University of Delaware

QUANTUM SCIENCE AND ENGINEERING PROGRAM

ACADEMIC PROGRAM APPLICATION

AUGUST 2021

PROGRAM POLICY STATEMENT

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I. Program Purpose

A. What is Quantum Science and Engineering

Quantum Science and Engineering (QSE) as a discipline is focused on understanding and leveraging the unusual behavior of particles and excitations governed by the laws of quantum mechanics. Leveraging this unusual behavior could lead to the creation of quantum computers that can perform calculations that are not feasible with classical computers, quantum sensors that can measure tiny changes not accessible to classical sensors, and quantum encryption that is unbreakable. Research in this area has historically taken place in Physics departments and has mainly focused on understanding the rules of quantum mechanics and creating proof-of-concept devices. Recently, there has been a significant investment by both industry and the federal government to create larger scale devices that leverage the principles of quantum mechanics. Quantum technologies are expected to be as transformational as the invention of the transistor. The "Quantum Workforce" required to meet this need must have a solid foundation in quantum physics, a deep understanding of materials and device engineering principles and constraints, and a firm grasp of quantum algorithms. This mix of skills is not provided by traditional disciplinary graduate programs. We are proposing a new interdisciplinary degree program in Quantum Science and Engineering to address this need.

B. Program details

The QSE program will offer both M.S. and Ph.D. degrees. All M.S. degrees are intended to be with a thesis, but a non-thesis option will be available. We will develop the curriculum in the 2021-2022 academic year and matriculate the first students in Fall 2022. The program will be housed in the Graduate College.

C. Goals

1) Establish a degree program that trains students with the science, engineering, and communication skills required by the Quantum Workforce.
2) Recruit, support, and retain a student population more diverse than traditional STEM disciplines relevant to QSE (e.g. Physics). Goal: URGs totaling 30% of student population.
3) Incorporate active, inquiry-driven, project- or problem-based educational opportunities in every core QSE class.
4) Expand convergent research in QSE at UD.

II. Admission

The minimum requirements for admission to the QSE program, for both M.S. and Ph.D. candidates, are the following:

1) A baccalaureate degree in engineering, physics, chemistry, mathematics, computer science, or a closely related field from an international or accredited US institution with an undergraduate cumulative grade point average in engineering, science, and mathematics courses of at least 3.0 on a 4.0 scale, or comparable to that ratio for degrees that use a different scale. Applicants with degrees in other disciplines may be admitted with provisional status and may be required to complete prerequisite courses that are deemed necessary for appropriate preparation for courses in the program. The GPA restrictions mentioned above apply also to applicants with academic backgrounds outside the traditional science and engineering disciplines. All international transcripts must be accompanied by a degree certificate showing the title earned and the date awarded.

2) Undergraduate courses in quantum mechanics are not required. All students are required to have taken linear algebra and to have the background necessary for the course work in the track to which they apply. Students applying to the Quantum Nanotechnology or Quantum Theory tracks are required to have taken course work in differential equations. Students applying to the Quantum Algorithms and Computation track are required to have taken course work in probability and statistics.
3) Consistent with University policy, a minimum of 100 on the Internet-based Test of English as a Foreign Language (TOEFL) or a score of at least 600 (paper based) is required for non-native English speakers who have completed prior degrees at non-English speaking institutions. A waiver of proof of English Proficiency can be granted when a bachelor's, master's, or doctoral degree has been or will be earned from a university recognized by the ministry of education in a country where English is the primary language.

Candidates are required to provide the following additional documents as part of their application package:

1) Three letters of recommendation from former teachers or supervisors
2) Resume or curriculum vitae
3) Statement of purpose

To receive priority in admissions and funding decisions, applications must be completed by January 15 for the following fall. Applicants will typically be notified of acceptance no later than mid-March and will be expected to respond to the offer by April 15.

Admission to the graduate program is competitive. Those who meet stated requirements are not guaranteed admission, nor are those who fail to meet all of those requirements necessarily precluded from admission if they offer other appropriate strengths.

Students wishing to transfer into the program from a graduate degree program at another institution should submit a regular application by the January 15 deadline. Students wishing to transfer into the program from another graduate degree program at UD should contact the graduate program advisor and the Associate Program Director. Students wishing to transfer from the program to another graduate degree program at UD should contact the graduate program advisor of the program they are wishing to transfer to. The Graduate Committee will consider and approve or deny the transfer request, which can be executed by a Change of Major form. Potential transfer students should understand that they will be expected to fulfill all degree requirements.

Students already enrolled in the M.S. program who wish to transfer into the Ph.D. program should meet with the Associate Program Director to discuss the possibility. In general, transfer into the Ph.D. program will be allowed only after the completion of the M.S. degree requirements, will be contingent on good performance in course work, and will be permitted only if the program is able to support an additional Ph.D. student. Students enrolled in the Ph.D. program who wish to transfer to the M.S. program should similarly meet with the Associate Program Director. The Graduate Committee will have decision authority over all transfer requests between the M.S. and Ph.D. programs.

III. Academic

A. M.S. Degree Requirements

The QSE M.S. degree requires a minimum of 32 credit hours. As shown in Table 1, students will follow one of three tracks: 1) Quantum Nanotechnology (required courses in black and green), 2)

Quantum Theory (required courses in black and red), or 3) Quantum Algorithms and Computation (required courses in blue and black). Students will indicate the track to which they are applying at the time of application and are welcome to consult with the graduate advisor when making this decision. In general, students planning to do experimental work will follow the Quantum Nanotechnology track. Students planning to do theoretical work that requires knowledge of physical systems (e.g. atoms or solid state materials) will follow the Quantum Theory track. Students planning to work on quantum algorithms, quantum computing applications, or classical computing that facilitates quantum computing will follow the Quantum Algorithms and Computation track.

All students will take three common required courses in their **first semester**:

1. Introduction to Quantum Computation and Quantum Information (3 credits),
2. Engineering the Quantum Revolution (3 credits), and
3. Professional Communication in Quantum Science and Engineering (1 credit).

Students in the Quantum Nanotechnology or Quantum Theory tracks will typically take Applied Quantum Mechanics (3 credits) in the fall semester. Students in either of these tracks who have already taken course work on Quantum Mechanics may take an elective in lieu of Applied Quantum Mechanics in the fall and take Quantum Mechanics 1 (PHYS811) in the spring instead. Students wishing to exercise this option should contact the graduate program director. Students following the Quantum Algorithms and Computation track will take, in the fall semester, one 3 credit course from the following options: Algorithm Design and Analysis (CISC621), Introduction to Machine Learning (CISC684), Elements of the Theory of Computation (CISC601), Advanced Topics in Algorithms and Complexity Theory (CISC830), Computational Methods for Equation Solving and Function Minimization (MATH612).

In the **second semester** of their first year, students following the Quantum Nanotechnology track will take:

1. Introduction to Quantum Hardware (3 credits),
2. Experimental Techniques for Quantum Systems (3 credits),
3. Semiconductor Device Design and Fabrication (3 credits) and
4. Professional Communication in Quantum Science and Engineering (1 credit).

In the **second semester** of their first year, students following the Quantum Theory track will take

1. Introduction to Quantum Hardware (3 credits),
2. Advanced Topics in Quantum Information (3 credits),
3. An elective of their choice (3 credits) and
4. Professional Communication in Quantum Science and Engineering (1 credit).

In the **second semester** of their first year, students following the Quantum Algorithms and Computation track will take

1. Advanced Topics in Quantum Information (3 credits),
2. Quantum Algorithms (3 credits),
3. An elective of their choice (3 credits) and
4. Professional Communication in Quantum Science and Engineering (1 credit).

In their **third semester**, all students will take two elective courses (3 credits each).

In summary, M.S. Quantum Nanotechnology track students will take 20 credits of core requirements, 6 credits of elective courses, and 6 thesis research credits. M.S. Quantum Theory track students will take 17 credits of core requirements, 9 credits of elective courses, and 6 thesis research credits. M.S. Quantum Algorithms and Computation track students will take 17 credits of core requirements, 9 credits of elective courses, and 6 thesis research credits. Students who wish to do a summer internship may opt for internship course credit (QSE864) and/or a non-thesis degree in lieu of thesis research credit. Students who wish to conduct thesis research as part of a summer internship may do so provided a) a QSE faculty member is involved in and approves the research project plan and b) the results can be freely published as part of the students' M.S. thesis and/or in academic journals.

Students must receive a B- or higher in all core courses for them to count toward their degree. The graduate committee will have sole discretion to determine the appropriate action for any student earning below a B- in any course. In most cases the student will be given an opportunity to repeat the course, but will not be allowed to take any additional courses for which the course in question is a prerequisite. In cases of extremely poor performance the graduate committee may recommend dismissal from the program. Students will not typically be permitted to repeat a course more than once. In addition, students must maintain a minimum 3.0 GPA in accordance with the University of Delaware policy.

Table 1: M.S Course credit requirements (32 credits required)

Semester 1 (Fall)	Semester 2 (Spring)	Summer	Semester 3 (Fall)
Intro. to Quantum Computation and Quantum Information (PHYS 650, 3 credits)	Intro. to Quantum Hardware (3 credits) OR Intro. to Quantum Hardware (3 credits) OR Quantum Algorithms (3 credits)	Thesis Research (QSEG869, 4 credits, potentially conducted at internship site)	Elective (3 credits)
Applied Quantum Mechanics (MSEG640, 3 credits) OR Applied Quantum Mechanics (MSEG640, 3 credits) OR Limited Elective 1 (3 credits, see below list)	Experimental Techniques for Quantum Systems (3 credits) OR Advanced Topics in Quantum Information (3 credits) OR Advanced Topics in Quantum Information (3 credits)	OR Internship (QSEG864, 4 credits)	Elective (3 credits)
Engineering the Quantum Revolution (3 credits)	Semiconductor Device Design and Fabrication (ELEG650, 3 credits) OR Elective (3 credits) OR Elective (3 credits)		Thesis Research (QSE869, 2 credits) OR Non-Thesis Research (QSE868, 2 credits)
Professional Communication in Quantum Sci / Eng (1 credit)	Professional Communication in Quantum Sci / Eng (1 credit)		

Courses shown in black are required for all M.S. students. Courses shown in green are required for the Quantum Nanotechnology track. Courses shown in red are required for the Quantum Theory track. Courses shown in blue are required for the Quantum Algorithms and Computation Track. Color text alternative: All information in this table is provided in raw text format in Section IIIA.

B. Ph.D. Degree Requirements

The QSE Ph.D. degree requires a minimum of 41 credits. As shown in Table 2, students will follow one of three tracks: 1) Quantum Nanotechnology (required courses in black and green), 2) Quantum Theory (required courses in black and red), or 3) Quantum Algorithms and Computation (required courses in blue and black). Students will indicate the track to which they are applying at the time of application and are welcome to consult with the graduate advisor when making this decision. In general, students planning to do experimental work will follow the Quantum Nanotechnology track. Students planning to do theoretical work that requires knowledge of physical systems (e.g. atoms or solid state materials) will follow the Quantum Theory track. Students planning to work on quantum algorithms, quantum computing applications, or classical computing that facilitates quantum computing will follow the Quantum Algorithms and Computation track.

All students will take three common required courses in their **first semester**:

1. Introduction to Quantum Computation and Quantum Information (3 credits),
2. Engineering the Quantum Revolution (3 credits), and
3. Professional Communication in Quantum Science and Engineering (1 credit).

Students in the Quantum Nanotechnology or Quantum Theory tracks will typically take Applied Quantum Mechanics (3 credits) in the fall semester. Students in either of these tracks who have already taken course work on Quantum Mechanics may take an elective in lieu of Applied Quantum Mechanics in the fall and take Quantum Mechanics 1 (PHYS811) in the spring instead. Students wishing to exercise this option should contact the graduate program director. Students following the Quantum Algorithms and Computation track will take, in the fall semester, one 3 credit course from the following options: Algorithm Design and Analysis (CISC621), Introduction to Machine Learning (CISC684), Elements of the Theory of Computation (CISC601), Advanced Topics in Algorithms and Complexity Theory (CISC830), Computational Methods for Equation Solving and Function Minimization (MATH612).

In the **second semester** of their first year, students following the Quantum Nanotechnology track will take:

1. Introduction to Quantum Hardware (3 credits),
2. Experimental Techniques for Quantum Systems (3 credits),
3. Semiconductor Device Design and Fabrication (3 credits) and
4. Professional Communication in Quantum Science and Engineering (1 credit).

In the **second semester** of their first year, students following the Quantum Theory track will take

1. Introduction to Quantum Hardware (3 credits),
2. Advanced Topics in Quantum Information (3 credits),
3. An elective of their choice (3 credits) and
4. Professional Communication in Quantum Science and Engineering (1 credit).

In the **second semester** of their first year, students following the Quantum Algorithms and Computation track will take

1. Advanced Topics in Quantum Information (3 credits),
2. Quantum Algorithms (3 credits),
3. An elective of their choice (3 credits) and
4. Professional Communication in Quantum Science and Engineering (1 credit).

In their **third semester**, all students will take two elective courses (3 credits each).

In summary, Ph.D. Quantum Nanotechnology track students will take 20 credits of core requirements, 6 credits of elective courses, 6 research credits, and 9 dissertation credits. Ph.D. Quantum Theory track students will take 17 credits of core requirements, 9 credits of elective courses, 6 research credits, and 9 dissertation credits. Ph.D. Quantum Algorithms and Computation track students will take 17 credits of core requirements, 9 credits of elective courses, 6 research credits, and 9 dissertation credits. Students are welcome and encouraged to do an internship during the summer after their first year. Students in their second year and beyond are welcome to do internships provided their faculty advisor approves and it does not detract from their progress toward graduation. Students participating in such internships typically receive a stipend directly from their sponsoring laboratory or company. Students participating in internships may register for and receive internship course credit (QSE864), but such credits do not count toward the total number of credits required for the degree. Work conducted as part of an internship or in collaboration with a company may be considered part of a students' required dissertation and/or research credits (QSEG868 or QSEG969) provided a) a QSE faculty member is involved in and approves the research project plan and b) the results can be freely published as part of the students' dissertation and/or in academic journals.

Students must receive a B- or higher in all core courses for them to count toward their degree. The graduate committee will have sole discretion to determine the appropriate action for any student earning below a B- in any course. In most cases the student will be given an opportunity to repeat the course, but will not be allowed to take any additional courses for which the course in question is a prerequisite. In cases of extremely poor performance the graduate committee may recommend dismissal from the program. Students will not typically be permitted to repeat a course more than once. In addition, students must maintain a minimum 3.0 GPA in accordance with the University of Delaware policy.

Table 2: Ph.D. Course credit requirements (41 credits required)

Semester 1 (Fall)	Semester 2 (Spring)	Summer	Semester 3 (Fall)
Intro. to Quantum Computation and Quantum Information (PHYS 650, 3 credits)	Intro. to Quantum Hardware (3 credits) OR Intro. to Quantum Hardware (3 credits) OR Quantum Algorithms (3 credits)	Internship (QSEG864, 1-6 credits)	Elective (3 credits)
Applied Quantum Mechanics (MSEG640, 3 credits) OR Applied Quantum Mechanics (MSEG640, 3 credits) OR Limited Elective 1 (3 credits, see below list)	Experimental Techniques for Quantum Systems (3 credits) OR Advanced Topics in Quantum Information (3 credits) OR Advanced Topics in Quantum Information (3 credits)	OR Begin research with faculty advisor	Elective (3 credits)
Engineering the Quantum Revolution (3 credits)	Semiconductor Device Design and Fabrication (ELEG650, 3 credits) OR Elective (3 credits) OR Elective (3 credits)		Research (QSEG868, 6 credits)
Professional Communication in Quantum Sci / Eng (1 credit)	Professional Communication in Quantum Sci / Eng (1 credit)		

Courses shown in black are required for all Ph.D. students. Courses shown in green are required for the Quantum Nanotechnology track. Courses shown in red are required for the Quantum Theory track. Courses shown in blue are required for the Quantum Algorithms and Computation Track. Color text alternative: All information in this table is provided in raw text format in Section IIIB.

C. Course descriptions

Required Courses

See Appendix B for complete descriptions of courses

Applied Quantum Mechanics (MSEG640) OR **Quantum Mechanics 1 (PHYS811)**
Introduction to Quantum Computation and Quantum Information (PHYS650)
Engineering the Quantum Revolution (new course)
Experimental Techniques for Quantum Systems (new course)
Introduction to Quantum Hardware (new course)
Advanced Topics in Quantum Information (new course)
Quantum Algorithms (new course)
Professional Communication in Quantum Science and Engineering (new course)
Semiconductor Device Design and Fabrication (ELEG650)

Elective Courses

Existing elective courses: Quantum Mechanics II (PHYS812), Advanced Quantum Mechanics (PHYS814), Probability Theory Applications (MATH630), Functional Analysis (MATH806), Quantum Statistical Mechanics (PHYS813); Materials for Optics, Nanophotonics, and Plasmonics (MSEG867); Algorithm Design and Analysis (CISC621); Solid State Materials (MSEG841); Condensed Matter Physics (PHYS624); Introduction to Atomic, Molecular, and Optical Physics (PHYS626), Introduction to Machine Learning (CISC684), Elements of the Theory of Computation (CISC601), Advanced Topics in Algorithms and Complexity Theory (CISC830), Computational Methods for Equation Solving and Function Minimization (MATH612).
Planned elective courses: Quantum Optics/Quantum Communication; Material Selection for Quantum Applications; Quantum Languages and Programming; Topological Methods in Quantum Science, Quantum Error Correction
Other courses not on these lists may be used to satisfy the elective requirement with the advance approval of the Graduate Committee.

D. Transfer of credits / Course Substitutions
Students who have already taken courses, in other departments or at other institutions, that they believe satisfy the requirements of a required course for this degree may request that a course requirement be waived. Such applications must be submitted to the graduate program advisor and Associate Program Director in writing. Applications must be accompanied by a) documentation of the content covered in the prior course (e.g. syllabus, copies of homework or exams) and b) evidence of satisfactory completion of the prior course. Applications will be evaluated and approved / denied by the graduate committee, typically in consultation with the UD instructor of the course for which a waiver has been requested. Students whose requests are approved will select, in consultation with the graduate program advisor, Associate Program Director, and their advisor, a different course to take to meet the total number of credits required for the degree. The graduate program advisor will complete a course substitution form to document the approved substitution.

E. Program Structure
The Quantum Science and Engineering (QSE) program is an interdisciplinary program that will be housed in the Graduate College. The leadership of the QSE program will comprise a Program Director (initially Prof. Matthew Doty from MSEG) and an Associate Program Directory (TBD).

The Program Director responsibilities include organizing teaching assignments, working with our corporate partners, coordinating our active recruiting, maintaining interactions with our Internal Advisory Board and Independent Advisory Committee, and chairing faculty meetings. To organize teaching assignments, the Program Director will work with the chairs of the relevant departments to ensure that all required QSE courses will be taught. Working with corporate partners includes coordinating summer internships, evaluating the success of the internship program, recruiting new corporate partners, and running the Fall semester symposium. As part of our active recruiting efforts, the Program Director will coordinate our visits to and collaborations with our partner institutions. The program director will be responsible for scheduling and leading meetings with our Internal Advisory Board and Independent Advisory Committee at least once per year. Finally, the Program Director will chair meetings of all the QSE faculty which will be held at least once per semester. The Program Director will be appointed to renewable 3 year terms by the Dean of the Graduate College, in consultation with the Deans of the Colleges of Engineering and Arts and Science. The Dean of the Graduate College will solicit both nominations for and approval of the Program Director from the QSE faculty.

The Associate Program Director will be responsible for all aspects of the graduate curriculum and all other graduate student concerns. This includes refining the curriculum to ensure appropriate content knowledge and that the program meets its educational goals, organizing course development workshops, and running the bi-weekly student seminar series. The Associate Program Director will also be responsible for recruiting students, overseeing admissions, and facilitating students' match with research advisors. To assist with these responsibilities, a Graduate Committee will be appointed that will comprise at least 3 additional QSE faculty. The Associate Program Director will chair this committee. The Associate Program Director will be appointed to renewable 3 year terms by the Dean of the Graduate College, in consultation with the Program Director, the Deans of the Colleges of Engineering and Arts and Science, and the QSE faculty. The Dean of the Graduate College will solicit both nominations for and approval of the Associate Program Director from the QSE faculty.

The Governance Committee will consist of the Program Director, Associate Program Director, and 3 voting members. The voting members will be nominated and elected by the QSE faculty and serve for a 3-year term. Any QSE faculty member other than the PD and APD are eligible to serve as voting members of the governance committee and there is no restriction on the distribution of these faculty among the participating departments. Terms will be staggered so that one member is re-elected each year. The governance committee will have decision authority for changes to the program policy and structure.

The initial membership of the “QSE faculty” is defined by the list of participating faculty in Appendix A. All members of the program faculty have both voting rights and permission to accept and supervise students, following the program procedures outlined here. UD faculty wishing to become program members will submit a request to the Program Director. Membership applications will be approved or declined by a majority vote of the Governance Committee. All faculty members at UD who self-identify as having research and educational interests aligned with quantum science and engineering are welcome and encouraged to become members.

The Graduate Committee will consist of 3 QSE faculty who work with the Associate Program Director to manage graduate student admissions, graduate student advisor matching, curriculum revisions, and all other graduate student concerns. The members of the graduate committee will be appointed by the Program Director in consultation with the relevant departmental chairs.

F. Internship Program

All Ph.D. trainees will be encouraged to participate in internships with our corporate and national lab partners. There are three goals for this internship program. First, we want trainees to understand the industry context in which the skills they are learning will be used. For this reason, trainees will typically participate in internships during the summer after their first year. Second, the internships will create a network of contacts upon which trainees can draw after graduation. Third, we want the needs of industry to be continuously brought back into our research programs. Microsoft Quantum West, IBM, Hewlett Packard, HRL, Northrop Grumman, Argonne, and Brookhaven have already committed to host interns and typically provide financial support.

In some disciplines the summer after the first year of a Ph.D. program has been considered relatively early to undertake an internship. Our first-year courses will equip trainees with basic knowledge such as quantum mechanics, quantum hardware, and experimental techniques for quantum systems (including nanofabrication). These knowledge areas have been identified by our corporate partners as key weaknesses in the present workforce pool. Moreover, our corporate partners have all expressed their eagerness to host interns at this stage in their training in order to develop stronger and longer-lasting relationships. The Program Director will manage the internship program and match trainees with hosts based on the trainees' interests and career aspirations. Each internship will last 8 to 10 weeks and will end with a trainee report to both the corporate partners and UD QSE trainees and faculty. These presentations, delivered at the start of the fall semester, will help new first year trainees identify the internship sites of interest to them. The internship program will be evaluated in terms of its impact on our goal to "Train students with the science, engineering, and communication skills required by the Quantum Workforce."

G. Committees for exams, thesis, or dissertations

1. Advisor choice

- M.S. students

The majority of Master's students will be self-funded. Students will have access to information on the differences between and requirements of all three tracks before they apply for admission and will indicate their preferred track in their application materials. During orientation, students will work with the graduate program director to register for the first semester courses appropriate to their track. Students will meet with the Associate Program Director in the spring of their first year to select a research project to begin in the summer of their first year or in the fall of their second year if they do an internship. Master's students may be supported by QSE faculty provided that the faculty member has outside funding for the student.

- Ph.D. students

Ph.D. students will be admitted as a cohort and supported by the QSE program for their first year as long as they are making satisfactory progress toward their degree (taking and passing all courses and meeting with faculty to find a research group). This support may be in the form of a fellowship, a research assistantship, and/or a teaching assistantship. During the spring semester of their first year, students are expected to meet with QSE faculty to discuss potential research opportunities. Students will decide which lab to join by the end of the spring semester in consultation with the Associate Program Director. Co-advising relationships are possible and require approval of both advisors as well as the Associate Program Director. Students interested in working with an advisor who is not a member of the QSE program faculty should contact the Associate Program Director to discuss this possibility.

- Changing advisors

It is anticipated that the vast majority of students will remain with their initial advisors for the entirety of their graduate career. Students who wish to change advisors should first have a conversation with the Associate Program Director about the circumstances that result in the desire to change groups. If the Associate Program Director is involved (either as the previous advisor or a potential new advisor), students should instead meet with the Program Director. The Associate Program Director or Director will typically keep these conversations confidential to the extent possible while complying with university and state regulations governing mandatory reporters. After that conversation, and with approval from the Associate Program Director or Program Director, a student can approach potential new research advisors. As long as students are being financially supported by their current advisor, they are expected to be making progress on the project through which they are funded. If a new research advisor is identified, the student and advisor should again talk to the Associate Program Director to ensure as smooth and positive a transition as possible.

- Changing Tracks

Transfer between tracks requires the approval of the Associate Program Director and approval is not guaranteed. Factors that will be considered include the variations in background knowledge required for each track and the distribution of available funding and advisers in the sub-disciplines of QSE associated with each track. Students who switch tracks will be required to complete all of the requirements of the track they switch into. Students who are interested in switching tracks should contact the Associate Program Director

2. Committee selection

The advisor and student should discuss potential committee members who would be willing and able to provide support and advice for the student's research. It is the responsibility of the graduate student to ask each committee member if they are willing to serve.

Responsibilities of the committee members include:

- Work with the student to develop a program of study and research
- Ensure acquisition of technical skills and professional development
- Serve as advisory body during period of candidacy
- Administer written and oral qualifying examinations to Ph.D. candidates and provide recommendations
- Establish the contribution of the thesis or dissertation to chosen area of expertise and determine the degree of scholarship attained by the student

For Ph.D. students the committee will comprise at least four members: the advisor, at least two other QSE faculty members, and one external member. The QSE faculty members should represent at least two traditional departments. The external member may be a UD faculty member or an outside Ph.D. scientist. The external faculty member may be a member of the QSE faculty, but may not be from the same academic home department as the student's primary advisor. Students are encouraged to choose an industrial or national lab partner as their outside committee member. For M.S. students, the committee must comprise at least two members of the QSE faculty and will typically also include the UD technical staff or industrial partner member working most closely with the student on their research activities (if any). For both M.S. and Ph.D. students the committee composition must be approved by the Associate Program Director. If it becomes necessary, committee members may be added or removed with the permission of the advisor and Associate Program Director, however the composition of the committee must always comply with the above.

3. Qualifying exams

Ph.D. students are required to pass qualifying exams to enter candidacy. Qualifying exams should generally be scheduled in Year 2 but must be completed by the end of Year 3. If a student does not pass the qualifying exam by the end of Year 3, they will be asked to leave the program. In the case of extenuating circumstances, the student may petition the Graduate Committee for an extension.

The qualifying exams comprise two parts: a written and an oral exam. The written paper, which serves as a dissertation proposal, is prepared by the student. The student's advisor should review the paper to ensure that it conforms with these requirements and may offer constructive feedback to the student. After this review, the paper should be sent to the student's committee at least two weeks before the date of the qualifying exam. The paper should be no longer than 12 pages in length (single space, 12 pt font, Times New Roman or equivalent) including figures. Substantial references, demonstrating that students are familiar with the background literature in the field, should be included in the paper and are not included in the 12 page maximum. References should be in a standard format that complies with NSF guidelines.

The paper must include the following sections:

- Introduction and Motivation explaining the importance of the research problem
- Background summarizing the scientific foundations and important prior work in the field.
- Statement of the Research Problem that will be the focus of the student's dissertation research, including a statement of hypotheses to be tested.
- Proposed Approach describing the methods to be employed in conducting the research. This section should include citations to references that established the techniques to be employed and a description of why these techniques are appropriate for the proposed research.
- Timeline of the proposed research
- Progress to Date describing the student's efforts on the project thus far. Demonstration of substantial progress and/or results is not required.

Additional sections as appropriate to the proposed topic and field are welcome.

When students preparing to take their qualifying exam are the lead author of a published or submitted journal or full-length conference paper, they may request that this paper be accepted in lieu of the written qualifying exam paper. The graduate committee will approve or deny this request. If the request is granted, the student will be expected to submit to her/his committee both the approved paper and a short (approximately 3 page) description of specific future research plans and timeline.

The student should prepare an oral presentation with slides. The slides should cover all of the required sections of the written paper and should include a final slide with a tentative project timeline. The presentation should be designed to be 30 minutes in length if delivered without interruption. Students should expect frequent interruptions to discuss the slide content and to probe the student's knowledge of the material presented and how it relates to underlying scientific principles. To ensure the examination adequately tests the student's ability to synthesize knowledge from courses and apply it to a research project, examiners are free to ask questions about any scientific topic related to the proposed project, including topics covered in either the written paper or oral presentation. All background knowledge probed should be germane to the proposed project. Exams typically take between 90 and 120 minutes. This should include a hard stop at least 10 minutes prior to the end of the examination to permit time for the faculty to deliberate without the student in the room.

Evaluation Criteria

Students will be evaluated according to the following criteria:

- Has the student demonstrated the ability to integrate foundational material and concepts in order to understand the scientific foundations of the research problem?
- Does the student understand the scientific underpinnings of the approaches to be employed?
- Has the student demonstrated knowledge of the important prior results in the field?
- Has a clear research problem or objective been identified and clearly explained?
- Does the proposed approach describe a feasible path to addressing this research problem?

Based on these evaluation criteria, the committee shall form a consensus on whether the student Passes, Passes Provisionally, or Fails the examination. Feedback should be provided to the student. A "Passes Provisionally" shall entail whatever provisions and timeline the committee deems necessary to address the shortcomings that resulted in that outcome. The advisor is responsible for ensuring these provisions are met and shall notify both the student's committee and the graduate program director in writing how the provisions were met. In the event a student fails the examination, the committee should explain the reasons for the failure. The student shall, at the discretion of the advisor, be permitted to retake the exam one additional time within six months.

H. Timetable and definition of satisfactory progress towards the degree

1. Thesis approval

For. M.S. students pursuing a degree with a thesis, the written thesis containing original results of the student's research effort must be presented and approved by the committee and the Program Chair. The written document should be given to the committee at least two weeks in advance of the oral examination and must comply with UD thesis formatting standards. The final oral examination comprises a presentation by the student on their research. This presentation will be open to all interested parties. After the presentation, the student will be examined on the thesis by the committee. The committee will approve the thesis. The student will be responsible for making all corrections to the thesis document and for meeting all Graduate College deadlines for submission. Acceptance of the thesis will be recommended if no more than a single dissenting vote is cast by the committee.

2. Dissertation approval

For Ph.D. students, a dissertation containing original results of the student's research effort must be presented and approved by the committee and the Program Chair. The written document should be given to the committee at least two weeks in advance of the oral examination and must comply with UD dissertation formatting standards. The final oral examination comprises a presentation by the student on their research. This presentation will be open to all interested parties. After the presentation, the student will be examined on the dissertation by the committee. In addition to examining the results of the original research contained in the dissertation, the committee will pay particular attention that suggestions for future work shall constitute a well-formulated and coherent plan to extend the research. The committee will approve the dissertation. The student and advisor will be responsible for making all corrections to the dissertation document and for meeting all Graduate College deadlines for submission. Acceptance of the dissertation will be recommended if no more than a single dissenting vote is cast by the committee. Ph.D. candidates must have at least one year between their qualifying exam and their dissertation defense. Exceptions to this one-year rule can be approved by the graduate program committee for unusual cases such as students transferring from another school.

3. Timeline

a. M.S. students

The M.S. program is designed to be completed in three semesters. Part-time students may take longer, but the maximum time for completion of an M.S. degree is five years from time of entry.

- Beginning of second semester: meet with Associate Program Director to choose a research project and advisor
- End of second semester: submit committee membership to Associate Program Director/Graduate Committee for approval
- End of third semester: defend thesis work at the annual QSE symposium. Thesis draft is due to the committee at least two weeks before the presentation.

b. Ph.D. students

The maximum time to completion for the Ph.D. program is seven years from the time of entry.

- Beginning of second semester: meet with prospective advisors to discuss research projects
- End of Year 1: find research advisor in consultation with the Associate Program Director
- Summer after Year 1: internship for most students; thesis research otherwise
- Year 2: establish dissertation committee and take qualifying exam
- Year 3-4: meet with committee to discuss progress as necessary
- Year 5: write and defend dissertation

4. Consequences of unsatisfactory academic progress

The QSE Graduate Committee will meet once each semester to evaluate each student's progress. Signs of satisfactory progress include: (a) taking and passing required courses on the expected timetable, (b) entering a relationship with a primary research advisor by the end of the first year, (c) taking and passing the qualifying exam before the end of the second year, and (d) making suitable research progress as defined by the primary advisor and the thesis/dissertation committee. If a student is failing to make satisfactory progress towards a degree, the committee will recommend suitable action to the QSE Program Director. Possible actions include (but are not limited to): (i) requirement for additional courses, (ii) suspension of financial support, and (iii) recommendation for dismissal.

5. Standards of student conduct

All graduate students are subject to University of Delaware regulations regarding academic honesty. Violations of the UD regulations regarding academic honesty or other forms of gross misconduct may result in immediate dismissal from the Program.

6. Dismissal

The procedures for dismissal as detailed in the University Catalog will be followed. Briefly, the Graduate Committee will report its recommendation and reason for dismissal to the QSE Program Director. The Director will make a recommendation to the Dean of the Graduate College, who will decide whether to dismiss the student. The student may appeal this decision to the Graduate College, following the procedure given in the University Catalog.

7. Graduate student grievance procedures

Students who feel that they have been graded inappropriately or receive what they perceive as an unfair evaluation by a faculty member may file grievances in accordance with University of Delaware policies. Students are encouraged to contact the QSE Graduate Program Director prior to filing a formal grievance in an effort to resolve the situation informally.

IV. Program Educational Goals

Students who successfully complete this program will be able to:

- Demonstrate a mastery of the foundational knowledge and skills of core aspects of research and development for quantum technologies.
- Utilize foundational knowledge to develop deeper expertise within a specialized area of quantum technologies.
- Employ a shared vocabulary that enables collaboration between specialists working on different aspects of quantum technologies.
- Act professionally and ethically.
- Employ methods of effective communication within the discipline.
- Demonstrate the depth of knowledge and skills required for professional employment in at least one aspect of quantum technology.
- Explore the intersection of different aspects of quantum technologies in order to identify and pursue opportunities that cross the boundaries of traditional disciplines.

V. Financial aid

A. Financial Awards

1. Teaching assistantship (TA) awards

TA awards are offered for graduate students to perform teaching and other instructional activities by individual departments. For QSE students, TA appointments may be in the QSE program or in traditional departments. The amount of service may vary from week to week but the average is usually expected to be 20 hours per week. A teaching assistantship provides full tuition and a stipend. Award of TA will be decided by the primary advisor, Program Director and the needs of the QSE program and traditional departments.

2. Research assistantship (RA) awards

RA awards are generally funded by research grants and contracts provided by external funding agencies. Students may be supported as an RA through their faculty advisor's research funds. A research assistantship provides appropriate amount of tuition per College guidelines, and a stipend. The RA's advisor is responsible for defining the student's responsibilities and for evaluating the student's performance. The amount of service or research may vary from week to week but the average is usually expected to be 20 hours per week.

Admission to the QSE Graduate Program does not automatically entitle an applicant to financial aid. Students may seek financial aid opportunities, such as fellowships or scholarships from sources within the University and from private and federal agencies. Interested students should check the Graduate College website for the most current opportunities (https://grad.udel.edu/).

Financial aid is awarded on a competitive basis from the pool of admitted applicants. The University of Delaware's policies apply to all forms of financial aid. Please refer to the University Policies for Graduate Student Assistantships and Fellowships.

VI. Departmental Operations

A. General student responsibilities

1. Up-to-date addresses, etc.

Graduate students are required to provide the QSE program with an up-to-date address and other contact information and to update this address whenever it changes.

2. Laboratories and research equipment

Graduate students must comply with all UD safety regulations when working in any UD laboratory. Individual labs may have additional rules and regulations; students are expected to comply with these as well. All members of QSE are responsible for creating a safe working environment for each other. If anyone notices unsafe working conditions, they should bring it to the attention of the lab manager. If students have serious and/or ongoing safety concerns, these should be brought to the attention of the QSE Program Director and/or the Associate Program Director or to the UD Environmental Health and Safety group (http://www1.udel.edu/ehs/).

3. Hazardous Chemical Information Act

All students, staff, and faculty are expected to comply with the Delaware Hazardous Chemical Information Act (delcode.delaware.gov/title16/c024/index.shtml). Any questions regarding compliance should be directed to the lab manager and/or to the UD Environmental Health and Safety group (http://www1.udel.edu/ehs/).

4. Vehicles

UD vehicles can be rented by students if needed to perform duties associated with the QSE program (https://sites.udel.edu/transportation/motor-pool/). Students should consult with their advisor or the QSE Program Director before renting a vehicle.

5. Keys, offices, mail, telephone, copy machine, computer terminals, etc.

Students are responsible for laboratory keys. If a key is lost, a replacement fee may be charged. Upon graduation, all keys must be returned to the QSE program. Offices will be provided to students by the QSE program or by individual departments. Every effort will be made to provide students with offices in locations proximate to their research, but location cannot be guaranteed. Students can receive mail at the QSE program office. This address should only be used for professional communications; no personal mail or deliveries can be accepted by the QSE staff. Telephones are available for professional use only in laboratories and in the QSE program office. A copy machine/printer is available in the QSE office for professional use only. Computer terminal(s) are available in the QSE office for professional use only. If other common office supplies or resources are needed, students should contact their advisors for assistance.

B. Student government and organizations

Students are encouraged to participate in the UD Graduate Student Government (https://sites.udel.edu/gsg/) and in any other on-campus organizations that they are interested in. QSE students will be encouraged to form a graduate student group to plan professional development and other activities. Finally, students are encouraged to join professional organizations related to QSE like the American Physical Society, the Optical Society of America, IEEE, the Materials Research Society, etc. Most professional organizations have discounted student membership fees.

C. Travel for professional meetings or presentations

Students are generally expected to travel for professional meetings and to present results at conferences. Funding for student travel can come from a variety of sources: advisor research grants, UD Graduate College Travel Awards (grad.udel.edu\travel-award-application), professional society grants, conference travel grants, etc. Students should consult with their advisors on appropriate conferences to attend and how to fund their travel. While at conferences, students are representing UD and are expected to abide by the UD Student Code of Conduct and any professional codes of conduct implemented by the conference.

Appendix A: Initial Membership of the QSE faculty

Name	Department	College
Nii Attoh-Okine	CIEG	COE
Rahmat Beheshti	CIS	COE
Chitraleema Chakraborty	MSEG	COE
Siu-Tat Chui	DPA	CAS
James Clause	CIS	COE
Matthew Doty	MSEG	COE
Rudi Eigenmann	ELEG	COE
Xing Gao	CIS	COE
Javier Garcia-Frias	ELEG	COE
Mahya Ghandehari	MATH	CAS
Tingyi Gu	ELEG	COE
Lars Gundlach	DPA	CAS
Zubaer Hossain	MEEG	COE
Anderson Janotti	MSEG	COE
Yi Ji	DPA	CAS
Benjamin Jungfleisch	DPA	CAS
Alexei Kananenka	DPA	CAS
Mark Ku	DPA	CAS
Stephanie Law	MSEG	COE
Li Liao	CIS	COE
Mokshay Madiman	MATH	CAS
Chaoying Ni	MSEG	COE
Branislav Nikolic	DPA	CAS
Edmund Nowak	DPA	CAS
Bob Opila	MSEG	COE
Xi Peng	CIS	COE
Jamie Phillips	ELEG	COE
Petr Plechac	MATH	CAS
Ilya Safro	CIS	COE
Marianna Safronova	DPA	CAS
Vishal Saxena	ELEG	COE

Swati Singh	ELEG	COE
Ivan Todorov	MATH	CAS
Amo Tong	CIS	COE
Nektarios Tsoutsos	ELEG	COE
Xi Wang	MSEG	COE
Xiugang Wu	ELEG	COE
John Xiao	DPA	CAS
Yuping Zeng	ELEG	COE
Joshua Zide	MSEG	COE

MSEG640 Applied Quantum Mechanics (*Existing Course*)
and
PHYS811 Quantum Mechanics 1 (*Existing Course*)

<u>Essential Concepts</u>
fundamentals and mathematical formalism (Schrodinger's equation, eigenfunctions, Dirac notation), realistic examples (quantum wells, atoms), perturbation theory, approximation methods

<u>Course Description</u>
MSEG640 Applied Quantum Mechanics: This course will teach students the basics of quantum mechanics with a focus on skills needed by scientists and engineers working with electronic materials. Students are not required to have any knowledge of quantum mechanics before taking this course. This course will cover Schrodinger's equation, 1D analytically-solvable problems (infinite well, finite well, harmonic oscillator, triangular well), operators, approximation methods (T-matrices, perturbation theory, finite matrices), quantum mechanics of crystalline materials, hydrogen atom, spin, and particle statistics. This class will have a strong emphasis on practical problems that use real material and device parameters. By the end of this course, students will be able to use quantum mechanics to understand the materials and devices they encounter in their research.

PHYS811 Quantum Mechanics 1: Develops formal description of quantum systems as states in a complex vector space. Topics include time evolution, path integrals, symmetry groups and conservation laws, parity, angular momentum and tensor operators, operator treatment of the harmonic oscillator, identical particles, time independent and time dependent perturbation theory, and radiative transitions. Includes a summary of special functions and boundary problems appropriate to simple quantum systems.

QSEG650/PHYS650 Introduction to Quantum Computation and Quantum Information
<u>Essential Concepts</u>
Two-level systems (qubits, Bloch sphere, Rabi oscillations, pi pulses), difference between quantum and classical computation, quantum measurement, entanglement, decoherence, quantum gates and circuits, quantum algorithms, quantum communication, applications of quantum computing, quantum simulations, quantum key distribution, quantum error correction.

<u>Course Description</u>
This course will introduce quantum computation and quantum information. Essential concepts will be discussed: two-level quantum systems, quantum measurements, entanglement, decoherence, difference between quantum and classical computation, and quantum logic gates. Students will learn to understand the operation of quantum circuits on several examples, including quantum teleportation. Applications of quantum computing will be discussed which will include efficient quantum algorithms (quantum Fourier transform and its applications and quantum search algorithms) and quantum simulations. Quantum cryptography and quantum key distribution will be introduced with their applications. The quantum error-correction codes will be discussed, with the example of an error-correction circuit considered in detail. Examples of physical implementations of some concepts will be given throughout the course for illustration and preparation for the quantum hardware course. This course will present students with a broad overview of the quantum information field, its rapid progress, and relevant scientific literature.

To further this goal, the students will carry out literature research on a quantum computing topic of their choice (approved by the course instructor), write a paper and present their topic in class.

QSEG610 Engineering the Quantum Revolution

Essential Concepts

Engineering and design concepts. Scalability and reliability in classical integrated electronic and photonic circuits, scaling challenges for quantum systems including no cloning theorem, decoherence, and gate times. Gate-level machine language and error correction in the classical and quantum regimes. Development of programming languages from gate-level primitives. Essential elements of efficient programming. Fault-tolerant quantum computation. Architecture of quantum integrated circuits. Engineering Quantum interconnects/challenges.

Course Description

This course will introduce students to the concepts that underlie the engineering and production of scalable, robust, and reliable devices. The course will cover hardware, software (i.e. gate-level machine language), and programming (i.e. languages). The hardware portion of the course will introduce the engineering tools used to achieve scalability and reliability in classical integrated electronic and photonic circuits, including limiters, thresholds, and process design kits. The course will then explore the challenges and limits to developing similar methods for quantum systems. Examples include the limits imposed by inhomogeneity, the no cloning theorem, and decoherence. The gate-level software portion of the course will introduce and compare classical and quantum gates and error correction algorithms and explore how quantum systems must be designed to prevent or accommodate errors arising from decoherence. The language portion of the course will explore how programming languages are built up from gate-level primitives and introduce best practices for efficient programming in a multi-user environment.

QSEG620 Professional Skills in Quantum Science and Engineering 1
QSEG621 Professional Skills in Quantum Science and Engineering 2
(taught as a 2 semester sequence @ 1 credit/semester)

Essential Concepts

research ethics and social/environmental implications of quantum technologies, best practices in research, reasons and techniques for minimizing bias, effective verbal and written communication within the discipline and to broader communities (including via social media), Networking and professional conduct.

Course Description

This two-semester sequence of courses focuses on the durable skills required for success in quantum careers. A significant portion of the course will be devoted to developing skills for clear written and verbal communication both within the discipline and to broader communities. Other skills to be covered include best practices in research, ethics, and rationale/techniques for minimizing bias.

QSEG810 Introduction to Quantum Hardware

Essential Concepts

advantages, disadvantages, and applications of the most common quantum hardware and material platforms, including superconducting qubits, defect centers, quantum dots, trapped ions, neutral atoms, photonic qubits, and hybrid qubits

Course Description
This course will introduce students to the range of hardware and material platforms under consideration as elements of quantum devices. Platforms to be covered include: photonic qubits (for both QKD and linear optics quantum computing), superconducting qubits, atomic and ionic qubits, and spin orientations localized to point defects, quantum dots, or other localized potentials. Fundamental concepts in two-level system will be introduced and applied to each qubit system. In all cases the course will discuss the building materials, operating regimes required (i.e. temperature, vacuum, etc), the methods for controlling qubits, the means for mediating qubit interactions, and the hardware necessary to implement all required control. The currently achievable T_1, T_2, and T_2^* times will be discussed and compared to the current speeds at which quantum control can be performed. The dominant mechanisms for decoherence in each material platform will be discussed in order to explore both the likely fundamental limits on lifetimes and the research required to reach those limits. Current applications of quantum technologies and which qubit system is appropriate for each will be discussed. The course will involve a project in which the student can gain a deeper understanding of a particular qubit system of choice.
Pre-reqs: MSEG640 or PHYS811

QSEG830 Experimental Techniques for Quantum Systems
Essential Concepts
safe use of the experimental tools of QSE, including vacuum (pumping, minimizing contamination), cryogenics, optics (lasers, bandwidth, jitter, detectors), and electronics

Course Description
This course will introduce students to the safe and effective use of the most common tools of experimental quantum science and quantum engineering. Students are not required to have prior knowledge of any of these skills before taking this course. This course will cover vacuum systems (including measuring pressure, the various methods of pumping required to achieve different low-pressure regimes, standard strategies for working with vacuum equipment, and types of contaminants), cryogenics (including insulation, expansion, closed-cycle hardware, and thermal load management to reach different temperature regimes), optics (including simple optical instrument design, principles for aligning optics, principles for aligning and using lasers, electronics (including sourcemeter, function generators, oscilloscopes, pulse generators, lock-in amplifiers), working principle of superconducting DC magnet, vector magnet, magnet quenching, and microwave electronics including waveguide and cavity designs and transmission/reflection measurement. This is a laboratory course in which students will receive a practical hands-on introduction to the experimental methods, safe handling of equipment, and debugging methods. Students will conduct exercises that reinforce and practice these skills.

QSEG851 Advanced Topics in Quantum Information
Essential Concepts
Probability, Information, Entropy, Density Operator formalism, Generalized measurement (projective and POVM), Entanglement and tensor products, Open Quantum systems, Classical and quantum entropy (from Shannon to von Neumann)

Course Description
This course will introduce the essential concepts and tools of theoretical quantum information

science research. The course begins with discussing foundational concepts in classical information theory, such as the connection between probability, information, and entropy. Quantum concepts will be introduced starting with the density operator formalism and measurement operators outlining the backaction of the measurement process. The mathematical formalism for entanglement using tensor products will be introduced with emphasis on bipartite systems. After introducing these pure states, the Master equation formalism for treating open quantum systems will be discussed. Finally, the connection between classical and quantum information theory will be established by introducing von Neumann entropy and related concepts.

QSEG820 Quantum Algorithms

Essential Concepts

Quantum algorithms, Quantum optimization, Quantum machine learning, Algorithm complexity

Course Description

This course will introduce most important quantum and hybrid quantum-classical algorithms such as various versions of Quantum Approximate Optimization, Variational Quantum Eigensolver, Harrow-Hassidim-Lloyd, Quantum Fourier Transform, elements of Quantum Machine Learning, error correction and elements of mathematical optimization for both problems being solved on quantum devices and accelerating quantum computation. Students will implement algorithms and run them on quantum simulators and real quantum machines.

QSEG864 Internships in Quantum Science and Engineering (variable 1-6 credits, Pass / Fail)

Essential Concepts

Experience working in national lab or industrial environments

Course Description

Students will conduct internships working with or at national lab or corporate partners. The course will provide students with real-world experience in conducting quantum science and engineering research, development, or production activities.