Robotics Institute / School of Computer Science

Course of Study
for the Robotics Ph.D. Program

Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

Revised and applied ongoing from August 2025.

This document defines the degree requirements for students in the Ph.D. Program in Robotics at Carnegie Mellon. It is maintained by the Robotics Program Committee.

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1.0 Overview

This document defines the degree requirements for candidates in the Ph.D. Program in Robotics in the School of Computer Science at Carnegie Mellon University. The program is designed so that a well-prepared student can complete the doctoral degree in four to five years. The Ph.D. program requires completion of:

- Course Qualifiers (Core and Specialized)
- Research Qualifier
- Thesis

The Course and Research Qualifiers are performed concurrently and are designed to take approximately equal amounts of time during the student's first two years. The doctoral dissertation and its associated research will normally require two to three further years for completion.

The exact degree requirements for a student in the program are as defined in the Course of Study as of the date that student first enrolls in the Robotics Ph.D. Program. Any subsequent changes to the Course of Study may optionally be selected by the student, or the student may choose to retain the previous requirements.

Occasionally, it is appropriate for a student to deviate slightly from the requirements as defined in the Course of Study. A student may request approval for a specific proposed alternative from the Chair of the Robotics Ph.D. Program. Generally, the Robotics Program Committee will review the request and make a recommendation to the Chairperson.

1.1 Preparation

The Robotics Doctoral Program accepts strongly motivated and exceptionally talented students from a wide range of educational backgrounds. It is each student's personal responsibility to arrive with, or to acquire rapidly thereafter, basic understanding (at the level of an introductory undergraduate course) in the following areas:

- Mathematics: calculus, linear algebra, numerical analysis, probability and statistics
- Computer Science: programming, data structures, algorithms
- Physics and Engineering: mechanics, dynamics, electricity and magnetism, optics

On request, the faculty will advise incoming students about individually appropriate alternative ways to satisfy these requirements, such as taking an undergraduate course, serving as a teaching assistant in an undergraduate course, or self-study by guided reading and discussion.

2.0 Course Qualifiers

Each student must complete two course qualifiers:

- Core Course Qualifier: Pass 48 units of core coursework in areas of robotics that every Ph.D. student is expected to be knowledgeable about.

- Specialized Course Qualifier: Pass 48 units of coursework defined by the student and for the purpose of acquiring specialized knowledge in particular areas.

Courses must be passed with a grade of B-, or better, to fulfill, or contribute to, completion of a course qualifier.

All of the necessary study and evaluation within the Robotics Ph.D. Program are contained in the Course Qualifiers. There are no other examination requirements for the Doctoral degree in Robotics. Students are encouraged to attend additional courses if they and their advisor agree it would be valuable, but such courses are not required for the Robotics degree and may be substituted for required courses only if approved by the Chair of the Robotics Program. Seminars are valuable educational experiences, but do not count for credit toward a course qualifier.

Students in the Robotics Ph.D. Program must register with the university and enroll for credit for all courses taken as part of fulfilling the Course Qualifiers.

2.1 Core Course Qualifier

Robotics research revolves around four core areas of knowledge, including

- **Sensing and Perception:** The observation and interpretation of a robot's environment as well as its own state.
- **Thinking about Actions:** The conception and selection of actions through planning, learning and control.
- **Robot Embodiment:** The design and realization of the physical robot.
- **Environment Interaction:** The interaction of a robot with its environment, whether animate (human robot interaction) or inanimate (manipulation, locomotion).

Every Ph.D. student of robotics is expected to be knowledgeable about these core areas. It is understood, however, that with a 48 unit limit, breadth and depth have to be traded off. In addition, with the diverse backgrounds that students entering the Robotics Institute Ph.D. program have, it is also understood that individual students will need to complement their prior training with knowledge and skills in foundational disciplines spanning math, software, and hardware.

To accommodate these points, the **core requirements** are as follows:

- Students must pass coursework worth 12 units in a Foundations area, providing essential prerequisites for mastering the four core areas.

- Students must pass 36 units worth of coursework in the four core areas of Sensing and Perception, Thinking about Actions, Robot Embodiment, and Environment Interaction. Specifically, students must
    1. take a course from each of the four core areas,
    2. pass two full semester courses each worth 12 units from two core areas that they wish to acquire deeper knowledge in, and
    3. pass two half-semester mini courses each worth 6 units from the remaining two core areas

The mini courses are designed to help students appreciate the broader value and research opportunities of the respective core area, equip them with the basic knowledge and practical skills to enter the area with further self-study, and provide them with sufficient competency to collaborate with an area expert.

- Students can replace each mini course with a full semester course in the same core area with the understanding that their course load in the core areas then increases beyond the required 36 units.

Courses that count toward satisfying the core requirements are

Foundations Area
16-706: Foundations of Linear Algebra (6 units)
16-707: Foundations of Optimization (6 units)
16-708: Foundations of Statistics (6 units)
16-709: Foundations of Software (6 units)
16-710: Foundations of Manufacturing (6 units)
16-811: Mathematical Fundamentals for Robotics (12 units)

Sensing and Perception Core Area
16-720: Computer Vision (12 units)
16-722: Sensing and Sensors (12 units)
16-820: Advanced Computer Vision (12 units)
16-822: Geometry-based Methods in Vision (12 units)
16-823: Physics-based Methods in Vision (12 units)
16-833: Robot Localization and Mapping (12 units)
16-705: Fundamentals of Computer Vision Mini (6 units)

Thinking about Actions Core Area
16-711: Kinematics, Dynamic Systems and Control (12 units)
16-714: Advanced Control (12 units)
16-745: Dynamic Optimization (12 units)
16-782: Planning and Decision Making (12 units)
16-831: Introduction to Robot Learning (12 units)
10-701: Machine Learning (12 units)
10-715: Advanced Machine Learning (12 units)
15-780: Graduate Artificial Intelligence (12 units)
16-702: Fundamentals of Learning Mini (6 units)
16-703: Fundamentals of Control Mini (6 units)

Robot Embodiment Core Area
16-778: Mechatronic Design (12 units)
16-878: Advanced Mechatronic Design for Robotics (12 units)
16-880: Engineering Haptic Interfaces (12 units)
16-704: Fundamentals of Mechatronics Design for Robotics (6 units)

Environment Interaction Core Area
16-741: Mechanics of Manipulation (12 units)
16-761: Mobile Robots (12 units)
16-867: Human Robot Interaction (12 units)
16-700: Fundamentals of Manipulation Mini (6 units)
16-701: Fundamentals of Human Robot Interaction Mini (6 units)

2.2 Specialized Course Qualifier

The Specialized Course qualifier is a sequence of courses chosen by the student to enhance the Core Course subject matter by adding greater depth in a particular area. These specialization courses must total at least 48 units of graduate coursework. In this way, the core science component of the program is complemented by studies that keep pace with new developments and current topics. The courses should have coherence in subject matter. They may be directly related to the student's thesis research but are not restricted to that topic.

The Specialized Course Qualifier must be defined by the student in conjunction with their Ph.D. Advisor and then approved by the Chair of the Ph.D. Program. Typically, the student will identify 4 graduate courses that relate to their interests and will complete and submit a Specialized Qualifier approval form. Students are strongly encouraged to seek approval before completing courses; any course completed prior to approval is at risk and may not be deemed eligible for their qualifier.

The Specialized Qualifier courses must total at least 48 units, usually four full-semester graduate courses. The following guidelines cover the usually applicable constraints and will help in composing a Specialized Qualifier sequence.

- Graduate level (600 - 800-level) courses only
- No more than 12 units of non-doctoral (600-level) graduate courses
- No more than 12 units of project-only courses
- No more than 12 units of independent study

  (Independent study courses must include syllabus, schedule, assignments, and evaluation criteria. Syllabus submitted with the SQ form.)
- Core courses can be used in the Specialized Qualifier sequence, but only in addition to 48-units of Core Qualifier courses
- Partial units (six units of a 12-unit course) taken in core courses cannot be applied to the Specialized Qualifier
- Teaching Assistantships cannot be included as Specialized Qualifier courses
- Seminar Courses cannot be included as Specialized Qualifier courses, e.g., 16-892, 16-895

2.3 Course Credit

Transfer credit for graduate courses completed at institutions other than Carnegie Mellon University is not granted in the Robotics Ph.D. program.

Core Course Qualifier: Previously completed core courses at Carnegie Mellon University will be automatically credited towards the core course qualifier.

Specialized Course Qualifier: Students are eligible to request application of up to three approved Carnegie Mellon University graduate-level courses towards the fulfillment of specialized qualifier requirements. The determination of the specific specialized course qualifier must be made in collaboration with the student's Ph.D. advisor and subsequently receive approval from the Ph.D. Program Chair.

The courses offered toward satisfying the qualifier cover different levels of advancement, encouraging students at all levels to learn more as they engage in the Robotics Institute Ph.D. program.

3.0 Research Qualifier

The Research Qualifier examines the skills that are important for every researcher to possess including scholarly research, speaking, writing, and teaching. The Research Qualifier typically requires half of the student's time and effort for two years and is to be completed concurrently with the Course Qualifiers. The primary component of the Research Qualifier is supervised research under the guidance of a faculty member who serves as the student's advisor. In addition, the research qualification process includes serving as a teaching assistant, writing a research paper, and presenting a technical talk.

To oversee this process, the student forms a Research Qualifier Committee consisting of three faculty members and one Robotics Ph.D. student who has completed their Ph.D. Research Qualifier (speaking, writing, research skills). One faculty committee member must hold a primary appointment in Robotics. The faculty members should include the student's advisor(s) and one faculty member who is not participating in the student's research. Forms to verify completion of the parts of the Research Qualifier must be filled out by each member of the Research Qualifier Committee (with the exception of the Teaching requirement, which must be filled out by the instructor of the course for which the student serves as teaching assistant).

It is the student's responsibility to ensure that reviews are completed and submitted by the relevant deadline.

The Research Qualifier comprises four components:

- **Research Skills:** the ability to create, explore, refine, and test new ideas in robotics. Students are expected to demonstrate awareness of previous work in their area of research, depth of insight into the problem, creativity in approaching the problem, and substance of results obtained. Students should meet and discuss their progress with every member of their Research Qualifier committee each semester until their skills component is complete.

- **Speaking:** the ability to communicate in oral presentation. Students are expected to demonstrate the ability to present technical material to a technical audience clearly and succinctly. The presentation must be made at a venue open to the public. Ideally, the Research Qualifying Committee will be in attendance, but committee members may designate proxies, subject to approval by the Program Chair, to evaluate the presentation.

- **Writing:** the ability to communicate in technical writing. A student is expected to produce a conference-length, or longer, paper, in which they are the sole, or the primary, author plus a one page executive summary in which they are the sole author. The paper should demonstrate a style, organization and clarity that enables researchers in the field to comprehend the problem, method, and results of the research. Students who have written papers prior to entering the Robotics Program may submit them for evaluation, provided they meet the above criteria.

- **Teaching:** the experience of teaching in a classroom environment. This includes demonstration of as many as possible of the following: lecturing, recitation instruction, homework and exam design, grading, office hours, curriculum design. Each student must serve as a teaching assistant in two (2) courses relevant to the Robotics Program. Allowable courses will be defined by the Chair of the Ph.D. Program. Students may arrange to serve as teaching assistant (TA) by contacting the Program Coordinator at the beginning of the semester before the semester in which the student will act as a TA. The student is expected to spend on average 10-15 hours per week or about one quarter of their time on teaching. The instructor should provide feedback to the student concerning the quality of the student's teaching. The instructor should report to the Program Coordinator his or her evaluation of whether the student has carried out the TA activities successfully.

  Students may serve as co-instructors for one class, provided that they have already satisfied both TA requirements, have completed the Eberly Future Faculty Program, and have the support of their research advisor.

  Note that the State of Pennsylvania requires proficiency in English to act as a teaching assistant. Non-native speakers must be evaluated at the Language Support in the Student Academic Success Center and either Pass or Restricted One on their ITA examination. It is the student's <u>responsibility</u> to achieve this proficiency in time to start (in their second year) to complete their required TA assignments (in their fourth year).

3.1 Master's Writing and Speaking

Students completing the Master of Science in Robotics (research masters) at Carnegie Mellon University who intend to matriculate into the Ph.D. program may waive the Writing and Speaking requirements for their Ph.D. upon successfully completing their Writing and Speaking requirements for their M.S.

The 168 units for the MSR degree may not double count for another undergraduate or master's program.

Students must still form a Ph.D. Research Qualifier Committee and complete the Ph.D. Research Skills Qualifier and Teaching components.

4.0 Thesis

The doctoral thesis represents a novel and significant contribution to the state of art in robotics. Researching, writing and presenting a thesis is intended to occupy approximately two to three years of activity, with these specific parts:

1. Thesis Proposal
2. Dissertation
3. Oral Defense of the Thesis

The evaluation of all three of these components must be performed by the Robotics faculty, as represented by the student's Thesis Committee. The committee will consist of at least four members: a minimum of three from Carnegie Mellon, at least two of whom must be faculty members affiliated with the Robotics Institute (at least one faculty member with a primary appointment in Robotics) and at least one qualified researcher who is external to Carnegie Mellon. The student's advisor(s) chair the Thesis Committee. The entire composition of the committee must be approved by the Chair of the Ph.D. Program <u>before the Thesis Proposal is scheduled</u>.

Prior to presenting the Thesis Proposal, the four Core Courses of the Course Qualifier and the research, speaking and writing skills portions of the Research Qualifier must be complete.

In the Thesis Proposal, the student is formally asking the faculty for permission to pursue a line of research leading to the Dissertation. To do this, the student must do the following:

- Describe a problem and its importance;

- Summarize and evaluate what previous work has been done by others to solve this problem;

- State what has been accomplished so far by the student and how and why it will lead to the solution, or partial solution, of the problem;

- Describe and state what the student intends to do to complete the dissertation and how long it is expected to take; and

- Identify what novel and significant contributions it will make to the field of Robotics that merit awarding the degree of Ph.D.

The oral presentation of the proposal is made publicly to the entire research community, including particularly the Thesis Committee. The Thesis Committee must then express approval to the Chair of the Program if the proposal is to be accepted.

The **Dissertation** itself is normally preceded by a year or more of research and writing after the proposal. The Dissertation is a scholarly document describing the problem, related work, the student's approach, the results and insights achieved, and the significance of the work. The written dissertation must be presented to the Thesis Committee for approval.

All Course and Research Qualifiers must be completed before scheduling a Thesis Defense.

The faculty of the Robotics program and the local community must receive notice of all thesis presentations at least one week in advance. Therefore, students are required to provide the Program Coordinator with complete information, no less than ten days before the scheduled presentation, including: title, abstract, committee members, on-line location of thesis document and/or hard copy. The Program Coordinator will advertise thesis presentations on appropriate on-line and physical venues.

When the committee gives preliminary approval, the **Oral Defense** of the thesis can take place. At the Oral Defense, the committee and the entire community will have the opportunity to publicly question the work critically. Finally, the Thesis Committee on behalf of the faculty must decide whether to approve the oral defense and whether, or under what conditions, to accept the dissertation and recommend awarding of the doctoral degree.

A student will be certified for graduation and allowed to attend commencement ceremonies when the thesis is unanimously approved by his or her Thesis Committee and it has been delivered to the Program Coordinator in final form. The student will be awarded the degree of Doctor of Philosophy in the field of Robotics.

5.0 Robotics Orientation

The student's research education begins in the Robotics Orientation, which all Robotics students must attend at the beginning of their first semester in the program. The Robotics Orientation is a series of lectures, discussions, and demonstrations that familiarize the students with Carnegie Mellon and the Robotics Program, introduce the research projects and faculty within the Program and affiliated departments, and describe the computational and other resources available to students in the Program. The Robotics Orientation gives students an opportunity to learn what it means to conduct research and to get to know the faculty in the Robotics Program.

6.0 Advising and Matching Process

The candidate's advisor will be the faculty member who works most closely with that student. This is usually the most important factor in the student's research education, so choice of an advisor should be based on careful consideration. New candidates and faculty will have extensive opportunity to meet to discuss research, assess compatibility, and evaluate interests. The Matching Committee will match students and faculty advisors based on the preferences of the students and the faculty, subject also to the research agenda (and funding) of the faculty.

In order to make this an informed process, the assignments are made approximately 6 weeks after the Robotics Orientation, giving an ample period of time for the new students to meet the faculty individually. Each new student should use this opportunity to talk to all the faculty whose research interests might overlap those of the student. In this way, the students can learn about all the available research areas of the faculty, and the faculty can meet and talk with the students, before commitments are made. Students and faculty present their preferences for advisor/advisee pairings, and these preferences are used in matching students and advisors. After the Matching process, each student begins guided research under supervision of the advisor.

The duties of the advisor include approving the student's selection of courses, mentoring the student in research, advising the student on methods and skills, providing research opportunities and facilities for the student, and reporting on the student's progress to the faculty.

Advising relationships are mutually agreed and are mutable. It is possible for a student to change advisors with approval of the Chair of the Ph.D. Program. A student may request to switch to a new advisor, to add an additional co-advisor, or to remove a co-advisor. In this way, the student's changing perspectives and research focus can be accommodated by the program. Generally, the student should discuss such matters first with their current advisor(s), then make a tentative agreement with the new advisor(s), then finally request that the new plan be approved by the Chair of the Ph.D. Program. The Chair of the Ph.D. Program is available to help guide the student through this process if needed.

7.0 Timeline of Study

It is expected that students will complete both the Course Qualifiers (Core and Specialized) in two years of dedicated study. Students who have completed at least half of the required courses in graduate study prior to entering the Program, such as in the Robotics Masters program, will be advanced one year in the timeline for completing the Course Qualifier. This means they are expected to complete remaining courses in only one year of dedicated study.

Concurrent with coursework, it is expected that students will complete the Research Qualifier, with the exception of one of two required teaching assignments, in two years of dedicated study. If necessary, the student may complete their second teaching assignment in their third year.

It is expected that the Thesis Proposal will require about half a year of productive research beyond the Research Qualifier for its preparation and that it will be presented during the student's third year in the Program.

Students who are more than one year beyond the expected completion time for a qualifier or proposal are not making satisfactory progress in the Program. Specifically if not complete with: the Course Qualifier after three years (or two years if advanced due to prior coursework) or the Research Qualifier after three years, final teaching assignment after four years, or the Thesis Proposal after four years, then students are not in good standing and, subject to the judgment of the faculty in the Review of Progress, may be removed from the Program.

8.0 Review of Progress

At the end of each semester, the entire faculty of the Robotics Program meets to discuss the record and progress of all students in the Program. The evaluation for each student is based on several factors:

- The student's status at the start of the semester, as expressed by the previous Doctoral Student Review evaluation;
- The student's accomplishments during the semester, as described by the student in a form submitted prior to the meeting, and summarized at the meeting by the student's advisor;
- The advisor's evaluation, expressed in the form of a draft of a Doctoral Student Review letter that the advisor proposes to be sent to the student;
- Input from other faculty who have had dealings with the student;

- Discussion by the faculty of all of the above factors at the Doctoral Student Review meeting, which may include modifications to the letter drafted by the advisor; and
- Final decision by the Chair of the Program based on the above discussion.

After the meeting, the Chair of the Program will send a letter of progress to each student, based on the recommendation of the faculty at the meeting. Through this mechanism, the faculty can report "satisfactory" or "unsatisfactory" progress, offer recommendations to the student and advisor, set specific progress goals that must be achieved, or, if necessary, terminate a student's participation in the program. The continuation or conditions of a student's funding may also be determined in the meeting, as described in the "Robotics Graduate Student Handbook".

In general, termination will be preceded by at least one unsatisfactory evaluation. An explicit warning (called an "N-1 letter") will normally be given one semester before any decision to terminate a student's participation in the program.

In addition to the progress review, the Doctoral Student Review meeting and resultant letters provide an opportunity for the faculty to learn about and acknowledge the students' contributions in service to the Program and achievements such as research publications and awards. Matters of academic policy are frequently discussed at the Doctoral Student Review meeting as they arise in the discussion of individual students.

The Doctoral Student Review process ensures that each student's progress is reviewed by the entire faculty, and not only by the advisor. The Doctoral Student Review process involves a careful consideration by the faculty of each student's case. If the student wishes to appeal the decisions reflected in their letter, the student should state their perspective in a request to the Chair of the Program to review the case again. The Chair will undertake such a review, in consultation with the faculty as appropriate, and issue a written response to the student. If the student is not satisfied with the Chair's response, it may be appealed as described in the Student Handbook for Carnegie Mellon University.

9.0 Master's Degree in Robotics

The Robotics Doctoral Program at Carnegie Mellon is principally a Ph.D. program. However a student who is working towards a Ph.D. may receive the degree of M.S. in Robotics by completing the requirements as defined by the current Masters Program course of study. This M.S. degree may be completed as a terminal degree or may be granted while still continuing to the Ph.D. degree.

A. Core Courses

A.1 Foundations Area

- **16-706: Foundations of Linear Algebra** (6 units)
- **16-707: Foundations of Optimization** (6 units)
- **16-708: Foundations of Statistics** (6 units)
- **16-709: Foundations of Software** (6 units)
- **16-710: Foundations of Manufacturing** (6 units)
- **16-811: Math Foundations for Robotics** (12 units). This course covers selected topics in applied mathematics. Topics covered in the past have included: polynomial interpolation and approximation; solution of nonlinear equations; roots of polynomials; approximation by orthogonal functions such as Fourier series; optimization; calculus of variations; probability; numerical solution of differential equations.

A.2 Sensing and Perception Core Courses

- **16-720: Computer Vision** (12 units). This course introduces the fundamental techniques used in computer vision, that is, the analysis of patterns in visual images to reconstruct and understand the objects and scenes that generated them. Topics covered include image formation and representation, camera geometry, and calibration, computational imaging, multi-view geometry, stereo, 3D reconstruction from images, motion analysis, physics-based vision, image segmentation and object recognition. The material is based on graduate-level texts augmented with research papers, as appropriate.

- **16-722: Sensing and Sensors** (12 units). The principles and practices of quantitative perception (sensing) illustrated by the devices and algorithms (sensors) that implement them. Learn to critically examine the sensing requirements of robotics applications, to specify the required sensor characteristics, to analyze whether these specifications can be realized even in principle, to compare what can be realized in principle to what can actually be purchased or built, to understand the engineering factors that account for the discrepancies, and to design transducing, digitizing, and computing systems that come tolerably close to realizing the actual capabilities of available sensors.

- **16-820 Advanced Computer Vision** (12 units)**.** Moves at a slightly faster pace compared to 16-720. This course introduces the fundamental techniques used in computer vision, that is, the analysis of patterns in visual images to reconstruct and understand the objects and scenes that generated them. Topics covered include camera geometry and calibration, multi-view stereo, 3D reconstruction, image detection, segmentation, and tracking, and physics-based vision. The homework involves considerable Python programming exercises.

- **16-822: Geometry-based Methods in Vision** (12 units). The course focuses on the geometric aspects of computer vision: The geometry of image formation and its use for 3D reconstruction and calibration. The objective of the course is to introduce the formal tools and results that are necessary for developing multi-view reconstruction algorithms. The fundamental tools introduced study affine and projective geometry, which are essential to the development of image formation models. Additional algebraic tools, such as exterior algebras are also introduced at the beginning of the course. These tools are then used to develop formal models of geometric image formation for a single view (camera model), two views (fundamental matrix), and three views (trifocal tensor); 3D reconstruction from multiple images; and auto-calibration.

- **16-823: Physics-based Methods in Vision (Appearance Modeling**) (12 units). Everyday, we observe an extraordinary array of light and color phenomena around us, ranging from the dazzling effects of the atmosphere, the complex appearances of surfaces and materials, and underwater scenarios. For a long time, artists, scientists, and photographers have been fascinated by these effects, and have focused their attention on capturing and understanding these phenomena. In this course, we take a computational approach to modeling and analyzing these phenomena, which we collectively call "visual appearance". The first half of the course focuses on the physical fundamentals of visual appearance, while the second half of the course focuses on algorithms and applications in a variety of fields such as computer vision, graphics and remote sensing and technologies such as underwater and aerial imaging.

- **16-833: Robot Localization and Mapping** (12 units). Robot localization and mapping are fundamental capabilities for mobile robots operating in the real world. Even more challenging than these individual problems is their combination: simultaneous localization and mapping (SLAM). Robust and scalable solutions are needed that can handle the uncertainty inherent in sensor measurements, while providing localization and map estimates in real-time. We will explore suitable efficient probabilistic inference algorithms at the intersection of linear algebra and probabilistic graphical models. We will also explore state-of-the-art systems.

- **16-705: Fundamentals of Computer Vision** (6 units)**.**

A.3 Thinking about Actions Core Courses

- **16-711: Kinematics, Dynamic Systems and Control** (12 units). This course covers fundamental concepts and methods to analyze, model and control robotic mechanisms which move in the physical world and manipulate it. Main topics include the fundamentals of kinematics, dynamics and control applied to the kinematics, dynamics and control of rigid body chains. Additional topics include state estimation and dynamic parameter identification.

- **16-714: Advanced Control** (12 units). This course will discuss advanced control algorithms that can make robots behave more intelligently. This course is directed to students primarily graduate although talented undergraduates are welcome as well interested in advanced control.

- **16-745: Dynamic Optimization** (12 units). This is a course about how to make robots move through and interact with their environment with speed, efficiency, and robustness. We will survey a broad range of topics from nonlinear dynamics, linear systems theory, classical optimal control, numerical optimization, state estimation, system identification, and reinforcement learning. The goal is to provide students with hands-on experience applying each of these ideas to a variety of robotic systems so that they can use them in their own research.

- **16-782: Planning and Decision Making** (12 units). Planning and Decision-making are critical components of autonomy in robotic systems. These components are responsible for making decisions that range from path planning and motion planning to coverage and task planning to taking actions that help robots understand the world around them better. This course studies underlying algorithmic techniques used for planning and decision-making in robotics and examines case studies in ground and aerial robots, humanoids, mobile manipulation platforms and multi-robot systems. The students will learn the algorithms and implement them in a series of programming-based projects.

- **16-831: Introduction to Robot Learning** (12 units). This class addresses how robots can learn to make sequential decisions to operate in the world and generalize to diverse environments. The "robot learning" problem and it spans topics in machine learning, visual learning and reinforcement learning. In this course, we will learn the fundamentals of topics in machine/deep/visual/reinforcement-learning and how such approaches are applied to robot decision making. We will study fundamentals of: 1) machine (deep) learning with emphasis on approaches relevant for cognition, 2) reinforcement learning: model-based, model-free, on-policy (policy gradients), off-policy (q-learning), etc.; 2) imitation learning: behavior cloning, dagger, inverse RL and offline RL; 3) visual learning geared towards cognition and decision making including topics like generative models and their use for robotics, learning from human videos, passive internet videos, language models; and 4) leveraging simulations, building differentiable simulations, and how to transfer policies from simulation to the real world; 5) we will also briefly touch topics in neuroscience and psychology that provide cognitive motivations for several techniques in decision making.

- **10-701: Machine Learning.** (12 units) Machine Learning is concerned with computer programs that automatically improve their performance through experience. This course covers the theory and practice of machine learning from a variety of perspectives. Topics covered include learning decision trees, neural network learning, statistical learning methods, genetic algorithms, Bayesian learning methods, explanation-based learning, and reinforcement learning. The course covers theoretical concepts such as inductive bias, the PAC and Mistake-bound learning frameworks, minimum description length principle, and Occam's Razor. Programming assignments include hands-on experiments with various learning algorithms. Typical assignments include neural network learning for face recognition, and decision tree learning from databases of credit records.

- **10-715: Advanced Machine Learning**. (12 units) The rapid improvement of sensory techniques and processor speed, and the availability in inexpensive massive digital storage, have led to a growing demand for systems that can automatically comprehend and mine massive and complex data from diverse sources. Machine Learning is becoming the primary mechanism by which information is extracted from Big Data, and a primary pillar that Artificial Intelligence is built upon. This course is designed for Ph.D. students whose primary field of study is machine learning. The topics of this course will in part parallel those covered in the general graduate machine learning course (10-701), but with a greater emphasis on depth in theory and algorithms. The course will also include additional advanced topics such as fairness in machine learning. Students entering the class are expected to have a pre-existing strong working knowledge of algorithms, linear algebra, probability, and statistics.

- **15-780: Artificial Intelligence**. (12 units) Introduction to Artificial Intelligence tailored toward the algorithms and applications of robotics, manufacturing, and engineering disciplines. Strong focus on modern numerical approaches to AI and robotics, including Bayes nets, classical decision-theoretical problems such as scheduling, and optimal and learning control of Markov systems. Motion planning and spatial reasoning, neural nets, qualitative reasoning, and fuzzy logic are covered in detail.

- **16-702: Fundamentals of Learning** (6 units)
- **16-703: Fundamentals of Control** (6 units)

A.4 Robot Embodiment Core Courses

- **16-778: Mechatronic Design** (12 units)**.** Mechatronics is the synergistic integration of mechanism, electronics, and computer control to achieve a functional system. This course is a semester-long multidisciplinary capstone hardware project design experience in which small (typically four-person) teams of electrical and computer engineering, mechanical engineering and robotics students deliver an end-of-course demonstration of a final integrated system capable of performing a mechatronic task. The students design, configure, implement, test and evaluate in the laboratory devices and subsystems culminating in the final integrated mechatronic system.

- **16-878: Advanced Mechatronic Design for Robotics** (12 units). This course is designed for students who have a background in mechatronics by having taken a mechatronics design course or through practice. The course will be a combination of laboratories and lectures and will culminate in a class project. The topics covered will be microcontroller hardware subsystems: timer systems, PWM, interrupts; analog circuits, operational amplifiers, comparators, signal conditioning, interfacing to sensors, actuator characteristics and interfacing; C language features for embedded software, register level programming, hardware abstraction layers, event driven programming, state machines, state charts.

- **16-880: Engineering Haptic Interfaces** (12 units). This course focuses on addressing challenges in the field of haptics from an engineer's perspective. We will begin by studying human haptic perception and an introduction into psychophysics. We will then study the design and control of haptic systems which provide touch feedback to a user.

- **16-704: Fundamentals of Mechatronics Design for Robotics** (6 units).

A.5 Environment Interaction Core Course

- **16-741: Mechanics of Manipulation** (12 units)**.** This course dives into the fundamentals of robotic manipulation. Through this course you will learn the kinematics, statics, and dynamics of robotic manipulators as they interact with the world to accomplish tasks. You will gain experience with the intelligent use of kinematic constraint, gravity, and frictional forces. Additional topics include rigid body mechanics, automatic planning based on mechanics, deformable manipulation, and simulation of dynamic manipulation. Applications of robotic manipulation are drawn from physical human-robot interaction, manufacturing, and other domains.

- **16-761: Mobile Robots** (12 units)**.** The course is targeted to graduate level students. The lectures will develop the fundamentals for enabling autonomy of multi rotor aerial vehicles. Students will individually complete assignments related to autonomous quadrotor flight, including motion planning, control, dynamics, state estimation, and perception.

- **16-867: Human Robot Interaction** (12 units). Robot interaction with people is inevitable: human engineers iteratively tune robot policies, autonomous cars navigate through crowded cities, construction workers teleoperate drones for building inspections, and assistive robots help end-users with daily living tasks. In this class we will formalize such human-robot interaction problems algorithmically. We will build the mathematical foundations for modeling human-robot interaction across robots and tasks, enable robots to understand human intent and predict human behavior, and study how robot learning changes in the presence of human feedback. The approaches covered will draw upon a variety of disciplines and tools such as sequential decision-making, cognitive science, Bayesian inference, and modern machine learning. Throughout the class, there will also be several guest lectures from experts in the field. Students will practice essential research skills including reviewing papers, writing project proposals, and technical communication.

- **16-700: Fundamentals of Manipulation** (6 units). As a core mini, this course will provide students with the fundamental knowledge and technical skills to begin exploring the topic of robot manipulation and collaborate with others in this field. The class will introduce students to core concepts of manipulation such as affordances, interactive perception, contact constraints, and grasp analysis. The course will also introduce students to how manipulation is seen from the perspective of control, task and motion planning, and machine learning. We will cover some of the core methodologies from each of these areas and how they address some of the challenges of robot manipulation. We will also discuss the complementary nature of these methods and how they can be used in unison.

The lectures will be supported by a set of assignments that will guide students through the implementation of different methods in a simulated manipulation task.

- **16-701: Fundamentals of Human Robot Interaction** (6 units). This course fulfills one mini requirement for the Robotics Ph.D. core. Robots often have to interact with and around people, and such human-robot interactions present both challenges and opportunities for robotics. In this introductory course on HRI, we will learn how a robot's algorithmic and behavioral design impacts the way people perceive and respond to it. We will cover basic human psychology principles like communication and theory of mind, and we will see how robots can use these principles to create more effective interactions. We will also learn how to conduct human-subjects experiments and analyze the resulting data in ways that allow us to learn more about HRI. The course will primarily involve lectures, in-class discussions, readings, and take-home exercises.

B. Research Qualifier

Some students may feel unprepared for the Research Qualifier. To help in that regard, there are courses and materials available that can prepare the student for speaking, writing, and teaching. For international students, the Language Support in the Student Academic Success Center can recommend remedial course work, workshops and seminars on an individual basis to help ensure that students have the language skills to pass these three portions of the Research Qualifier.

B.1 Research Skills

This is the most important skill learned as a Ph.D. student, and it is the primary responsibility of the advisor to mentor the student in research skills. Students and advisors should meet regularly to discuss research and plan approach. Additionally students should meet with every member of their Research Qualifier committee each semester.

B.2 Speaking

A suitable course for a student to take to improve speaking ability is:

90-718: Strategic Presentation Skills (6 units)

In addition, research talks by internal and external speakers are frequently scheduled throughout the year. Students are encouraged to attend these to get an understanding of what is expected from a research talk.

B.3 Writing

A suitable course for a student to take to improve writing skill is:

76-870: Professional and Technical Writing (12 units)

In addition, it is recommended that students read extensively in the field, especially award-winning papers, to get an idea of what good writing entails. The university Student Academic Success Center has many resources for improving writing and writing particular types of documents. A student's advisor can also provide opportunities to review papers for conferences and journals, another helpful tool in improving a student's writing skills.

B.4 Teaching (Non-Native Speakers of English)

There are many courses and seminars offered weekly and each semester through the Eberly Center that can be taken to improve teaching ability.

For non-native speakers of English, Carnegie Mellon policy, in accordance with the Pennsylvania English Fluency in Higher Education Act, requires that all students apply for language certification through Language Support in the Student Academic Success Center before they can be certified to serve as International Teaching Assistants (ITAs). Students can satisfy the certification requirement using either the TOEFL option if their speaking score is between 26-30 or applying for the ITA test option. A rating of "Pass" or "Restricted One" must be attained in order to qualify for certification.

While Carnegie Mellon and Commonwealth of Pennsylvania policies require the above standard of students teaching assistants in undergraduate courses, the Robotics Institute requires these standards of all teaching assistants in any Robotics course, and all Robotics students assisting in a course in Robotics or any other department. This holds for both graduate and undergraduate courses. The Program Coordinator will monitor the status of all international students to ensure that a Pass or Restricted One has been attained before any student will be permitted as a teaching assistant. Students found to be out of status by assisting before they have attained a Pass or Restricted One will risk not having the teaching assistant assignment count toward his or her Research Qualifier and having to act as teaching assistant again once the required standards are met.