Graduate Field Handbook

Cornell University
School of Electrical and Computer Engineering

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ECE Ph.D. Program Overview

The Ph.D. Degree Program in the School of Electrical and Computer Engineering at Cornell prepares students for a successful career in research, development and teaching through vigorous coursework and cutting-edge study.

Students will work with our world-renowned faculty as they work together to find solutions to some of today's biggest problems. Whether you're interested in power and energy, bioelectrical engineering, computer architecture, imaging, nanotechnology, photonics, neuroscience, or computing, you'll find your home in Cornell ECE.

Our Ph.D. Program is interdisciplinary, which allows our students to take advantage of a wide variety of research opportunities both in ECE, across both the Ithaca and New York City Tech Campuses.

- Take advantage of the wide range of research opportunities on our campuses through our multidisciplinary program and study anything from physics to bioscience, from mathematics to economics.
- Enjoy the flexibility of determining your individualized curriculum in consultation with your Committee Chair / Advisor and Special Committee Membership.
- Receive advanced training in current technology and engineering design.
- Virtually all of our Ph.D. students receive full financial support in the form of Fellowships, Graduate Research Assistantships and Teaching Assistantships during throughout their Ph.D. Program.
- The financial support covers tuition, a stipend and a student health insurance package. This funding is provided through the duration of a student's Ph.D. Program, providing that they remain in good academic standing, as determined by our Field.
- A Ph.D. from Cornell ECE will empower you to reach your goals and your potential. Our graduates go on to highly successful careers at universities and colleges and in industry and research settings around the world.

Research and Study Opportunities

Ongoing research activities in electrical engineering involve both theory and experimentation, and range from the atomic scale at which solid-state devices are studied to the global dimensions of geophysical plasmas. Projects currently underway concern the properties of materials, the fabrication of devices from these materials, the interconnection of devices to form systems, and the properties of systems, including control systems, computer systems, systems for transmitting power and information, and systems for processing signals and data.

Foundations of Information, Networks, and Decision Systems

Communications, networks, cyber-physical systems, energy conversion and power systems, biological and medical systems; coding and information theory, machine learning and statistical inference, adaptive control, image and video processing and compression.

Computer engineering and robotics

Computer architecture, computer systems, parallel and distributed processing, cloud computing, embedded systems, and computer networks; VLSI design, hardware verification, CAD, and simulation; robotics, embodied computation, hardware/software co-design, and micro robotics.

Plasma physics, space science and engineering, and electromagnetics

Upper atmosphere, ionospheric and magnetospheric science, radar, satellites, and sounding rockets; fusion, solar system, and fundamental plasmas; pulsed power, electron and ion beams, and plasma radiation; plasma fabrication; electromagnetics.

Solid-state electronics and optoelectronics

Electronic, magnetic and optoelectronic materials and devices; devices, circuits, and system integration; beyond-CMOS devices and circuits; power electronics; photonics; microwave and millimeter-wave devices and systems; sensors and actuators, micro- and nanoelectromechanical systems.

Intended Student Learning Outcomes

The first important goal of the ECE Ph.D. education is to ensure that our graduates can define and solve an important ECE problem. This requires that they apply fundamental ECE knowledge to a novel concept, synthesize useful techniques from relevant areas, and make discovery that impacts society. The graduate Ph.D. should be prepared broadly, not just in the specific area of the dissertation topic, but also for a career on the forefront of knowledge making contributions to engineering applications.

Effective teamwork and dissemination of research results demand that an ECE Ph.D. master and demonstrate effective communication skills in writing, speaking and public presentations. The Ph.D. candidates are expected to acquire these skills as part of their course work and research projects, and should be involved in generating journal publications and conference presentations for both active learning and knowledge distribution. These communication skills are essential for practicing engineers. Practicing engineers also need to be ethically responsible and understand the social impacts of their work. ECE Ph.D. students are expected to adhere to the highest standards of professional conduct in their research and abide by the IEEE Code Ethics.

ECE Ph.D. Program Degree Requirements

Residency Requirement

Timeline - There is a One (1) Semester Residency Requirement for all first-year ECE Ph.D. students enrolled at the Cornell Ithaca Campus in their First Semester of Enrollment.

1. All new incoming Students will be required to enroll at the Cornell Ithaca Campus and take courses during their First Semester of Enrollment in the ECE Ph.D. Program.
2. Ph.D. students will initiate their Committee Chair / Advisor Selection Process from the members of the ECE Graduate Field Faculty located at either the Cornell Ithaca Campus, or, the Cornell New York City Tech Campus.
3. Ph.D. students who may choose to work with a Committee Chair / Advisor at the Cornell New York City Tech Campus will be allowed to relocate to New York City as early as the beginning of their Second Semester of Enrollment in the ECE Ph.D. Program.

Course / Credit Hour Requirements

Timeline – To be completed prior to, or during the Third Year of Enrollment; Must be completed prior to the Scheduling of the A Exam

- All ECE Ph.D. students will be required to enroll in at least Eight (8) Credit Hours of ECE Courses, earning a Letter Grade of a "B" or better.
- All courses should be at the **5000 Level or Above**
- Students must complete the Eight (8) Credit Hour Course Requirement ***prior to the completion of their Admission to Candidacy Examination (A Exam)***.
- More detailed information can be found online here.

Responsible Conduct of Research (RCR) – Online "Foundational" Course

Timeline – To be completed before end of first academic year of enrollment

- The Cornell Graduate School requires that all first-year graduate students complete the Responsible Conduct of Research "Foundational" Course.
- The Course consists of four modules – authorship, peer review, plagiarism, research misconduct (data falsification, data fabrication, plagiarism).
- Students are strongly encouraged to complete the course during their first semester; you will be required to complete it ***before the end of your first year***.

Committee Chair / Advisor Selection

Timeline – To be completed by End of First Semester of enrollment *encouraged*; End of First Academic Year of enrollment *required*

- First-year Ph.D. students are *strongly encouraged* to make their Committee Chair / Advisor selection before the end of their first semester of enrollment; ***you will be required to do so before the completion of your first year of enrollment.***

- Students may only select an ECE Graduate Field Faculty Member to serve as their Committee Chair / Advisor; no exceptions will be allowed.
- Students can officially nominate their Committee Chair / Advisor via the student.
- More detailed information can be found online here as well as on Page 9.
- Students are strongly encouraged to complete the course during their first semester; you will be required to complete it ***before the end of your first year***.

Qualifying Examination

Timeline – To be completed by the Fourth Semester of Enrollment. Subject Area Exams are held annually near the end of the Spring Semester, usually in mid-April.

- All first-year ECE Ph.D. students will be required to participate in a Qualifying Examination (Q Exam). This will generally occur during the Second Semester of enrollment, usually in the spring semester.
- Each student must pass a total of Two (2) Subject Area Exams.
- More detailed information regarding the Q Exam format, timing, syllabi and specifics regarding the Subject Area Exams can be found online here as well as on Pages 11 - 13.

Minor Committee Membership Selection

Timeline – To be completed by end of Third Semester of Enrollment

- The Cornell Graduate School requires that all Ph.D. students complete the selection of their Special Committee Membership which will consist of their Advisor / Committee Chair, and Two (2) Minor Committee Members, prior to the end of their *Third Semester of Enrollment*.
- Students may select their Two (2) Minor Committee Members from any of Fields of Graduate Study at Cornell.
- Selection will be done in conjunction with input from your Advisor / Committee Chair.
- More detailed information on the selection process can be found online here.
- You will be required to nominate and form your Special Committee Membership (Advisor / Committee Chair, two Minor Members) ***before the end of your third semester of enrollment***.
- More detailed information can be found on Page 9 - 10.

Graduate Annual Review (GAR)

Timeline – To be completed by the Fourth Semester of Enrollment in April/May.

- The ECE Graduate Field Faculty Membership meets annually near the end of the Spring Semester for the Graduate Annual Review (GAR).
- The purpose of this meeting is to determine if ECE Ph.D. students have made the necessary academic progress in the early part of their Ph.D. Program.
- Factors determining successful progress will include official nomination of your Advisor / Committee Chair, Course Work Record to date, performance in Research and/or Teaching (if applicable) and performance on the Subject Area Examinations as part of the Q Exam.
- Results will be provided to students in the form of an official letter from the Field directly following the GAR.

Timeline – For Students attempting to re-take failed Subject Area Exam(s) from first year, they will participate in a Second GRA near the end of the Fourth Semester in the Second Year of Enrollment in April/May

Student Progress Review (SPR)

Timeline – Beginning with the Second Year of Enrollment (generally the Fourth Semester) in May/June; occurs annually during same timeframe to follow each subsequent year

- ***Beginning with the second year of graduate study***, all research-based degree students (MS, PhD) are required by the Cornell Graduate School to participate annually in the SPR.
- The SPR is the opportunity for students to have a formal conversation regarding their academic progress and future plans.
- Students fill out an online form that will include details regarding their recent accomplishments, identifying challenges and setting goals.
- The Advisor / Committee Chair reviews the document beforehand, and then will formally meet with the student to discuss its contents.
- The Advisor / Committee Chair will indicate whether the student's progress has been Excellent, Satisfactory, Needs Improvement, or Unsatisfactory.
- This will take place annually towards the completion of the Spring Semester.
- More information can be found online here.

Admission to Candidacy Examination (A Exam)

Timeline – To be Scheduled/Completed during the Fifth or Sixth Semester in Third Year of Enrollment

- The Cornell Graduate School requires that all Ph.D. students must schedule and attempt their Admission to Candidacy Examination (A Exam) ***prior to the start of their Seventh Semester of enrollment***.
- This is a comprehensive exam that gauges students' knowledge of their chosen research area and their readiness for independent research.
- This is an oral examination, administered by the members of the student's Special Committee.
- The exam typically begins with a presentation of preliminary research results and future plans by the student.
- The Special Committee members ask questions on the presentation as well as on general knowledge relevant to the student's research area(s).
- In this exam, students are expected to demonstrate broad knowledge in their research area as well as communication and presentation skills.
- Successful completion of the A Exam may result in the student earning a Non-Thesis Master of Science (MS) degree, providing the student's Committee Membership deems it appropriate.
- More information can be found online here as well as on Pages 14 - 15.

Thesis Defense / B Exam

Timeline – To be Scheduled/Completed by the Tenth Semester in the Fifth Year of Enrollment

- The Cornell Graduate School requires that all Ph.D. students must schedule and attempt their B Exam ***prior to the conclusion of their Fourteenth Semester of enrollment***.

- This is an oral examination, administered by the members of the student's Special Committee.
- The main component of the exam is a public presentation of the scholarly content of the Ph.D. dissertation, and is open to the public for dissemination and defense of findings.
- A successful candidate is expected to clearly demonstrate unique and novel ideas in this presentation, and be able to convey them to an audience of critical experts with a balanced presentation of key findings, and a well written dissertation that will become part of the public record.
- A pass of the B exam indicates completion of a Ph.D. program and completion of a dissertation with significant scholarly content and impact in the field of study.
- More information can be found online here as well as on Pages 16 - 17.

Committee Chair / Advisor Selection, Special Committee Membership and Minor(s) Selection

Committee Chair / Advisor Selection

1. All ECE Ph.D. Students are *encouraged* to make their formal selection of their Committee Chair / Advisor from the members of the ECE Graduate Field Faculty *by the end of their first semester of enrollment*.
2. All ECE Ph.D. Students are ***required*** to make their formal selection of their Committee Chair / Advisor from the members of the ECE Graduate Field Faculty ***by the end of their first year of enrollment***, in order to be considered making the necessary academic progress as determined by the Field.
3. The Committee Chair / Advisor must be a member of the ECE Graduate Field Faculty.

ECE Ph.D. students must nominate their Advisor / Committee Chair via the student.

Special Committee Membership Selection; Selection of Minor Members

Special Committee Membership will consist of Three (3) Faculty Members. The First will be the Committee Chair / Advisor. The Second Two will be considered the Minor Committee Members of the Committee.

1. The Committee Chair / Advisor must be selected from the ECE Graduate Field Faculty membership
2. The Two Minor Members may be selected from any of the current Cornell Graduate Faculty.

ECE Ph.D. students must nominate their Committee Chair / Advisor and Minor Committee Members via the student.

The selection of the Two Minor Members and the completion of the Special Committee Membership nominations must be done *no later than the end of the* **Third Semester of Enrollment**.

It should be noted that a Student's Special Committee Membership can have more than Three (3) Faculty Members.

Students may nominate an additional Minor Committee Member if they choose to.

Faculty Members who are not a part of a Cornell Graduate Field or affiliated with Cornell University may be included as part of the Special Committee as an Ad Hoc Committee Member. The submission of an Ad Hoc Committee Request form to the Cornell Graduate School is required for consideration.

Choosing a Minor / Selection of Minor Committee Members

All Ph.D. students at Cornell are required to participate in Two Minors that will be overseen by the Two Minor Members of the Special Committee. They will each represent the Field and its requirements to satisfy the Minor.

In ECE, many Ph.D. students will opt to nominate an ECE Graduate Field Faculty Member as one of their Minor Members, representing the Field ECE on their Special Committee. (Note, this is not a requirement, but it is fairly common.)

Satisfying the Minor Requirements

Since all Ph.D. students are required to have Two (2) Minor Members as part of their Special Committee, which means that the Minor Requirements for each of the Two (2) Graduate Fields of each Minor Member must be specifically satisfied.

Students will need to inquire from the Faculty Members that they ask to join their Special Committee as Minor Members what their requirements are in order to effectively satisfy the Minor for each of their Graduate Fields.

There is no level of consistency in the ways that Minor Requirements are to be satisfied. They are "Field specific," in that they are determined by each individual Graduate Field. Some have very specific requirements that must be adhered so, while others leave the requirements up to the judgement of the Faculty Member themselves. After speaking to the Faculty Member, it is advised to contact the Graduate Field directly as well, in order to be certain.

In many cases, the Minor Requirements will consist of specific courses that will need to be taken and a particular Letter Grade that must be earned as a result.

Be aware that the Graduate Field of ECE ***has no specific Minor Requirements***. The Minor Requirements are left up to the individual Faculty Member to determine was is most appropriate in each individual student's case what should be done to satisfy the Minor.

Changing Special Committee Membership

Students may change their Special Committee Membership at any time during their Ph.D. Program.

- Special Committee Membership changes after the completion of the A Exam will require the Dean's approval from the Cornell Graduate School.
- A Student cannot schedule their B Exam within Three (3) Months of making a Special Committee Membership change.
- Changing the Committee Chair / Advisor should be discussed in advance with the Director of Graduate Studies.
- It should be noted that any Special Committee Membership changes will require the approval from all Members of the newly formed Committee, including the Committee Chair / Advisor.
- Any Member of the Special Committee, including the Committee Chair / Advisor, has the right to resign at any time.

It is the responsibility of the student to reconstitute their Special Committee Membership. Failure on the part of the student to reconstitute their Special Committee will result in them not being permitted to continue to register as a student in the Graduate School.

More information can be found on the Cornell Graduate School's web site.

Examinations

All ECE Ph.D. students must participate and successfully complete a total of Three (3) separate examinations in order to earn their degree in the Field of ECE.

Qualifying Examination

Guidelines

The following is a set of guidelines to govern the administration of the School of Electrical and Computer Engineering (ECE) Graduate Field's Qualifying Examination. The purpose of these guidelines is to create a uniform, rigorous standard by which the ECE Graduate Field can assess the qualifications and preparation of students to continue in the ECE Ph.D. Program.

Format of the Qualifying Examination

The Qualifying Examination is an assessment of the qualification of incoming graduate students for a graduate program in the Field of Electrical and Computer Engineering. The overall outcome of the Qualifying Examination is determined during the Graduate Annual Review (GAR) by the entire ECE Field Faculty and holistically considers the following components to achieve one of two possible outcomes.

- Results for a Set of Subject Area Examinations
- Grades for all Graduate Level Coursework taken at Cornell to date
- Direct input from the student's Committee Chair / Advisor describing the student's Research Progress
- Direct input from the members of the ECE Graduate Field Faculty describing the student's Progress **and Demeanor as an ECE Ph.D. Student**

Outcomes of the Qualifying Examination

- **PASS** – Based on the above points of criteria, the student will have demonstrated the necessary ability and aptitude to continue in the ECE Ph.D. Program. A Pass may be determined by an outcome of "Excellent" or "Satisfactory."
- **FAIL** – Based on the above points of criteria, the student has not demonstrated the necessary ability to effectively continue in the ECE Ph.D. Program. The student will be instructed to meet with the Director of Graduate Studies and his/her Committee Chair / Advisor to discuss the proper course of action. A Fail will be determined by an outcome of "Unsatisfactory."

Timing of the Qualifying Examination

- The student's Qualifying Examination results will be considering during the Graduate Annual Review (GAR), which usually takes place soon after the Subject Area Examinations are completed.
- The Qualifying Examination is offered once a year, at the end of the Spring Semester.
- Students are eligible to participate in the Qualifying Examination at any time during their first Four (4) Semesters of Enrollment of graduate study in the ECE Ph.D. Program.
- Students must successfully complete the Qualifying Examination by the end of their **Fourth Semester** of enrollment of graduate study in the ECE Ph.D. Program, in order to remain in good academic standing as determined by the Field of Electrical and Computer Engineering.

Subject Area Examinations

Format of the Subject Area Examinations

- Subject Area Examinations are oral examinations with a duration of 20 – 30 minutes each.
- Each Subject Area Examination will focus on a specific subject within the ECE Graduate Field. They include the following Eight (8) separate subjects.
    1. Random Processes and Probability
    2. Computer Architecture
    3. Computer Systems
    4. Circuits and Devices
    5. Solid State and Quantum
    6. Electromagnetics and Optics
    7. Digital VLSI
    8. Linear Systems
- Each Subject Area Examination will focus on material covered in a reasonable undergraduate curriculum on Electrical and Computer Engineering. Subject Area Examinations will have an associated syllabus to act as a study guide.
- Subject Area Examinations are administered by a Two (2) Person Committee consisting of ECE Graduate Field Faculty Members acting as examiners that are well-versed in the corresponding subject.
- The Subject Area Examination Committee of examiners must not include a Student's Committee Chair / Advisor.

Subject Area Examination Outcomes

For each Subject Area Examination, the Subject Area Examination Committee of examiners will render One (1) of Three (3) Possible Outcomes:

- **EXCELLENT** – Student has demonstrated an excellent understanding of the corresponding Subject Areas that exceeds the expectations of a reasonable Ph.D. Candidate within the ECE Graduate Field.
- **SATISFACTORY** – Student has demonstrated a satisfactory understanding of the corresponding Subject Areas that meets the expectations of a reasonable Ph.D. Candidate within the ECE Graduate Field.
- **UNSATISFACTORY** – Student has demonstrated an unsatisfactory understanding of the corresponding Subject Areas that is beneath the expectations of a reasonable Ph.D. Candidate within the ECE Graduate Field.

The Subject Area Examination Committee of examiners will provide a written review of the student's performance on the Examination(s) and the justification for the awarded outcome.

Achieving an outcome of either **EXCELLENT** or **SATISFACTOR**Y on Two (2) or more Subject Area Examinations covering at least Two (2) separate Subjects is sufficient to complete the exam criteria of the Qualifying Examination.

Timing of the Subject Area Examinations

- Subject Area Examinations are administered annually during a one-week period near the end of the Spring Semester.

- The scheduled dates of the Subject Area Examinations are determined by the ECE Director of Graduate Studies each year and will be announced in advance.
- Subject Area Examinations may potentially be administrated at other times due to family, medical emergency or other exceptional circumstances only, as determined by the ECE Director of Graduate Studies.
- Students are encouraged to take Two (2) Subject Area Examinations on Two (2) Separate Subjects in their first year of enrollment of graduate study in the ECE Ph.D. Program.

Appeals of Subject Area Examination Results

1. Students may appeal the results of a Subject Area Examination if they believe that an error has been made in their case.
2. The student must file a written appeal to the ECE Director of Graduate Studies **within One (1) Week** of receiving the results of the Subject Area Examination.
3. The written appeal must be in the form of a formal, signed letter detailing the specific reasons why the student believes the outcome of the Subject Area Examination should be changed.
4. A finalized decision regarding the written appeal will be rendered by the ECE Director of Graduate in consultation with the Graduate Committee.

Requests for Accommodation for Students with Disabilities

- In compliance with the Cornell University's Policy and Equal Access Laws, the School of Electrical and Computer Engineering are happy to discuss appropriate academic accommodations that students with disabilities may require in order to participate in the Subject Area Exams as part of the Qualifying Examination.
- Requests for academic accommodations should occur at least **One (1) Month** in Advance of the Qualifying Examination and Subject Area Exams, in order to make any and all necessary arrangements. ECE encourages students to register with the student to verify their eligibility for suitable accommodations.

Please see the Appendix on Pages 25 - 31, for detailed copies of the Subject Area Examination Syllabi.

All Subject Area Examination Syllabi information is also available online.

Examinations – Admission to Candidacy Examination (A Exam)

Overview

Students are eligible to schedule their A Exam after Two (2) Semesters of Registration have been completed in the ECE Ph.D. Program.

The A Exam must be taken ***PRIOR TO THE BEGINNING*** of a Student's Seventh Semester of Registration.

The format of the A Exam is up to the discretion of the student's Special Committee Membership. In general, it is an oral examination. The student will present the topic that has been chosen to devote their dissertation to.

Scheduling the Admission to Candidacy Examination (A Exam)

The student will need to schedule the A Exam at a time that is convenient for both them and their Special Committee Membership. Students are encouraged to complete the scheduling process well in advance of the date of the A Exam itself.

Reserving a Room for the A Exam

Once a date and time have been established, the student should reserve a Conference Room where the A Exam will be held. There are conference rooms of varying size available in Phillips Hall, Rhodes Hall and Duffield Hall that can be reserved. Students will need to work with ECE Administrative Staff in order to reserve a conference room.

Schedule A Examination and Research Compliance Form

Filling It Out, Obtaining Online Approvals, Submitting the Form

- The student will need to go online and fill out the **Schedule A Examination and Research and Compliance Form**. The form can be found on the Graduate School's Forms page listed under "Exams and Research."
- The student will fill out the form completely before submitting for the necessary approvals of their entire Special Committee Membership, the ECE Director of Graduate Studies, and the ECE Assistant Director of M.Eng./Ph.D. Program (listed as "Graduate Field Assistant" on the form).
- The student will be responsible for obtaining the completion of all required online approvals in order for the form to be submitted to the Graduate School.
- Once all online approvals have been submitted, an automated email will be sent by the Graduate School confirming the scheduling of the student's A Exam.

Deadline for Submission of A Examination and Research Compliance Form

- ***The completed Schedule A Examination and Research Compliance Form must be submitted to the Graduate School a minimum of Seven (7) Calendar Days prior to the date of the scheduled A Exam***.
- There are ***no exceptions*** to this rule. Late submission of the Schedule A Examination and Research Compliance Form will result in the A Exam having to be re-scheduled.

Announcement of the A Exam

The Date, Time and Location of the student's A Exam will be made public and posted to the ECE Events Calendar.

Results for Admission to Candidacy Examination (A Exam) Form

Filling It Out, Obtaining Online Approvals, Submitting the Form

- The student will need to go online and fill out the **Results for Admission to Candidacy Examination (A Exam) Form**. It can be found on the Graduate School's Forms page listed under "Exams and Research."
- The student will fill out the form completely before submitting for the necessary approvals of their entire Special Committee Membership, the ECE Director of Graduate Studies, and the ECE Assistant Director of M.Eng./Ph.D. Program (listed as "Graduate Field Assistant" on the form).
- The student will be responsible for obtaining the completion of all required online approvals in order for the form to be submitted to the Graduate School.
- Once all online approvals have been submitted, an automated email will be sent by the Graduate School confirming the receipt of the student's Results for Admission to Candidacy Examination (A Exam) Form.

Deadline for Submission of Results for Admission to Candidacy Examination (A Exam) Form

- ***The completed Results for Admission to Candidacy Examination (A Exam) Form must be submitted to the Graduate School within Three (3) Business Days of the completion of the A Exam.***
- There are ***no exceptions*** to this rule. Late submission of the Results of Admission for Candidacy Examination (A Exam) Form will result in the results of the student's A Exam ***not being accepted***.

Master of Science (MS) without Thesis Degree

All Students who successfully complete their A Exam are eligible to earn a Master of Science (MS) without Thesis Degree. The student may only be awarded the MS degree if their Committee Membership deems it appropriate.

The student should discuss this option with their Special Committee Membership ***in advance*** of participating in their A Exam.

When the student's Committee Chair / Advisor submits their online approval for the Results of Admission to Candidacy (A Exam) Form, they should then indicate if the student should be receiving the Non-Thesis MS degree and continuing on in the ECE Ph.D. Program.

Please be aware that the Graduate School will only award the Non-Thesis MS degree if it is clearly indicated on the Results for the Admission to Candidacy Examination (A Exam) Form. The Graduate School will **NOT** retroactively award the Non-Thesis MS degree if it was not specifically indicated at the time of the submission of the Results for Admission to Candidacy Examination (A Exam) Form.

Examinations – Ph.D. Thesis Defense – B Exam

Students are eligible to schedule their B Exam after Six (6) Semesters of registration have been completed in the ECE Ph.D. Program.

Be aware that the student will be required to be enrolled *for a minimum* of Two (2) Semesters of registration between their A and B Exams.

Submission of Thesis Draft to Special Committee Membership

Prior to Scheduling B Exam:

- The Graduate School's policy according to the Code of Legislation states, ***"A Student must submit a completes draft of the thesis or dissertation to all Members of the Special Committee at least Six (6) Weeks before the Final Examination, unless the Special Committee modifies this requirement."***
- The student must confirm with their Special Committee Membership after they have reviewed the draft if it is appropriate to move forward with scheduling the B Exam.

Scheduling the B Exam

The student will need to schedule the B Exam at a time that is convenient for both them and their Special Committee Membership.

Reserving a Room for the B Exam

Once a date and time have been confirmed, the student should reserve a Conference Room where the B Exam will be held. There are Conference Rooms of varying size available in Phillips Hall, Rhodes Hall and Duffield Hall that can be reserved. You will need to work with the ECE Administrative Staff in order reserve a Conference Room.

Schedule B Examination Form

Filling It Out, Obtaining Online Approvals, Submitting the Form

The student will need to go online and fill out the **Schedule B Examination Form**. It can be found on the Graduate School's Forms page listed under "Exams and Research."

- The student will fill out the form completely before submitting it for the necessary approvals of their entire Committee Membership, the ECE Director of Graduate Studies and the ECE Assistant Director of M.Eng./Ph.D. Programs (listed as "Graduate Field Assistant" on the form).
- The student will be responsible for obtaining the completion of all required online Approvals in order for the form to be submitted to the Graduate School.
- Once all online Approvals have been submitted, an automated email will be sent by the Graduate School confirming the scheduling of the student's B Exam.

Deadline for Submission of Schedule B Examination Form

- ***The completed Schedule B Examination Form must be submitted to the Graduate School a minimum of Seven (7) Calendar Days prior to the date of the scheduled examination.***
- There are ***no exceptions*** to this rule. Late submission of the Schedule B Examination Form will result in the examination having to be re-scheduled.

Announcement of the B Exam

The Date, Time and Location of the student's B Exam will be posted on the ECE Events Calendar.

Results for Final Defense of Ph.D. Degree (B Exam) Form

Filling Out the Form, Obtaining Online Approvals, Submitting the Form

- At the conclusion of the B Exam, the student will need to go online and fill out the **Results for Final Defense of Ph.D. Degree (B Exam) Form**. It can be found on the Graduate School's Forms page listed under "Exams and Research."
- The student will fill out the form completely before submitting it for the necessary approvals of their entire Committee Membership, the ECE Director of Graduate Studies and the ECE Assistant Director of M.Eng./Ph.D. Programs (listed as "Graduate Field Assistant" on the form).
- The student will be responsible for obtaining the completion of all required online Approvals in order for the form to be submitted to the Graduate School.
- Once all online Approvals have been submitted, an automated email will be sent by the Graduate School confirming the receipt of the student's Results for Final Defense of Ph.D. Degree (B Exam) Form.

Deadline for Submission of Results for Final Defense of Ph.D. Degree (B Exam) Form

- ***The completed Results for Final Defense of Ph.D. Degree (B Exam) Form must be submitted to the Graduate School within Three (3) Days of the completion of the B Exam.***
- There are ***no exceptions*** to this rule. Late submission of the B Exam Results Form will result in the results of the student's B Exam not being accepted.

Suggested Timeline Towards ECE Ph.D. Degree

Semester / Year	**Milestone / Details**
First Semester; First Year	Attend ECE Ph.D. Orientation. Enroll in courses; consult with ECE Faculty Members for course selection. Begin search for Committee Chair / Advisor. Contact ECE Faculty Members you are interested in working with. Submit Committee Chair / Advisor official nomination via Student Center when selection is made.
Second Semester; First Year	Continue search for Committee Chair / Advisor. Submit Committee Chair / Advisor official nomination via Student Center when selection is made. Committee Chair / Advisor search must be completed prior to the end of your second semester of enrollment.
Second Semester; First Year; April	Qualifying Examination / Subject Area Exams are scheduled during the month of April.
Second Semester; First Year; April/May	Graduate Annual Review will be held to determine if ECE Ph.D. Students have made necessary progress in early part of their Ph.D. Program.
Second Semester; First Year	Students must complete Responsible Conduct of Research (RCR) online foundational course. RCR must be completed prior to the end of the first year of enrollment.
Third Semester; Second Year	Students must nominate the two Minor Members of their Special Committee prior to completion of third semester of enrollment.
Fourth Semester; Second Year; April	Students who did not successfully pass the Subject Area Examination after their first attempt will have the opportunity to re-take their Examination(s).
Fourth Semester; Second Year; April/May	Second Graduate Annual Review will be held to determine if ECE Ph.D. students have made necessary progress in early part of their Ph.D. Program for students attempting Subject Area Exam(s) for second time.
Fourth Semester; Second Year; May/June	Beginning with the end of the second year of enrollment, students must begin participation in the annual Student Progress Review.

	Occurs annually during the spring semester.
Fifth Semester/Sixth Semester; Third Year	Completion of Eight (8) Credit Hours of required ECE Coursework. Must be completed prior to the Scheduling of the A Exam.
Fifth Semester/Sixth Semester; Third Year	Begin working with Committee Membership towards planning for the scheduling of the A Exam. The A Exam must be scheduled and completed prior to the start of the Seventh Semester of enrollment.
Sixth Semester; Third Year; May/June	Students must participate in the annual Student Progress Review. Occurs annually during the spring semester.
Seventh Semester – Tenth Semester	Students should be meeting annually with their entire Special Committee Membership. Discussion of research progress and in particular, from the Eighth Semester on, to discuss plans for graduation. Updated materials such as the CV, conference abstracts, publications and transcripts, should be distributed in advance of these meetings.
Eighth Semester; Fourth Year; May/June	Students must participate in the annual Student Progress Review. Occurs annually during the spring semester.
Tenth Semester; Fifth Year; May/June	Students must participate in the annual Student Progress Review. Occurs annually during the spring semester.
Tenth Semester; Fifth Year	Expected scheduling and completion B Exam and Ph.D. Degree Conferral

Students should bookmark and regularly visit the Graduate School's web page "Understanding Deadlines and Requirements" in order to following a definitive timeline towards their graduation.

Financial Support

There are three types of available funding that we offered to applicants who receive admission offers. Each of them include a Full Tuition Fellowship, an Academic Year Stipend and a Student Health Insurance Package.

Fellowship

- Admission offers of a Fellowship are generally One (1) or Two (2) Semesters in duration
- The Fellowship Stipend will be a slightly higher dollar amount for the first year only.
- While being supported on a Fellowship, you will have no formal obligations such as teaching of research for a specific group.

Graduate Research Assistantship (GRA)

- An admission offer of a GRA will come directly from a specific ECE Faculty Member who has expressed a specific interest in having the admitted student join their research group upon entering our Ph.D. Program.
- Incoming GRAs are expected to begin focusing on research in the group of the ECE Faculty Member who has extended the offer or admission.
- Students are generally supported as GRAs by their Committee Chair / Advisor during the summer session.

Teaching Assistantship (TA)

- An admission offer of a TA comes directly from ECE.
- Incoming TAs are expected to perform the required duties to support the course they will be assigned to which may include:
    - Teaching Recitations
    - Holding Office Hours
    - Grading Exams and Homework Assignments
    - Overseeing Lab Sections
- Specific TA duties are determined by the Course Instructor of the course they are assigned to.

ECE Annual Ph.D. Student Awards

Cornell ECE Outstanding Ph.D. Thesis Research Award

- Awarded annually; Nominations are due by end of the fall semester
- Students are nominated by their Committee Chair / Advisor
- Required materials from Students are a CV, Cornell Transcript, Innovative Claims and Major Impacts (describing their research), Thesis Draft or Collection of Research Papers
- Required materials from Faculty are a Nomination Letter from the Committee Chair / Advisor and two additional supporting Recommendation Letters
- An Ad Hoc Committee based on the ECE Graduate Committee evaluates all submissions and selects a winner
- Results are announced by the end of January
- Winner receives a $3,000.00 cash award and an engraved plaque

Cornell ECE Outstanding Ph.D. TA Award

- Awarded annually; Nominations are by in mid-spring semesters
- Students are nominated by an ECE Course Instructor for a course that they served as a Ph.D. TA for
- Required materials from the Course Instructor are a completed Nomination Form
- Required materials from Students are Teaching Philosophy and Major Contribution (describing their teaching style and method), a CV, a Recommendation Letter from a student who was registered in the course that the TA provided support for)
- An Ad Hoc Committee based on the ECE Graduate Committee evaluates all submissions and selects a winner
- Results are announced by late April
- Winner receives a $3,000.00 cash award and an engraved plaque

ECE Leadership and Contact Information

Name	Title	Office	Email
Prof. Alyssa Apsel	Department Chair	229 Phillips Hall	aba25@cornell.edu
Prof. Qing Zhao	Director of Graduate Studies	325 Rhodes Hall	qz16@cornell.edu
Prof. Aaron Wagner	Associate Director	388 Rhodes Hall	abw35@cornell.edu
Megan Whitman	Director of Administration	227 Phillips Hall	mlw57@cornell.edu
Scott Coldren	Assistant Director M.Eng. and Ph.D. Programs	223 Phillips Hall	sec36@cornell.edu

Graduate School Resources

The Office of Academic and Student Affairs works with graduate faculty and graduate students on academic policy and programs, academic integrity and misconduct, responsible conduct of research, petitions requesting exceptions to graduate school policy as outlines in the Graduate Faculty's Code of Legislation, and academic progress and students status. The office also offers academic, writing and professional development programs, including proposal/thesis/dissertation writing boot camp, the Productive Writer email (Sign Up), Graduate Write-Ins, Productive Writing workshops, Fellowship Application Writing Workshops and Fellowship Listserv Tips, Productive Fellowship Writer Mailing List, Writing and Publishing Workshop Series, Three Minute Thesis Competition, and the Advising Guide for Research Students.

The Office of Inclusion and Student Engagement (OISE) supports an inclusive and welcoming environment for all graduate and postdoctoral scholars, but especially for those from marginalized communities and/or backgrounds historically excluded from and underrepresented in the academy. OISE supports systemic change and promotes a climate of diversity, belonging, equity, engagement, and achievement, which are integral components of graduate and postdoctoral education. OISE supports scholar success through recruitment, diversity fellowships, mentoring, professional, leadership, and community development programming, and ongoing support.

Recognizing that health and academic performance are intimately linked, the Office of Graduate Student Life is a source of information, support, and advocacy that creates a more student-centered graduate student life experience. In addition to being a first point of contact for students who are struggling or experiencing any form of distress, the Office of Graduate Student Life serves as a coordinating hub with campus-partners that focus on promoting a healthy and holistic student experience. More information on support is available online.

Graduate School Contacts

Name	Title	Phone	Email
Jan Allen	Associate Dean for Academic and Student Affairs	607-255-4603	jan.allen@cornell.edu
Sara Xayarath Hernández	Associate Dean for Inclusion and Student Engagement	607-255-3030	sh267@cornell.edu
Jason Kahabka	Associate Dean for Administration	607-254-3324	jek15@cornell.edu
Janna Lamey	Senior Assistant Dean for Graduate Student Life	607-255-5184	janna.lamey@cornell.edu

APPENDIX – Syllabi for ECE Subject Area Examinations

All Subject Area Examination Syllabi information is also available online.

Subject Area: Random Processes and Probability

Reference:

Probability, Statistics, and Random Processes for Electrical Engineering by Alberto Leon-Garcia.

Basic Concepts:

Sample spaces, probability measures, outcomes, events, combinatorial approaches to computing probabilities, conditioning, total probability, independence, Bayes' rule.

Random Variables:

Definition of, probability mass functions (PMFs), probability density functions (PDFs), cumulative distribution functions (CDFs), commonly used distributions, expectations, characteristic functions, moment inequalities.

Random Vectors:

Definition of, joint PMFs, PDFs, and CDFs, joint characteristic functions, conditional distributions and conditional expectation, joint moments, covariance matrices and their properties, jointly Gaussian random variables.

Limit Theorems:

Law of large numbers, central limit theorem.

Estimation:

LLSE and MMSE estimators.

Detection:

MAP and ML detectors.

Second-Order Random Processes:

Stationarity and wide-sense stationarity, autocorrelation, power spectral density, white noise, filtered random processes.

Discrete-Time Markov Chains:

Definition, conditions for stationarity, n-step transition probabilities, stationary distributions, occupancy rates.

Continuous-Time Markov Chains:

Definition, conditions for stationarity, the forward and backward equations, Poisson processes, the M/M/1 queue, occupancy rates.

Subject Area: Computer Architecture

Helpful Resources:

The area exam will cover the topics listed below. The following resources may be helpful in studying the topics.

- Cornell Undergraduate Courses: ECE2300, ECE4750
- References: “Digital Design and Computer Architecture” by Harris & Harris, “Computer Architecture: A Quantitative Approach” by Hennessy & Patterson, “On-Chip Networks (Synthesis Lectures on Computer Architecture)” by Peh and Jerger.

Boolean Algebra:

Axioms and main theorems of Boolean algebra; combinational logic minimization: Algebraic simplification, Karnaugh maps, don’t-cares, races.

Combinational Blocks:

Mux, demux, decoder, encoder; carry-propagate adder, carry-save adder, carry- lookahead adder; integer multiplication.

Sequential Logic:

D-latch and SR-latch; master-slave D-flip-flop; timing of latches and flip-flops (setup/hold times); timing analysis (max. clock frequency, critical path, clock skew); race conditions; FSMs, communicating FSMs; Mealy and Moore automata; sequential logic design; registers, counters, timers.

Processors (basic):

Instruction set architectures; single-cycle processor datapath and control unit; hardwired vs. microcoded processors; pipelined processors; resolving structural, data, control, and name hazards; handling exceptions; analyzing processor performance (iron law of processor perf.); transition from CISC to RISC.

Memories:

Memory technology (registers, register files, SRAM, DRAM); spatial vs. temporal locality; direct-mapped vs. associative caches; write-through vs. write-back caches; replacement policies; parallel-read, pipelined-write caches; integrating processors and caches; analyzing memory performance (avg. memory access latency); virtual memory, page table, TLB; virtually vs. physically addressed/tagged caches; cache coherence, MSI; memory consistency; locks, barriers.

Networks:

Integrating processors, caches, and networks; analyzing network performance (ideal throughput, zero-load latency).

Processors (advanced):

Superscalar execution; out-of-order execution: scoreboard, issue queue, reorder buffer, handling exceptions; register renaming: pointer-based, value-based schemes; memory disambiguation: finished-store buffer, finished-load buffer, load/store queues, in-order vs. out-of-order load/store issue; branch prediction: software-based, predication, one-level and two-level branch-history tables, tournament predictors, branch-target buffer, return address stack; speculative execution; VLIW processors: loop unrolling, software pipelining; SIMD processors: subword-SIMD, vector-SIMD; multithreaded processors: vertical multithreading, simultaneous multithreading.

Note: It is not enough just to be able to describe concepts; you will need to be able to apply concepts in new contexts, and also be able to evaluate design alternatives.

Subject Area: Computer Systems

Helpful Resources:

The area exam will cover the topics listed below. The following resources may be helpful in studying the topics.

- Cornell Undergraduate Courses: ECE2400, ECE3140, CS4410, [CS4450]
- References: “All of Programming”, Hilton & Bracy, “Hard Real-Time Computing Systems” by Buttazzo (available online through Cornell Library), “Operating Systems: Three Easy Pieces” by Arpaci-Dusseau & Arpaci-Dusseau.

Programs:

Instruction set architectures: instruction encoding, register organization, endianness, control flow; compiling, linking, and loading.

Calling Conventions and Stack:

Parameter-passing conventions; stack structure; stack frame.

Interrupts and Exceptions:

Polling; interrupts; exceptions; software traps; system calls.

Process Management:

Time-sharing; context switching; scheduling: FCFS, round-robin, priority, SJF; aperiodic real-time: EDD/EDF; periodic real-time; rate-monotonic scheduling; inter-process communication.

Memory Management and Storage:

Program layout, stack, heap; Memory protection, translation, and virtualization: base/bound, paging, segmentation; TLB; virtual memory; memory allocation; basic I/O; storage.

Concurrency:

Critical sections; atomicity; mutual exclusion, progress, fairness; locks and monitors; RMW operations, t&s; ticket lock; semaphores; wait/signal; Hoare vs. Mesa semantics; readers and writers; producers and consumers; priority inversion, PIP, PCP.

Networking:

End-to-End argument, Physical networking: wireless, circuit-and packet-switched, mobile networks; data link: MAC addresses, error correcting codes; medium access: ethernet, wireless LANs, bridging; network layer: routing, congestion control, QoS; transport layer: sockets, UDP, TCP; application layer: remote procedure calls, DNS; security: basic crypto, symmetric key algorithms, public key, digital signatures, key management, firewalls/IPSec, authentication protocols, web security (SSL).

Note: It is not enough just to be able to describe concepts; you will need to be able to apply concepts in new contexts, and also be able to evaluate design alternatives.

Subject Area: Circuits and Devices

The Circuits and Device area Subject Area Exam tests for the physical understanding of the behavior of semiconductor electronic devices and the principles underlying the behavior, and the ability and understanding of the design, analysis, and limitations of fundamental circuits.

This therefore includes the breadth of the behavior of electrons and holes and their transport in devices; modeling of that behavior in static, low frequency and high frequency conditions; and the application of such devices to circuits. Students are expected to demonstrate an understanding of devices (diodes, transistors and memories), transfer functions, feedback, and the limitations to the analysis of the physical behavior and models and the limits this places on their applicability.

A list of Topical Areas in Circuits includes:

- Derive transfer functions of RLC circuits in Laplace and Fourier domains and be able to sketch the Bode plot of a transfer function.
- Apply Millers theorem to an amplifier with feedback (This includes real amplifiers such as common-source, common drain, etc).
- Analyze basic op-amp circuits assuming an ideal op-amp.
- Draw complete (with capacitors) small-signal model of a MOSFET or BJT.
- Bias and Analyze a i) common source/common emitter amplifier, ii) common drain/common collector amplifier, and iii) common gate/common base amplifier for small signal gain, Zin and Zout for both low- and high-frequency cases (ie with and without including capacitors)
- Analyze a CMOS inverter in large signal, low frequency behavior, both single and multi-stage
- Analyze a cascode amplifier at low frequency for small signal gain, Zin and Zout.
- Analyze a differential pair at low frequency for small signal gain, Zin and Zout.
- Perform small-signal high-frequency analysis of an active current mirror.
- Calculate common-mode gain of a differential pair biased with a current mirror.
- Calculate the gain and transfer function of a simple op-amp.
- Be able to estimate the input impedance of an op-amp or other large amplifier.
- Calculate open- and closed-loop transfer function of a feedback loop in the following situations o Op-amp circuits
    - Common mode feedback
- Be able to describe the benefit of feedback for: o Increase bandwidth
    - Improve linearity
    - Stabilize unstable systems
    - Understand noise sources due to pn-junctions, BJTs, MOSFETs, and flicker.

A list of Topical of Areas in Devices includes:

- Electrons and holes in semiconductors (donors, acceptors, carrier populations, thermal equilibrium, electrostatic potential, Fermi energy, quasi-Fermi energy, temperature dependences, transport by drift and diffusion, generation and recombination).
- Energy description of device structures via band diagrams (conduction and valence band edges, quasi-Fermi energy and heterostructures).

- Junctions and diodes (metal-semiconductor junctions, ohmic contacts based on tunneling and interface recombination, p/n junction) in static, quasistatic, dynamic, and at high frequencies and their models.
- MOS junction (charge analysis, low-frequency, high frequency, deep depletion behavior, inversion layers, quantum-confinement effects).
- MOSFET (sheet charge modeling of MOSFET, gradual channel approximation, characteristics in sub-threshold and supra-threshold conditions with drift and diffusive flow, quasistatic and small-signal models).
- MOSFET at small scale (scaling, short channel effects, parasitic bipolars, gate tunneling, drain-induced barrier lowering, gate-induce drain leakage, hot electron effects, Instabilities and stress-induced leakage currents, and transistors based on SOI, double-gate, strain, high-permittivity and fins).
- Memories (static and dynamic random access memories, non-volatile FLASH memories)
- Bipolar transistors (Design, polysilicon emitters, Ebers-Moll models, breakdown, Gummel plots, graded heterostructure bases, SiGe, IIIV, high frequency and digital models).
- Noise (Thermal, shot and 1/f noise, and such noise in MOSFETs and bipolar transistors)
- A reasonable text that tackles much of this breadth is Y. Taur and T. H. Ning, "*Fundamentals of modern vlsi devices*," Cambridge, ISBN 978-0-521-83294-6

Subject Area: Solid State and Quantum

The Material covered in ECE 4070 (Solid State Physics of Semiconductors and Nanostructures) and material on introductory quantum mechanics.

Material covered in ECE 4070 can be found at the following course website:

- https://courses.cit.cornell.edu/ece407/ (all lecture handouts)

Material on introductory quantum mechanics can be found in the following book:

- Title: Introduction to Quantum Mechanics (Chapters 1 through 9)
- Author: David J. Griffiths
- Publisher: Pearson Prentice Hall

Subject Area: Electromagnetics and Optics

There are five general areas in E&M that you are expected to understand with sufficient depth to be able to describe the physics and limitations of a simple device or process.

Electrostatics

- Coulomb's law
- Poisson, Laplace equations
- Gauss's law of electrostatics
- Potential energy
- Image charges
- Boundary value problems
- Energy stored in the electric field

Magnetostatics

- Biot-Savart law
- Ampere's law of magnetostatics
- Vector potential
- Lorentz force and torque
- Energy stored in the magnetic field

Maxwell's equations

- Faraday's law, induction
- Displacement current
- Constitutive relations
- Wave equation
- Solutions with rectilinear, cylindrical, and spherical boundary conditions
- Plane electromagnetic waves, wave propagation, and evanescent waves
- Polarization
- Reflection, refraction, interference
- Energy conservation and Poynting's vector

Waveguides, Resonant cavities, and Modes

- Electromagnetic boundary conditions
- TE, TM, TEM waveguide modes
- Fabry-Perot resonators

Radiation

- Electric dipole fields and radiation
- Magnetic dipole fields and radiation
- Simple dipole arrays, and image dipoles

Subject Area: Digital VLSI

Helpful Resources:

The area exam will cover the topics listed below. The following resources may be helpful in studying the topics.

- Cornell Undergraduate Courses: ECE2300, ECE4740
- References: "Digital Design and Computer Architecture" by Harris & Harris, "CMOS VLSI Design: A Circuits and Systems Perspective" by Weste & Harris.

VLSI General:

Moore's Law; Kryder's Law; Koomey's Law.

Boolean Algebra:

Axioms and main theorems of Boolean algebra; combinational logic minimization: Algebraic simplification, Karnaugh maps, don't-cares, races.

MOSFET:

P-N junction and diodes; operation regimes; body effect; short-channel effects; parasitic capacitances; switch model; pass transistors and transmission gates.

CMOS Inverter:

Voltage transfer characteristics; operation regimes; regenerative property and noise margins; latch-up; dynamic behavior; propagation delay; sizing (logical effort).

Static CMOS:

Pull-up and pull-down networks; CMOS gate synthesis and analysis; standard-cell design; stick diagrams and Euler path; timing characteristic (worst/best case delay, rise/fall times); gate sizing (logical effort); pass-transistor (PT) logic; transmission-gate (TG) logic.

Dynamic Logic:

Dynamic CMOS; domino logic; np-CMOS, zipper, and NORA logic.

Sequential Logic:

D-latch and SR-latch; master-slave D-flip-flop; timing of latches and flip-flops (setup/hold times); timing analysis (max. clock frequency, critical path, clock skew); race conditions.

Wire Models:

RC model; fringing capacitance; wire parasitics and crosstalk; Elmore delay; IR drop.

Energy/Power Consumption:

Static CMOS power consumption; dynamic CMOS power consumption; statistical power analysis; low-power design techniques; voltage-frequency scaling; leakage reduction.

Architecture Transforms:

Area/delay trade-off; coarse- and fine-grain pipelining; retiming; replication; iterative decomposition; time sharing.

Adder Circuits:

Full adder (various designs); ripple-carry adder; Manchester-carry chain; carry-skip adder; carry-select adder; carry-save adder (CSA); carry-lookahead adder (CLA).

Arithmetic/Logic Circuits:

Two's complement/sign magnitude numbers; shifters and rotator circuits; comparator circuits; n-input multiplexers; array and CSA multipliers.

Memories and ROMs:

NAND and NOR ROM; SRAM (design and sizing of 6T cells); DRAM (3T and 1T cells); NAND/NOR row decoders; precharge circuitry; sense amplifiers.

Note: It is not enough just to be able to describe concepts; you will need to be able to apply concepts in new contexts, and also be able to evaluate design alternatives.

Subject Area: Linear Systems

References:

Linear algebra at the level of Gilbert Strang's *Introduction to Linear Algebra* (see also the MIT couseware) or Sheldon Axler's *Linear Algebra Done Right*. Signals and systems concepts at the level of A. V. Oppenheim and A. S Wilsky's *Signals and Systems*.

Linear Algebra:

Vector spaces, linear mappings, spanning sets, bases and dimension of finite-dimensional vector spaces; nullspace, range, and rank of arbitrary real and complex matrices; determinant, trace, invertibility, eigenvalues, and eigenvectors of square real and complex matrices; inner-product spaces and orthogonal/unitary diagonalizability of Hermitian matrices; singular-value decomposition of arbitrary real and complex matrices; condition number of invertible square matrices.

Signals Basics:

Real- and complex-valued continuous- and discrete-time signals; convolution in continuous and discrete time.

Systems Basics:

Single-input single-output LTI systems in continuous and discrete time; impulse response; causality and BIBO stability of SISO LTI systems (definitions and impulse-response criteria).

Spectral Concepts in Continuous Time:

Fourier series of continuous-time periodic signals; Fourier transforms of continuous-time signals; the idea of frequency content and bandwidth of continuous-time signals; frequency response of continuous-time LTI systems; ideal filters.

Spectral Concepts in Discrete Time:

The discrete-time Fourier transform and the Sampling Theorem; frequency response of discrete-time LTI systems; The DFT and the FFT for N-point signals.

Other Transforms and Applications:

The two-sided z-transform and two-sided Laplace transform; transfer functions of continuous- and discrete-time SISO LTI systems; criteria for BIBO stability in terms of transfer functions.