

**Course of Study
for the Robotics Ph.D. Program**

by the Faculty of the Ph.D. Program in Robotics

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Revised May 2014 and applied ongoing from August 2014.

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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Overview of Doctoral Program

This document defines the degree requirements for students in the Ph.D. Program in Robotics at Carnegie Mellon. The program is designed so that a well-prepared student can complete the doctoral degree in four to five years. The program outline is:

1. Course Qualifiers
2. Research Qualifier
3. Thesis

Parts 1 and 2, the qualification process, are concurrent and are designed to take approximately equal amounts of time during the student's first two years. Part 3, the thesis, will normally require two more years for completion. These requirements are detailed in this document.

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.

The Robotics Doctoral Program sometimes 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, e.g., taking an undergraduate course, serving as a teaching assistant in an undergraduate course, or self-study by guided reading and discussion.

1 Course Qualifiers

Each student must complete the two course qualifiers:

- Core Courses, consisting of one course from each of four core areas
- Specialized Courses, comprising 48 units of coursework (typically four graduate courses) in a specialized area defined by the student

All courses must be passed with a grade of B-, or better.

All of the requirements for courses and exams within the Robotics Ph.D. Program are contained in the Course Qualifiers. There are no other course or exam requirements for the Doctorate 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 without course numbers are also frequently valuable educational experiences, but generally do not count for course credit.

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

1.1 Core Course Qualifier

Students must pass four Core Courses, one course from each of the following four Core Areas:

- **Perception:** vision, image sensors, range data interpretation, tactile and force sensors, inertial guidance, and other sensors. Core courses in Perception are 16-720 Computer Vision, and 16-722 Sensing and Sensors.
- **Cognition:** artificial intelligence for robotics, knowledge, representation, planning, task scheduling, and learning. Core courses in Cognition are 15-780 Artificial Intelligence, and 10-701 Machine Learning.
- **Action:** kinematics, dynamics, control, manipulation, and locomotion. Core courses in Action are 16-741 Mechanics of Manipulation, and 16-711 Kinematics, Dynamic Systems, and Control.
- **Math Foundations:** optimal estimation, differential geometry, computational geometry, and operations research. The one core course in this area is 16-811 Math Fundamentals for Robotics.

1.2 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 a particular area. These specialization courses must total at least 48 units of graduate coursework. In this way, the foundational 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 Program Committee Chairperson. Typically the student will identify 4 graduate courses that relate to their interests and will complete the required 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. (See also the guidelines on the Specialized Qualifier form.)

Students who have completed graduate courses prior to entering the Ph.D. program and have acquired relevant knowledge and experience that is directly related to their area of specialization may request that some portion of their Specialized Qualifier be waived. For graduate courses completed at Carnegie Mellon, the Ph.D. Program Chairperson will review the waiver. For graduate courses completed at any other institution, a subject area expert from the faculty will be assigned for the waiver review. (See 1.3 Waivers)

1.3 Waivers

On the basis of previous related course work, students may apply by completing a waiver request form to waive any course. The Chair of the Program will then assign a suitable faculty member to handle the request, typically the relevant course instructor or an expert in the topic. In some cases, the faculty may determine that a student has demonstrated significant knowledge of the research area, but not quite sufficient enough to waive the course requirement entirely. In such cases, the faculty may grant a conditional waiver, contingent upon additional work, such as successfully acting as teaching assistant in the course or completing some designated project. If a student disagrees with the outcome, he or she may petition the Program Chair or the Program Committee, through the Program Committee Chair, to review the case.

2 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 his or her second year of study. 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).

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.
- **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 he/she is the sole, or the primary, author plus a one page executive summary in which he/she is 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 (TA) in one course relevant to the Robotics Program. Allowable courses will be defined by the Chair of the Program. Students may arrange to serve as 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 not required to spend more than twenty hours, but is not prohibited from doing so. 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.

3 Thesis

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 Dissertation

The evaluation of all three of these steps must be performed by the Program 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 Program before the Thesis Proposal is scheduled.

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
- Tell what 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 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.

All Qualifiers must be completed before scheduling the Thesis Defense.

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. When the committee gives preliminary approval, the **Oral Defense** can take place. At the Oral Defense, the committee and the entire community will have the opportunity to question the work critically. Finally, the Thesis Committee must decide whether to approve the thesis.

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 these presentations on appropriate on-line and physical venues.

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 has been delivered to the Program Coordinator in final form, at which time the student will be awarded the degree of Doctorate of Philosophy in the field of Robotics.

4 The Robotics Immigration Course

The student's research education begins in the Robotics Immigration Course, which all Robotics students must attend at the beginning of their first semester in the program. The Robotics Immigration Course 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 Immigration Course gives students an opportunity to learn what it means to conduct research and to get to know the faculty in the Robotics Program.

5 Advising and The Matching Process

The student'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. After the Robotics Immigration Course, students are assigned to faculty advisors by the Matching Committee. The assignments are 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 several weeks after the Robotics Immigration Course, giving an additional 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.

It is possible for a student to change advisors with approval of the Chair of the 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 Program. The Chair of the Program is available to help guide the student through this process if needed.

6 Timeline of Study

It is expected that students will complete both the Course and Research Qualifiers concurrently 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.

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 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.

7 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 (for historical reasons called "Black Friday"). 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 Black Friday 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 Black Friday 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 Black Friday 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 Black Friday 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 Black Friday meeting as they arise in the discussion of individual students.

The Black Friday process ensures that each student’s progress is reviewed by the entire faculty, and not only by the advisor. The Black Friday process involves a careful consideration by the faculty of each student’s case. If the student wishes to appeal the decisions reflected in their Black Friday 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.

8 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 upon request by the student and upon completion of the following requirements:

- Four Core Courses from the Course Qualifiers
- 36 units of coursework from the student’s approved Specialized Qualifier
- The Writing and Speaking portions of the Research Qualifier.

9 Directed Research

All students are expected to conduct research, starting in their first semester in the Ph.D. program. During a student's first two years, research will be conducted at least half time; once all coursework is completed, directed research is the primary activity and occurs full time (except when teaching or attending to other academic activities). Students commonly use the summer semester to make progress on their Ph.D. research. Students should enroll for 24-48 units of either Graduate Reading and Research (16-997) or Practicum (16-990) for each semester (Fall, Spring and Summer) in which they are active (excludes LOA and ABS status; and dual degree Portugal students). Directed research is graded pass/fail. If students choose a Practicum (internship) for directed research, they must complete a form that is available from the Program Coordinator and to perform a Practicum more than 4 times, they must have prior approval from the Ph.D. Program Chair.

A. Core Courses

A.1. Perception Core Courses

- **16-720: Computer Vision.** Topics covered include image formation and representation, camera geometry and calibration, multi-scale analysis, segmentation, contour and region analysis, energy-based techniques, reconstruction of based on stereo, shading and motion, 3-D surface representation and projection, and analysis and recognition of objects and scenes using statistical and model-based techniques.
- **16-722: Sensing and Sensor.** 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 proposed applications of robotics to real problems, 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, 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.

A.2. Cognition Core Courses

- **15-780: Artificial Intelligence.** 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.

- **10-701: Machine Learning.** 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.

A.3. Action Core Courses

- **16-711: Kinematics, Dynamic Systems, and Control.** Basic concepts and tools for the analysis, design, and control of robotic mechanisms. Topics covered include foundations of kinematics, kinematics of robotic mechanisms, review of basic systems theory, control of dynamical systems. Advanced topics will vary from year, including motion planning and collision avoidance, adaptive control, and hybrid control.
- **16-741: Mechanics of Manipulation.** Kinematics, statics, and dynamics of robotic manipulator's interaction with a task, focusing on intelligent use of kinematic constraint, gravity, and frictional forces. Automatic planning based on mechanics. Application examples drawn from manufacturing and other domains.

A.4. Math Foundations Core Course

- **16-811: Mathematical Fundamentals for Robotics.** 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.

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 Intercultural Communication Center can recommend remedial course work and ICC 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 is to mentor the student in research skills.

B.2. Speaking

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

90-718: Professional Speaking (6 units)

In addition, the School of Computer Science has many videotapes of distinguished lecturers that are available for students to review.

B.3. Writing

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

76-369 Technical Writing for Engineers (9 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. Many papers and presentations exist on techniques for writing well, including Marc Raibert's "Good Writing". 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 be tested by the Intercultural Communication Center (ICC) before they can be certified to serve as International Teaching Assistants (ITAs). The ITA test is offered several times during the year. A rating of "Pass" or "Restricted I" must be attained in order to qualify for certification. Students with

Restricted I status are permitted to teach, but they must continue to take language training with the ICC during their teaching semester.

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 I has been attained before any student will be permitted as a teaching assistant. Restricted I students will be monitored throughout the teaching semester to ensure that they are continuing with required training. Students found to be out of status, either by assisting before they have attained a Pass or Restricted I, or by not continuing the required tutoring during the teaching semester, 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.