery and Learning (18-697) – 12 Units
This course is designed to give students a thorough grounding in the methods, theory, mathematics and algorithms needed to do research and applications in machine learning. The topics of the course draw from machine learning, classical statistics, data mining, Bayesian statistics and information theory and other areas. This course is project-oriented and is intended to give students abundant hands-on experience with different machine learning algorithms. Students who have already taken CS 10-701/15-781 Machine Learning should not take this course.

Neural Signal Processing (18-698) – 12 Units
The brain is among the most complex systems ever studied. Underlying the brain's ability to process sensory information and drive motor actions is a network of roughly 1011 neurons, each making 103 connections with other neurons. Modern statistical and machine learning tools are needed to interpret the plethora of neural data being collected, both for (1) furthering our understanding of how the brain works, and (2) designing biomedical devices that interface with the brain. This course will cover a range of statistical methods and their application to neural data analysis. The statistical topics include latent variable models, dynamical systems, point processes, dimensionality reduction, Bayesian inference, and spectral analysis. The neuroscience applications include neural decoding, firing rate estimation, neural system characterization, sensorimotor control, spike sorting, and field potential analysis. Prerequisites: 18-290; 36-217, or equivalent introductory probability theory and random variables course; an introductory linear algebra course; senior or graduate standing. No prior knowledge of neuroscience is needed

Technical Writing for Engineers: Linguistic Foundations (18-701) – 6 Units
Mini 1 (Linguistic Foundations) is designed for engineering students who are preparing for taking Qualifying exams. We will review the structure of Quals that have succeeded and Quals that have been less successful. Students will learn the linguistic foundations of successful overview papers (like those required in qualifying exams). They will learn the linguistic basis of appropriate citation and the competent elaboration of the work of others. They will learn effective linguistic practices of transitioning from the work of others to their own work and elaborating their own work. They will learn principles of concision, character/action, topical coherence, cohesion, and emphasis, principles that work together to provide the written portion of a Qualifying exam with an easy flow and readability. They will learn how this system of principles can help them detect gaps in knowledge they will need to fill in by the time of the oral examination, if not in the written portion of the Qual itself. To the greatest extent possible, students will learn to apply these linguistic principles on the written portion of the Quals they are preparing that semester or have prepared in previous semesters. Prerequisites: ECE PhD standing is required.

Technical Writing for Engineers: Genre Foundations (18-702) – 6 Units
Mini 2 (Genre Foundations) is designed for engineering students ready to focus on archival genres that report new knowledge, genres including but not limited to conference papers and journal publications. Students will learn principles of academic novelty and its history in the Royal Society. We will use customized software that give students a "zoomed-in" look at the impressive variety

through which introductions establish significance and how they open a "gap" that the author's research was designed to fill. We will overview the important genre features and functions of the various sections of the archival paper. Students are expected to bring to the course archival documents they are currently preparing to submit. Students will use the mini to execute a systematic revision of their document based on the genre functions and features discussed. Prerequisites: ECE PhD standing is required.

Managing and Leading Research and Development (18-703) – 12 Units

This course will provide an insider's look at issues in industrial research and development laboratories that future industrial R&D personnel are likely to face.

The instructor, Prof. Mark Kryder spent nine years as Chief Technical Officer and Senior Vice President, Research for Seagate Technology, the largest disk drive manufacturer in the world. In the course, he will try to give students an improved understanding of how research and development are done in a major high-tech firm today. The course is built around the instructor's personal experiences, but also draws heavily from business management literature and business case studies. It is expected that the course will make the transition from the university to industry easier and faster for students who have taken it and enable them to become more effective in an industrial setting in a shorter period of time. Examples of issues to be discussed will be the impact of various organizational structures upon R&D; What characteristics are desired in a research staff member vs. a staff development engineer?, What is the importance of diversity in a R&D setting? What are the relative importance of technology, marketing expertise and corporate business models in determining success of a product?, What is meant by "corporate culture" and how does it get defined?, How important are collaboration and teamwork in R&D and are they different?, What is Six Sigma and how important is it in today's business world?, How do you measure performance in R & D?, How do you effectively transfer technology from research to development?, how can you effectively leverage university research and industrial consortia?, How important is intellectual property in various industries? How important is corporate size?, What is the role of technology vision?, What are the effects of globalization on R&D?, What is a technology steering council and how can it be used to facilitate technology transfer and development?

Elements of Photonics for Communication Systems (18-712) – 12 Units

The aim of this course is to provide students with a basic understanding of the elements of photonics, including the necessary primary devices that form the building blocks of modern optical communication systems. The photon is the fundamental unit particle of light, with frequencies in the range of several hundred Terahertz (~100 x 1012 Hz). It is a fact of the fundamental theorem of communication that information capacity increases directly with frequency. It is no wonder then that photonic communication systems have become the backbone of modern, ultra-fast and high capacity communication networks. The use of light in communication systems involves the generation, transmission, and detection of photons, along with the encoding (modulation) of signals of interest onto the light carrier wave, and the subsequent decoding (de-modulation) at the destination.

This course begins with an introduction to basic electromagnetic theory (in the frequency range that corresponds to light). The introduction includes Maxwell's equations in both free space and dielectric media. The scalar wave equation derived from the vector Maxwell equations is solved in free space as well as in dielectric media, taking into account the boundary conditions that affect the transmission and reflection of light at the dielectric interfaces. This background is then used in the discussion of the dielectric slab and the related fiber-optic waveguide that is used in the transmission of optical signals in short- and long-haul communication systems.

The course continues with a discussion of semiconductor light generators, with a particular focus on edge-emitting and surface-emitting lasers. Photon detectors—of the semiconductor variety—are then discussed. The course ends with a discussion of other important optical components such as modulators, filters, couplers, multiplexers and demultiplexers. Prerequisites: 18-300 and 18-310 and (18-402 or 33-439) and senior or graduate standing.

Physics of Applied Magnetism (18-715) – 12 Units

In this course we address the physics of magnetism of solids with emphasis on magnetic material properties and phenomena which are useful in various applications. Various applications of magnetism are used to motivate the understanding of the physical properties and phenomena. The content of this course includes the origins of magnetism at the atomic level and the origins of magnetic ordering (ferro-, ferri-, and antiferro-magnetism), magnetic anisotropy, magnetic domains, domain walls, spin dynamics and electronic transport at the crystalline level. The principles of magnetic crystal symmetry, tensors, and energy minimization are utilized to explore magnetic properties such as resonance, domain structures, magneto crystalline anisotropy, magnetostriction and magnetoelasticity, and susceptibility. Phenomenological properties, such as the technical magnetization process, are used to describe mechanisms of coercivity, eddy current effects and losses, while energy minimization and relaxation are used to explain properties such as single domain particle behavior, memory mechanisms, magnetic aftereffects and thermal stability. Prerequisite: 18-300 or equivalent background in electromagnetic fields; senior level solid state physics and materials, or the equivalent, and a senior or graduate student standing.

Advanced Analog Integrated Circuits Design (18-721) – 12 Units

This course will familiarize students with advanced analog integrated circuit design issues. Analog circuit design issues play an important role in creating modern ICs. First and foremost, analog circuits act as the interface between digital systems and the real world. They act to amplify and filter analog signals, and to convert signals from analog to digital and back again. These analog interfaces appear in all communications devices (e.g., cell phones) both to condition the "transmitted" signal and as sensitive "receivers." In addition, these analog interfaces appear in sensors (e.g., accelerometer). The goal of this course is to familiarize students with some of the advanced analog circuit design ideas that are involved in these tasks. Specific topics will include analog filtering (continuous-time and discrete-time), sample-and-hold amplifiers, analog-to- digital converters, digital-to-analog converters. Prerequisites: 18-623 (was 18-523 before Fall 2005) and senior or graduate standing.

RFIC Design and Implementation (18-723) – 12 Units

This course covers the design and analysis of radio-frequency integrated systems at the transistor level using state of the art CMOS and bipolar technologies. It focuses on system-level trade-offs in transceiver design, practical RF circuit techniques, and physical understanding for device parasitics. Accurate models for active devices, passive components, and interconnect parasitics are critical for predicting high-frequency analog circuit behavior and will be examined in detail. The course will start with fundamental concepts in wireless system design and their impact on design trade-offs in different transceiver architectures. Following that, RF transistor model, passive matching networks will be discussed. Noise analysis and low-noise amplifier design are studied next. The effects of nonlinearity are treated along with mixer design techniques. Practical bias circuit for RF design will be illustrated. Then, the importance of phase noise and VCO design will be considered together. The course will conclude with a brief study of frequency synthesizer and power amplifier design. Senior or graduate standing required.

Advanced Digital Integrated Circuit Design (18-725) – 12 Units

The purpose of this course is to study the design process of VLSI CMOS circuits. This course covers all the major steps of the design process, which include: logic, circuit and layout design. A variety of computer-aided tools are discussed and used in class. The main objective of this course is to provide VLSI design experience that includes design of basic VLSI CMOS functional blocks, verification of the design, testing and debugging. During the course, one complex VLSI project is submitted for fabrication. 4 hrs. lec.

Network Security (18-731) – 12 Units

Some of today's most damaging attacks on computer systems involve exploitation of network infrastructure, either as the target of attack or as a vehicle to advance attacks on end systems.

This course provides an in-depth study of network attack techniques and methods to defend against them. Topics include firewalls and virtual private networks; network intrusion detection; denial of service (DoS) and distributed denial-of-service (DDoS) attacks; DoS and DDoS detection and reaction; worm and virus propagation; tracing the source of attacks; traffic analysis; techniques for hiding the source or destination of network traffic; secure routing protocols; protocol scrubbing; and advanced techniques for reacting to network attacks. Prerequisite: 18- 630 OR 18-730, and senior or graduate standing.

Applied Cryptography (18-733) – 12 Units

A wide array of communication and data protections employ cryptographic mechanisms. This course explores modern cryptographic (code making) and cryptanalytic (code breaking) techniques in detail. This course emphasizes how cryptographic mechanisms can be effectively used within larger security systems, and the dramatic ways in which cryptographic mechanisms can fall vulnerable to cryptanalysis in deployed systems. Topics covered include cryptographic primitives such as symmetric encryption, public key encryption, digital signatures, and message authentication codes; cryptographic protocols, such as key exchange, remote user authentication, and interactive proofs; cryptanalysis of cryptographic primitives and protocols, such as by side-channel attacks, differential cryptanalysis, or replay attacks; and cryptanalytic techniques on deployed systems, such as memory remanence, timing attacks, and differential power analysis. Senior or graduate standing required.

Foundation of Privacy (18-734) – 12 Units

Privacy is a significant concern in modern society. Individuals share personal information with many different organizations - healthcare, financial and educational institutions, the census bureau, web services providers and online social networks - often in electronic form. Privacy violations occur when such personal information is inappropriately collected, shared or used. We will study privacy in a few settings where rigorous definitions and enforcement mechanisms are being developed - statistical disclosure limitation (as may be used by the census bureau in releasing statistics), semantics and logical specification of privacy policies that constrain information flow and use (e.g., by privacy regulations such as the HIPAA Privacy Rule and the Gramm-Leach-Bliley Act), principled audit and accountability mechanisms for enforcing privacy policies, anonymous communication protocols - and other settings in which privacy concerns have prompted much research, such as in social networks, location privacy and Web privacy (in particular, online tracking & targeted advertising).

Special Topics in Computer Systems: Engineering Safe Software Systems (18-737) – 12 Units

Modern software systems suffer from poor reliability and security due to overwhelming complexity. Traditional software testing and debugging, which account for more than half the cost of software development, often fail to find critical bugs in software. In recent years there has been an increasing interest in developing automated techniques for improving software reliability. These techniques combine ideas from program analysis, constraint solving, and model checking and have shown great promises in making software more reliable and secure. In this course, we will study these new techniques, with emphasis on automated test-case generation based on symbolic execution and fuzz testing. We will see how these techniques can be used for detecting bugs in software, finding performance bottlenecks, detecting and preventing security vulnerabilities, and analyzing the reliability of software components. We will further study component-based verification and emerging techniques for automated software repair. Finally, we will discuss challenges related to the analysis of systems with deep learning components, which have a simpler structure than more traditional software but tend to be massive in scale. Senior or graduate standing required.

Sports Technology (18-738) – 12 Units

The course's lecture content will cover background material on key aspects of sports technology,

including topics such as computer vision, artificial intelligence, data mining, the physics of sports and understanding of real-world systems and guest lectures from experts in the field. The topics covered in depth will include the types of sensors and algorithms used in real-world systems deployments today, as well as new applications of the Internet of Things to different aspects of sports, including training, performance, coaching, etc.
This course also comprises a semester-long project experience and research paper geared towards the development of skills to design realistic and practical embedded/mobile systems and applications that enhance various aspects of the training, coaching, playing and scouting of different sports, including football, hockey, baseball, soccer, etc. Students will work in teams on a project that will involve the hands-on design, configuration, engineering, implementation and testing of an embedded-system prototype of an innovative sports technology of their choice. Students will be expected to leverage proficiency and background gained from other courses, particularly with regard to embedded real-time principles, software systems and embedded programming. The project will utilize a synergistic mixture of skills in system architecture, modular system design, software engineering, subsystem integration, debugging and testing. From inception to demonstration of the prototype, the course will follow industrial project practices, such as version control, design requirements, design reviews, user studies and quality assurance plans. Advanced undergraduate or graduate standing required.

Energy Aware Computing (18-743) – 12 Units
This course provides a comprehensive coverage of topics related to energy aware and green computing. While it is widely recognized that power consumption has become the limiting factor in keeping up with increasing performance trends, static or point solutions for power reduction are beginning to reach their limits. This course is intended to provide an insight into: (i) power and energy consumption modeling and analysis; (ii) energy aware computing, i.e., how various power reduction techniques can be used and orchestrated such that the best performance can be achieved within a given power budget, or the best power efficiency can be obtained under prescribed performance constraints; and (iii) green computing in the context of large scale computing systems or smart grid-aware computing. Recommended: basic VLSI design, basic computer system organization, basic compiler design and OS knowledge. Prerequisites: Senior or Graduate Standing.

Connected Embedded Systems Architecture (18-744) – 12 Units
Connected Embedded Systems Architecture (CESA) is a one-semester lab-based course that addresses the core concepts of modern embedded systems with a particular emphasis on the emerging field of apps that span small, embedded devices (including wearable electronics, so-called Internet of Things devices, and mobile phones) to the cloud. We will examine the evolution of the nature of IoT from the early days of wireless sensor networks to the future vision of federated, time-synchronized, scalable, virtualized "fog computing" platforms.
The course is designed to take a systems approach and, as such, will include relevant topics from both software (cloud, network, device) and hardware (network and device). The course content is aimed at systems engineers who wish to architect, develop and deploy cloud-connected embedded systems in which the "apps" change, mature and evolve over time. The course stresses the creation of engineering frameworks in which tradeoffs can be rationally made between computing and storage that should be done on coin-cell-powered devices vs. computing and storage that should be done in the network or in the cloud.

Rapid Prototyping of Computer Systems (18-745) – 12 Units
This is a project-oriented course which will deal with all four aspects of project development; the application, the artifact, the computer-aided design environment, and the physical prototyping facilities. The class, in conjunction with the instructors, will develop specifications for a mobile computer to assist in inspection and maintenance. The application will be partitioned between human computer interaction, electronics, industrial design, mechanical, and software components. The class will be divided into groups to specify, design, and implement the various subsystems.

The goal is to produce a working hardware/software prototype of the system and to evaluate the user acceptability of the system. We will also monitor our progress in the design process by capturing our design escapes (errors) with the Orthogonal Defect Classification (ODC). Upon completion of this course the student will be able to: generate systems specifications from a perceived need; partition functionality between hardware and software; produce interface specifications for a system composed of numerous subsystems; use computer-aided design tools; fabricate, integrate, and debug a hardware/software system; and evaluate the system in the context of an end user application. This course is cross-listed as 18540.

Storage Systems (18-746) – 12 Units
This course covers the design, implementation, and use of storage systems, from the characteristics and operation of individual storage devices through the OS, database, and networking approaches involved in tying them together and making them useful to key applications' demands and technology trends. Topics to be covered include: network-attached storage, disk arrays, storage networking, storage management, advanced file systems, disk performance enhancement, wide-area data sharing, and storage security. 3 hrs. lec. The class will continue to be like previous years, with the same advanced content and high-level expectations.

Wireless Device Architecture (18-747) – 12 Units
Growth of the Internet of Things depends on semiconductor devices systems-on-chip (SoC) with significant computational, communications and sensing capabilities. Integration of entire systems on one or a very small number of dies has made it possible to deploy hundreds of billions of end-points that will link the cyber world with the physical world. At this scale, a key design requirement is that such devices can be handled at most once during their lifetime. Batteries should be life-long, and reprogramming should be over-the-air. How then should such devices be architected? We begin by examining modern digital communications including modulation and coding schemes, basic RF subsystems and antennas. We examine the computational structures that allow us to reduce communication to computation. Anticipating that such devices will need to be highly programmable, we consider concepts from traditional computer architecture and their applicability to this energy-constrained domain. We also examine the rapid evolution of transducer technologies and how these are being integrated into SoCs. Then, we consider how an architect can make tradeoffs across these domains to meet design objectives. Students will take advantage of a purpose-built experimental platform called PowerDué that enables deep exploration of these topics in realistic applications. Background in computer architecture, signals and systems, and E&M field theory is recommended. Graduate standing is required to register for this course.

Wireless Sensor Networks (18-748) – 12 Units
The use of distributed wireless sensor networks have surged in popularity in recent years with applications ranging from environmental monitoring, to people- and object-tracking in both cooperative and hostile environments. This course is targeted at understanding and obtaining hands-on experience with the state of the art in such wireless sensor networks which are often composed using relatively inexpensive sensor nodes that have low power consumption, low processing power and bandwidth. The course will span a variety of topics ranging from radio communications, network stack, systems infrastructure including QoS support and energy management, programming paradigms, distributed algorithms and example applications. Some guest lectures may be given. Each discussion-oriented lecture will be preceded by the reading of 1-2 papers, resulting in a rich collection of papers by the end of the semester. Early in the semester, hands-on exercises will be used to teach the programming of FireFly sensor nodes by using the 'nano-RK' power-aware sensor real-time operating system (RTOS) and using 802.15.4 radio communications. Then, project groups of no more than 3 students will define, design, implement and test a sensor network project. Final in-class project presentations will be supplemented by a written report. A final exam may be conducted to evaluate the students' understanding of the materials covered. Grading criteria will include classroom participation, course project content and report, and a final exam. Class size will be limited to 20 students or

less. Hands-on experience with network programming, operating systems and assembly language are essential. Exceptions only with explicit permission of instructor. Prerequisites: 15- 213 and ((18-348 or 18-349) or 15-410), and senior or graduate standing.

Building Reliable Distributed Systems (18-749) – 12 Units

The course provides an in-depth and hands-on overview of designing and developing reliable distributed systems, throughout a system's lifecycle, starting from fault-tolerant design and execution (replication, group communication, databases) to fault-recovery (fault-detection, logging, check-pointing, failure-diagnosis) for various classes of faults (crashes, communication errors, software upgrades). The course will cover real-world practices for reliability, supplemented by case studies of large-scale downtime incidents. The concepts will be taught in the context of contemporary cloud-computing platforms, and the course will include a hands-on project that involves the design, implementation and empirical evaluation of a reliable distributed cloud-based system. Students will be taught to write, review, and present a conference-style research paper by the end of the semester, with the goal of documenting the design, lessons learned and experimental results of their team project. Students can expect to learn about the reliability issues underlying cloud computing, the tools and best practices for implementing and evaluating reliability, and the strengths and weaknesses of current cloud- computing platforms from the perspective of reliability. Prerequisites: Graduate standing or instructor permission

Wireless Networks and Applications (18-750) – 12 Units

This course introduces fundamental concepts of wireless networks. The design of wireless networks is influenced heavily by how signals travel through space, so the course starts with an introduction to the wireless physical layer, presented in a way that is accessible to a broad range of students. The focus of the course is on wireless MAC concepts including CSMA, TDMA/FDMA, and CDMA. It also covers a broad range of wireless networking standards, and reviews important wireless network application areas (e.g., sensor networks, vehicular) and other applications of wireless technologies (e.g., GPS, RFID, sensing, etc.). Finally, we will touch on public policy issues, e.g., as related to spectrum use. The course will specifically cover: Wireless networking challenges Wireless communication overview Wireless MAC concepts Overview of cellular standards and LTE Overview of wireless MAC protocols WiFi, bluetooth and personal area networks, etc. Wireless in today's Internet: TCP over wireless, mobility, security, etc. Advanced topics, e.g., mesh and vehicular networks, sensor networks, DTNs, localization, sensing, etc. Although students in 18-750 will share Lectures and Recitations with students in 18-452, they will receive distinct homework assignments and exams from students in 18-452. The main project will also be different. The students in the two version of the course will also be graded on a separate curve.

Estimation, Detection and Learning (18-752) – 12 Units

This course discusses estimation, detection, identification and machine learning, covering a variety of methods, from classical to modern. In detection, the topics covered include hypothesis testing, Neyman-Pearson detection, Bayesian classification and methods to combine classifiers. In estimation, the topics include maximum-likelihood and Bayesian estimation, regression, prediction and filtering, Monte Carlo methods and compressed sensing. In identification and machine learning, topics include Gaussian and low-dimensional models, learning with kernels, support vector machines, neural networks, deep learning, Markov models and graphical models.

Information Theory (18-753) – 12 Units

The first half of the course comprises of the concepts of entropy, mutual information, the Asymptotic Equipartition property, applications to source coding (data compression), applications to channel capacity (channel coding), differential entropy and its application to waveform channel capacities, and a subset of advanced topics such as network information theory, or rate-distortion theory, as time permits. The second half of the course comprises finite- field algebra, Hamming codes, cyclic codes (CRC and BCH codes), a brief introduction to Reed- Solomon codes, and perhaps universal codes (Lempel-Ziv coding). Prerequisites: 36-217 and senior or graduate standing.

Error Control Coding: Theory and Applications (18-754) – 12 Units
Modern digital communication systems and digital data storage systems owe their success, in part to the use of error control coding. By careful insertion of redundant bits or symbols in the transmitted or stored bit streams, the receiver can detect and correct errors induced by channel impairments such as noise, inter-symbol interference and noise. For example, compact disc (CD) owes its ruggedness to the use of cross-interleaved Reed-Solomon (CIRC) code. High-speed networks employ Cyclic Redundancy Check (CRC) to ensure that the data was transmitted accurately. This course is aimed at introducing the basic theory and select applications of error control coding (ECC). Towards that goal, following topics will be covered. Mathematical background Linear block codes Low density parity check (LDPC) codes Cyclic codes Reed-Solomon (RS) codes Convolutional codes Turbo codes Example application of ECC in digital communications Example application of ECC in digital data storage.

Networks in the Real World (18-755) – 12 Units
18-755 is a graduate-level course that focuses on networks and their applications to various natural and technological systems. Specifically, this class delves into the new science behind networks and their concrete applications technological, biological, and social systems, as well as various design synergies that exist when looking at these systems from a cyber-physical perspective. By scope and contents, this is not just another class on networks. Want to know how complex networks dominate our world? How communities arise in social networks? How group behavior dominates Twitter? How swarms of bacteria can navigate inside the human body? How patterns of interaction can be identified in hardware and software systems? Want to work on cutting edge projects involving systems and synthetic biology? Or social networks? Or networks-on-chip and internet-of-things? Then this class is for you! Course requirements consist of a few homework assignments, a semester-long project, and in-class presentations of relevant papers. By structure and contents, this class targets primarily the computer engineering and computer science students, but it also provides a valuable foundation for interdisciplinary research to students in related disciplines. Senior or graduate standing is required to take this course.

Wireless Communications (18-758) – 12 Units
In this course, the communication problem will be introduced, and channel impairments such as noise, inter-symbol interference and fading will be described. Solutions to combat these impairments, based on digital communication theory, will be described. These will include signal space analysis, detection, equalization, coding and diversity. Examples drawn from communication standards will illustrate how the theory is implemented in practical communication systems.

VLSI CAD: Logic to Layout (18-760) – 12 Units
A large digital integrated circuit (IC) may require 100,000 lines of high-level description in a hardware modeling language, which then turns into 10,000,000 logic gates, which ultimately end up as 1 billion polygons on the masks that define the integrated circuit. This course describes in detail the important CAD tools that perform the many steps of the transformation from Boolean equations to fabrication masks. We focus on mathematical models, algorithms, and data structures. We will write programs for simple versions of these tools. We will look at, and experiment with, a few real tools. The course covers a review of Boolean algebra, followed by (i) synthesis tools for 2-level and multi-level logic, that transform Boolean equations and finite state machine descriptions into optimized logic, and (ii) verification tools that decide whether the logic you built does the same thing as the specification you started with. Finally, the course covers geometric layout synthesis tools for component partitioning, placement, and wire routing and timing verification tools that determine if performance constraints are met. The CAD algorithms covered in the lectures are applicable not only to VLSI systems, but also to non-silicon applications (e.g., social computing, biology, financial).

Circuit Simulation: Theory and Practice (18-762) – 12 Units
This course explores the models, numerical methods and algorithms that are used for simulation and optimization of circuits. The course begins with coverage of the algorithms that are used in the ubiquitous SPICE program and its many variants. This is followed by an overview of the numerous analog and digital simulation techniques that have followed since the introduction of SPICE. The course further covers some of the most recent modeling and simulation work including, but not limited to, model order reduction, harmonic balance methods, nonlinear macromodeling, compact device modeling, and statistical timing analysis. Finally, the use of circuit simulation algorithms for non-circuit problems will be explored. 4 hrs. lec.

Digital System Testing and Testable Design (18-675) – 12 Units
For this course, time- and topic-indexed videos of lecture, homework, projects, etc. will be available from the online learning portal/website. In addition to these resources, two 1-hour live sessions are scheduled per week for recitation. Each student is strongly urged to attend one of these two sessions each week, either remotely or in the classroom on the Carnegie-Mellon Pittsburgh campus. This course examines in depth the theory and practice of fault analysis, test generation, and design for testability for digital ICs and systems. The topics to be covered include circuit and system modeling; fault sources and types; the single stuck-line (SSL), delay, and functional fault models; fault simulation methods; automatic test pattern generation (ATPG) algorithms for combinational and sequential circuits, including the D-algorithm, PODEM, FAN, and the genetic algorithm; testability measures; design-for-testability; scan design; test compression methods; logic-level diagnosis; built-in self-testing (BIST); VLSI testing issues; and processor and memory testing. Advance research issues, including topics on MEMS and mixed- signal testing are also discussed. 4 hours of lecture per week Prerequisites: 18-240 and 15- 211 and (18-340 or 18-341) Senior or graduate standing required.

Linear Systems (18-771) – 12 Units
A modern approach to the analysis and engineering applications of linear systems. Modeling and linearization of multi-input-- multi-output dynamic physical systems. State-variable and transfer function matrices. Emphasis on linear and matrix algebra. Numerical matrix algebra and computational issues in solving systems of linear algebraic equations, singular value decomposition, eigenvalue-eigenvector and least-squares problems. Analytical and numerical solutions of systems of differential and difference equations. Structural properties of linear dynamic physical systems, including controllability, observability and stability. Canonical realizations, linear state-variable feedback controller and asymptotic observer design. Design and computer applications to electronic circuits, control engineering, dynamics and signal processing. 4 hrs. lec. Pre-Reqs: 18-470 or 18-474 and Graduate standing in CIT or MCS.

Non Linear Control (18-776) – 12 Units
This course provides an introduction to the analysis and design of nonlinear systems and nonlinear control systems; stability analysis using Lyapunov, input-output and asymptotic methods; and design of stabilizing controllers using a variety of methods selected from linearization, vibrational control, sliding modes, feedback linearization and geometric control. 4 hrs. lec.

Complex Large-Scale Dynamic Systems (18-777) – 12 Units
This course is motivated by the ever-growing complexity of man-made dynamic systems and the need for flexible monitoring, operations and design techniques for such systems. Of particular interest are systematic model-based methods for relating the key real-life problems for such systems and the state-of-the-art techniques for large-scale dynamic systems. Examples of such real-life complex systems are critical man-made infrastructure systems (electric power systems, gas networks, transport industries, data networks, and their interdependencies) as well as large-scale systems on chips. In this course we will first review the traditional large-scale methods for model simplification (aggregation), time scale separation of sub-processes and singular

perturbation techniques to account for these, stability analysis, and estimation and control. In the second, novel part of this course, we recognize the highly interactive nature of the evolving complex systems, in which much monitoring, data gathering, and decision making is made at the lower, physical levels of the system, and some coordination exists at the higher system level at which physical layers interact. Several conceptual challenges are posed for minimal coordination of such decision makers under high uncertainties, in order to have predictable performance. These concepts will be illustrated using the same man-made network systems of interest introduced at the beginning of the course. Requirements: Some background in dynamic systems is highly desirable. Students interested in large-scale real-life complex systems, their relation to the state-of-the-art methods available and new research challenges will gain from taking this course. 4 hrs lec. Prerequisites: senior or graduate standing.

Speech Recognition and Understanding (18-781) – 12 Units
The technology to allow humans to communicate by speech with machines or by which machines can understand when humans communicate with each other is rapidly maturing. This course provides an introduction to the theoretical tools as well as the experimental practice that has made the field what it is today. We will cover theoretical foundations, essential algorithms, major approaches, experimental strategies and current state-of-the-art systems and will introduce the participants to ongoing work in representation, algorithms and interface design. This course is suitable for graduate students with some background in computer science and electrical engineering, as well as for advanced undergraduates. Prerequisites: Sound mathematical background, knowledge of basic statistics, good computing skills. No prior experience with speech recognition is necessary. This course is primarily for graduate students in LTI, CS, Robotics, ECE, Psychology, or Computational Linguistics. Others by prior permission of instructor.

Machine Learning (18-782) – 12 Units
Machine Learning is a foundational discipline of the Information Sciences. It combines elements from Mathematics, Computer Science, and Statistics with applications in Biology, Physics, Engineering and any other area where automated prediction is necessary. The aim of the course is to present some of the topics which are at the core of modern Machine Learning, from fundamentals to state-of-the-art methods. Emphasis will be put both on the essential theory and on practical examples and lab projects. Each exercise has been carefully chosen to reinforce concepts explained in the lectures or to develop and generalize them in significant ways. This course is directed both at students without previous knowledge in Machine Learning, and at those wishing to broaden their expertise in this area. The course assumes some basic knowledge of probability theory and linear algebra. Nevertheless, the first module of the course will revisit these topics. Students are also expected to have knowledge of basic computer science principles and skills, at a level sufficient to write a reasonably non-trivial computer program. Students who have already taken CS 10-701/15-781 or ECE 18-697 should not take this course.

Wavelets and Multiresolution Techniques (18-790) – 12 Units
The goal of this course is to expose students to multiresolution signal processing methods and their use in real applications as well as to guide them through the steps of the research process. All the necessary mathematical tools are introduced with an emphasis on extending Euclidean geometric insights to abstract signals; the course uses Hilbert space geometry to accomplish that. With this approach, fundamental concepts---such as properties of bases, Fourier representations, sampling, interpolation, approximation, and compression---are often unified across finite dimensions, discrete time, and continuous time, thus making it easier to focus on the few essential differences. The course covers signal representations on sequences, specifically local Fourier and wavelet bases and frames. It covers the two-channel filter bank in detail, and uses this signal-processing device as the implementation vehicle for all sequence representations that follow. The local Fourier and wavelet methods are presented side-by-side, without favoring any one in particular. Through the project, students will learn how to choose an appropriate representation and apply it to the specific problem at hand. There will be 2-3 hours of pre- recorded video per

week that can be viewed online at any time. There will also be two 1-hour sessions in person that are not mandatory and can be viewed later online. The instructor will also be available for meetings in person or online as needed. The total amount of work per week is expected to be around 12 hours on average Pre-requisite: 18-491. Students are expected to have a good background in basic engineering mathematics, signal processing and linear algebra. This course is cross listed with 42-732

Methods in Medical Image Analysis (18-791) – 12 Units
Students will gain theoretical and practical skills in medical image analysis, including skills relevant to general image analysis. The fundamentals of computational medical image analysis will be explored, leading to current research in applying geometry and statistics to segmentation, registration, visualization, and image understanding. Student will develop practical experience through projects using the National Library of Medicine Insight Toolkit (ITK), a popular open-source software library developed by a consortium of institutions including Carnegie Mellon University and the University of Pittsburgh. In addition to image analysis, the course will include interaction with clinicians at UPMC. It is possible that a few class lectures may be videoed for public distribution. Prerequisites: Knowledge of vector calculus, basic probability, and either C++ or python.

Advanced Digital Signal Processing (18-792) – 12 Units
This course will examine a number of advanced topics and applications in one-dimensional digital signal processing, with emphasis on optimal signal processing techniques. Topics will include modern spectral estimation, linear prediction, short-time Fourier analysis, adaptive filtering, plus selected topics in array processing and hemimorphic signal processing, with applications in speech and music processing. 4 hrs. lec.

Pattern Recognition Theory (18-794) – 12 Units
Decision theory, parameter estimation, density estimation, non-parametric techniques, supervised learning, linear discriminant functions, clustering, unsupervised learning, artificial neural networks, feature extraction, support vector machines, and pattern recognition applications (e.g., face recognition, fingerprint recognition, automatic target recognition, etc.). 4 hrs. lec. Prerequisites: 36-217, or equivalent introductory probability theory and random variables course and an introductory linear algebra course and senior or graduate standing.

Bioimage Informatics (18-795) – 12 Units
Bioimage Informatics (formerly Bioimaging) 12 units This course gives an overview of tools and tasks in various biological and biomedical imaging modalities, such as fluorescence microscopy, electron microscopy, magnetic resonance imaging, ultrasound and others. The major focus will be on automating and solving the fundamental tasks required for interpreting these images, including (but not restricted to) deconvolution, registration, segmentation, pattern recognition, and modeling, as well as tools needed to solve those tasks (such as Fourier and wavelet methods). The discussion of these topics will draw on approaches from many fields, including statistics, signal processing, and machine learning. As part of the course, students will be expected to complete an independent project. Prerequisites: 18-396 Signals and Systems

Machine Learning for Signal Processing (18-797) – 12 Units
Signal Processing is the science that deals with extraction of information from signals of various kinds. This has two distinct aspects -- characterization and categorization. Traditionally, signal characterization has been performed with mathematically-driven transforms, while categorization and classification are achieved using statistical tools. Machine learning aims to design algorithms that learn about the state of the world directly from data. An increasingly popular trend has been to develop and apply machine learning techniques to both aspects of signal processing, often blurring the distinction between the two. This course discusses the use of machine learning techniques to process signals. We cover a variety of topics, from data driven approaches for

characterization of signals such as audio including speech, images and video, and machine learning methods for a variety of speech and image processing problems. Prerequisites: Linear Algebra, Basic Probability Theory, Signal Processing and Machine Learning. 18-797 is a cross listing of 11-755 offered by LTI.

Fundamentals of Semiconductors and Nanostructures (18-817) – 12 Units

This course is designed to provide students with a foundation of the physics required to understand nanometer-scale structures and to expose them to different aspects of on-going research in nanoscience and nanotechnology. Illustrative examples will be drawn from the area of semiconductor nanostructures, including their applications in novel and next-generation electronic, photonic, and sensing devices. The course begins with a review of basic concepts in quantum physics (wave-particle duality, Schrödinger's equation, particle-in-a-box, approximation methods in quantum mechanics, etc.) and then continues with a discussion of bulk three- dimensional solids (band structure, density of states, the single-electron effective-mass approximation). Size effects due to nanometer-scale spatial localization are then discussed within a quantum-confinement model in one-, two-, and three- dimensions for electrons. An analogous discussion for photons is also presented. The basic electronic, optical, and mechanical properties of the low-dimensional nanostructures are then discussed. A select number of applications in electronics, photonics, biology, chemistry, and bio-engineering will be discussed to illustrate the range of utility of nanostructures. Upon completion of the course, students will have an appreciation and an understanding of some of the fundamental concepts in nanoscience and nanotechnology. The course is suitable for first-year graduate students in engineering and science (but advanced undergraduates with appropriate backgrounds may also take it with permission from the instructor). Prerequisites: 09-511, 09-701, 09-702, 18-303, 18-310, 18- 402, 27-770, 33-225, 33-234 or familiarity with the material or basic concepts covered in these courses and senior or graduate standing.

Mobile and Pervasive Computing (18-843) – 12 Units

This is a course exploring research issues in the newly emerging field of mobile computing. Many traditional areas of computer science and computer engineering are impacted by the constraints and demands of mobility. Examples include network protocols, power management, user interfaces, file access, ergonomics, and security. This will be an "advanced" course in the truest sense --- most, if not all, the topics discussed will be ones where there is little consensus in the research community on the best approaches. The course will also offer significant "hand-on" experience in this area. Each student will have to present and lead the discussion on a number of papers. Students will work in groups of three under the guidance of a mentor on a hands-on project. Each student will also be required to write one of two documents: (a) a research proposal (similar in spirit to an NSF proposal) on an idea in mobile computing or (b) a short business plan for a commercial opportunity in mobile computing. Grading will be based on the quality of the presentations, the project, and the proposal or business plan. Prerequisites: 15-410 and senior or graduate standing.

Internet Services (18-845) – 12 Units

This course investigates the issues involved in providing scalable and highly available network services over the best-effort Internet. Examples of such services include Web servers, application servers, search engines, proxy caches, online auction systems, and remote visualization. Topics include network programming, server design, clustering, caching, proxies, remote execution, resource naming, discovery, and monitoring, and wide-area metacomputing. The course consists of lectures on existing technology, student presentations of research papers, and a project where students design and implement a significant network service.

Wireless Systems Design Experience (18-846) – 12 Units

This project-oriented course is the culmination of the MS ECE Wireless Systems Concentration. It provides third-semester students with a design experience that brings together concepts from the

Wireless Systems core to solve a real-world problem.
The class organizes the students as a design team to build an outdoor system for distributed sensing of physical quantities, wireless connectivity to a data repository, and analysis and presentation of the data. The specific problem domains (e.g., pavement-mounted traffic sensors, sensors for overland water flow, soil moisture, or stream height) are selected to present specific challenges in wireless connectivity, low-power operation, distributed synchronization, federation of dissimilar sensor types, real-time computation, and information presentation. The instructors and project sponsors (customers) will guide the students in developing an understanding of the problem domain (environment and requirements) and selecting suitable technologies for addressing the challenges specific to it, creating and documenting a system architecture with verifiable interfaces, decomposing the architecture into sub-problems that sub-groups of students can address, integrating the results into a single system, and verifying system performance against the documented requirements. Consistent with the Wireless Systems concentration methodologies, student work will be organized around fixed-length sprints followed by an evaluation of progress with the customer and instructors.
Upon completion of this course, the student will be able to: generate systems specifications from a perceived need; partition functionality between hardware and software; produce interface specifications for a system composed of wirelessly-connected subsystems; use power and RF modeling tools; fabricate, integrate, and debug a hardware/software system; and evaluate the system in the context of an end user application.

Engineering and Economics of Electric Energy Systems (18-875) – 12 Units
The course has two parts. The first part introduces basic components and networks used in the electric power industry. This is followed by systematic modeling of these components, as well as of the entire system. Methods for modeling and analyzing both system equilibria and dynamics are presented. Simulations and lab demos are given to simulate and analyze typical system blackouts. This is followed by introducing decision and control methods for preventing these problems, as well as for managing the system more reliably, securely and efficiently over broad ranges of its operating conditions. The emphasis is on IT, software and control (both distributed and coordination) for achieving pre-specified system performance. This part of the course will involve simulation demos and hands on studies in which students create their own power network, simulate it and assess for performance. The second part of the course will review the industry structure, the experience with deregulatio n, and economic issues concerning choice of generating fuel and technology, the costs of blackouts, and environmental discharges. The course will integrate engineering and economic aspects to examine the design, investment, and operations that satisfy public desires for low cost, nonpolluting, reliable, and secure power. Knowledge of basic electric circuits and/or basic economics is assumed. 3 hrs. lec., 1 hr. rec. Prerequisites: Basic electric circuits and/or basic economics and at least graduate standing.

M.S. Graduate Project (18-980) – Variable Units
Master's level research.

Introduction to Graduate Studies (18-989) – 1 Unit
The Introduction to Graduate Studies course is designed to increase awareness and understanding of academic integrity issues, Carnegie Mellon community standards and the ethical job search. This is done via various sessions/modules that are already offered via several entities throughout campus (such as the CPDC, ICC, and GCC). Topics covered include: paraphrasing and citation, participating in the US classroom, avoiding plagiarism, unconscious bias, combating sexual violence on campus, finding jobs and internships, negotiation, communication, relationship building and other topics of interest. The course culminates in students writing a reflection paper. For international students, the paper should compare western academic and cultural standards to those of their home country. For domestic students, the paper should be a reflection on CMU's community standards. Active participation in 5 sessions/modules in the above mentioned areas and the submission of the reflection paper will determine a pass/fail grade.

Internship for Electrical and Computer Engineering MS Students (18-994) – 3 Units

The Department of Electrical and Computer Engineering considers experiential learning opportunities important educational options for its graduate students. One such option is an internship, normally completed during the summer. The ECE Graduate Office will add the course to the student's schedule. This process should be used by any Electrical and Computer Engineering graduate student wishing to have their internship experience reflected on their official University transcript. International students should also be authorized by the Office of International Education (OIE). Completion of written assignments and requirements will determine the letter grade for the course. Prerequisites: Graduate standing in ECE