Quantum Engineering

Degrees Offered

• Graduate certificate in Quantum Engineering
• Master of Science (non-thesis)
• Master of Science (thesis)

Program Requirements

Quantum Engineering is an interdisciplinary program that seeks to equip students for careers in emerging technologies based on quantum entanglement. It encompasses a wide range of disciplines that include physics, materials science, computer science, and mathematics, and is necessarily a collaborative effort among many Mines departments. Two master’s degrees and one graduate certificate are offered.

For both degrees and the graduate certificate, Quantum Engineering has two "tracks" as summarized below. The Quantum Engineering Hardware (QEH) track will focus on experimental techniques relevant to quantum technology, while the Quantum Engineering Software (QES) track will focus on theory, algorithms and simulation. Students must choose a track to complete the program, but they may take courses from both tracks provided they meet the prerequisite requirements.

MS Degree Curriculum Requirements:

A Master of Science in Quantum Engineering will consist of 30 total credits. Students may choose a thesis or non-thesis option for this degree. For the thesis option, 9 credits out of the 30 are devoted to thesis research leading to an acceptable Master’s thesis. Students choosing the non-thesis option will devote all 30 credits to coursework. Regardless of the option chosen, 9 of the coursework credits will be devoted to the required core classes for the chosen track.

Reflecting the interdisciplinary nature of the program, we strongly recommend to our students that at least 9 total credits of the MS degree coursework should come from courses in a department outside of the student's undergraduate major. The required core courses, if outside of the student's major, would count toward this recommendation. Our guiding philosophy is that the problem of building a quantum computer is a complex, interdisciplinary one which requires contributions from a vast array of subfields, and young scientists who appreciate this will likely have a far better perspective on the field than those who do not.

MS Non-Thesis Software Track

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHGN519</td>
<td>FUNDAMENTALS OF QUANTUM INFORMATION</td>
<td>3.0</td>
</tr>
<tr>
<td>CSCI581</td>
<td>QUANTUM PROGRAMMING</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN545</td>
<td>QUANTUM MANY-BODY PHYSICS</td>
<td>3.0</td>
</tr>
<tr>
<td>Electives</td>
<td></td>
<td>21.0</td>
</tr>
<tr>
<td>Total Semester Hrs</td>
<td></td>
<td>30.0</td>
</tr>
</tbody>
</table>

MS Non-Thesis Hardware Track

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHGN519</td>
<td>FUNDAMENTALS OF QUANTUM INFORMATION</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG532</td>
<td>LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN535</td>
<td>INTERDISCIPLINARY SILICON PROCESSING LABORATORY</td>
<td>3.0</td>
</tr>
<tr>
<td>Electives</td>
<td></td>
<td>12.0</td>
</tr>
<tr>
<td>PHGN707</td>
<td>GRADUATE THESIS / DISSERTATION RESEARCH CREDIT</td>
<td>9.0</td>
</tr>
<tr>
<td>Total Semester Hrs</td>
<td></td>
<td>30.0</td>
</tr>
</tbody>
</table>

MS Thesis Software Track

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHGN519</td>
<td>FUNDAMENTALS OF QUANTUM INFORMATION</td>
<td>3.0</td>
</tr>
<tr>
<td>CSCI581</td>
<td>QUANTUM PROGRAMMING</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN545</td>
<td>QUANTUM MANY-BODY PHYSICS</td>
<td>3.0</td>
</tr>
<tr>
<td>Electives</td>
<td></td>
<td>12.0</td>
</tr>
<tr>
<td>PHGN707</td>
<td>GRADUATE THESIS / DISSERTATION RESEARCH CREDIT</td>
<td>9.0</td>
</tr>
<tr>
<td>Total Semester Hrs</td>
<td></td>
<td>30.0</td>
</tr>
</tbody>
</table>

MS Thesis Hardware Track

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHGN519</td>
<td>FUNDAMENTALS OF QUANTUM INFORMATION</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG/PHGN532</td>
<td>LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN535</td>
<td>INTERDISCIPLINARY SILICON PROCESSING LABORATORY</td>
<td>3.0</td>
</tr>
<tr>
<td>Electives</td>
<td></td>
<td>12.0</td>
</tr>
<tr>
<td>PHGN707</td>
<td>GRADUATE THESIS / DISSERTATION RESEARCH CREDIT</td>
<td>9.0</td>
</tr>
<tr>
<td>Total Semester Hrs</td>
<td></td>
<td>30.0</td>
</tr>
</tbody>
</table>

Coursework Details:

QES students will be required to take these courses in the following sequence:

In the fall:
• PHGN519, Fundamentals of Quantum Information

In the spring:
• CSCI581, Quantum Programming
• PHGN545, Quantum Many-Body Physics

QEH students will be required to take these courses in the following sequence:

In the fall:
• PHGN519, Fundamentals of Quantum Information

In the spring:
• PHGN535, Interdisciplinary Silicon Processing Laboratory
• PHGN532, Low Temperature Microwave Measurements for Quantum Applications

Approved Electives:

Physics Electives

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHGN520</td>
<td>QUANTUM MECHANICS I</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN521</td>
<td>QUANTUM MECHANICS II</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN530</td>
<td>STATISTICAL MECHANICS</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN550</td>
<td>NANO SCALE PHYSICS AND TECHNOLOGY</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN566</td>
<td>MODERN OPTICAL ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>PHGN581</td>
<td>LASER PHYSICS</td>
<td>3.0</td>
</tr>
</tbody>
</table>
PHGN585  NONLINEAR OPTICS  3.0

**Computer Science Electives**

CSCI542  SIMULATION  3.0  
CSCI561  THEORY OF COMPUTATION  3.0  
CSCI563  PARALLEL COMPUTING FOR SCIENTISTS AND ENGINEERS  3.0  
CSCI564  ADVANCED COMPUTER ARCHITECTURE  3.0  
CSCI571  ARTIFICIAL INTELLIGENCE  3.0  
CSCI575  ADVANCED MACHINE LEARNING  3.0  
CSCI574  THEORY OF CRYPTOGRAPHY  3.0  
CSCI580  ADVANCED HIGH PERFORMANCE COMPUTING  3.0  

**Electrical Engineering Electives**

EENG509  SPARSE SIGNAL PROCESSING  3.0  
EENG517  THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS  3.0  
EENG526  ADVANCED ELECTROMAGNETICS  3.0  
EENG528  COMPUTATIONAL ELECTROMAGNETICS  3.0  
EENG529  ACTIVE RF & MICROWAVE DEVICES  3.0  
EENG530  PASSIVE RF & MICROWAVE DEVICES  3.0  
EENG617  INTELLIGENT CONTROL SYSTEMS  3.0  
EENG618  NONLINEAR AND ADAPTIVE CONTROL  3.0  

**Metallurgy and Material Engineering Electives**

MTGN605  ADVANCED TRANSMISSION ELECTRON MICROSCOPY  2.0  
MTGN605L  ADVANCED TRANSMISSION ELECTRON MICROSCOPY LABORATORY  1.0  
MTGN656  ADVANCED ELECTRON MICROSCOPY  2.0  
MTGN656L  ADVANCED ELECTRON MICROSCOPY LABORATORY  1.0  
MLGN502  SOLID STATE PHYSICS  3.0  
MTGN573  COMPUTATIONAL MATERIALS  3.0  
MLGN515  ELECTRICAL PROPERTIES AND APPLICATIONS OF MATERIALS  3.0  
MLGN583  PRINCIPLES AND APPLICATIONS OF SURFACE ANALYSIS TECHNIQUES  3.0  
MLGN593  BONDING, STRUCTURE, AND CRYSTALLOGRAPHY  3.0  

**Applied Mathematics and Statistics Electives**

MATH506  COMPLEX ANALYSIS II  3.0  
MATH510  ORDINARY DIFFERENTIAL EQUATIONS AND DYNAMICAL SYSTEMS  3.0  
MATH536  ADVANCED STATISTICAL MODELING  3.0  
MATH538  STOCHASTIC MODELS  3.0  
MATH550  NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS  3.0  
MATH551  COMPUTATIONAL LINEAR ALGEBRA  3.0  

**Humanities, Arts, and Social Sciences Electives**

HASS523  ADVANCED SCIENCE COMMUNICATION  3.0  

---

### Mines' Combined Undergraduate/Graduate Degree Program:

Students enrolled in Mines’ combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

### Graduate Certificate Curriculum Requirements:

The certificate option consists of three of the four new courses, plus one additional elective chosen from the above list, for a total of 12 credits.

#### Graduate Certificate, Software Track

- PHGN519  FUNDAMENTALS OF QUANTUM INFORMATION  3.0  
- CSCI581  QUANTUM PROGRAMMING  3.0  
- PHGN545  QUANTUM MANY-BODY PHYSICS  3.0  
- Elective  3.0  

**Total Semester Hrs  12.0**

#### Graduate Certificate, Hardware Track

- PHGN519  FUNDAMENTALS OF QUANTUM INFORMATION  3.0  
- PHGN535  INTERDISCIPLINARY SILICON PROCESSING LABORATORY  3.0  
- EENG/PHGN532  LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING  3.0  
- Elective  3.0  

**Total Semester Hrs  12.0**

### Program Director

Eliot Kapit, Associate Professor, Physics

### Department of Applied Mathematics and Statistics

Cecilia Diniz Behn, Associate Professor

### Department of Computer Science

Neil Dantam, Assistant Professor  
Dinesh Mehta, Professor  
Hua Wang, Associate Professor  
Bo Wu, Associate Professor  
Dejun Yang, Associate Professor  
Hao Zhang, Associate Professor

### Department of Electrical Engineering

Peter Aaen, Professor
Payam Nayeri, Assistant Professor

Department of Metallurgical and Materials Engineering
Geoff Brennecka, Associate Professor
Brian Gorman, Associate Professor
Andriy Zakutayev, Research Assistant Professor

Department of Physics
Lincoln Carr, Professor
Serena Eley, Assistant Professor
Zhexuan Gong, Assistant Professor
Eliot Kapit, Associate Professor
Kyle Leach, Associate Professor
Meenakshi Singh, Assistant Professor

Affiliated Faculty
Matt Beard, Joint Appointment, NREL and Chemistry
Justin Johnson, Joint Appointment, NREL and Physics
Adele Tamboli, Joint Appointment, NREL and Physics