Establish a Master of Science in Quantum Computing (PCC 23048)

PRESENTED BY	**Wendy Stickle, Chair, Senate Programs, Curricula, and Courses Committee**
REVIEW DATES	**SEC – January 23, 2024 | SENATE – February 6, 2024**
VOTING METHOD	**In a single vote**
RELEVANT POLICY/DOCUMENT	
NECESSARY APPROVALS	**Senate, President, USM Board of Regents, and the Maryland Higher Education Commission**

ISSUE

The College of Computer, Mathematical, and Natural Sciences proposes to establish a Master of Science in Quantum Computing. This program exists currently as an iteration of the Master of Professional Studies (MPS) program. The 30-credit MPS program was established during the 2022-2023 academic year. Master of Professional Studies programs were first approved in 2005, when the University System of Maryland Board of Regents and Maryland Higher Education Commission approved an expedited review process for master's and graduate certificate programs that respond quickly to the changing market needs for working professionals. Once a new iteration of the MPS is approved through campus PCC review, it only needs approval by the USM Chancellor to become official.

A limitation of offering this program as an MPS iteration is that all Professional Studies programs must use the same generic Federal Classification of Instructional Programs (CIP) code, rather than a CIP code that accurately describes the program content. Those who search for academic programs by using the CIP codes related to Quantum Computing will not find this program. Moreover, some CIP codes are designated as "STEM" eligible by the US Department of Homeland Security, and international students with F1 visas who graduate from STEM designated programs may continue to work in the United States for two years longer than students in non-STEM designated programs. The generic CIP code for Professional Studies programs does not qualify as STEM-designated, even if the academic content of the Professional Studies program is STEM-related, as is the case with this program.

Consequently, the college proposes to transition the current program from a Master of Professional Studies program to a stand-alone Master of Science program in order for the program to be classified more accurately. The 30-credit curriculum will remain the same.

The Master of Science in Quantum Computing will provide students with the foundational, practical, and theoretical topics of quantum computing. Participants will discover current state-of-the-art quantum computing technology and areas of application, while also exploring its origins, evolution, and possible future states of this technology. The program consists of seven required 3-credit courses, and nine credits of electives. The program is a non-thesis program and will have both an in-person and distance education version. Course topics include quantum networks, quantum thermodynamics, quantum machine learning, quantum information theory, quantum Monte Carlo and simulations, and quantum computing hardware.

The proposal was approved by the Graduate School PCC committee on October 27, 2023, and the Senate Programs, Curricula, and Courses committee on December 1, 2023.

RECOMMENDATION(S)

The Senate Committee on Programs, Curricula, and Courses recommends that the Senate approve this new academic program.

COMMITTEE WORK

The committee considered this proposal at its meeting on December 1, 2023. Konstantina Trivisa, from the College of Computer, Mathematical, and Natural Sciences, presented the proposal and answered questions from the committee. The committee approved the proposal.

ALTERNATIVES

The Senate could decline to approve this new academic program.

RISKS

If the Senate declines to approve this new degree program, the university will lose an opportunity to apply a more accurate Federal CIP code to an existing program thereby making the program more marketable.

FINANCIAL IMPLICATIONS

There are no significant financial implications with this proposal as the program already exists as a self-supported Master of Professional Studies program.

913: QUANTUM COMPUTING

In Workflow

1. D-CHPH PCC Chair (jcrosby@umd.edu)
2. D-CHPH Chair (wth@umd.edu)
3. CMNS PCC Chair (jpresson@umd.edu; fourkas@umd.edu)
4. CMNS Dean (rinfanti@umd.edu)
5. Academic Affairs Curriculum Manager (mcolson@umd.edu)
6. Graduate School Curriculum Manager (jfarman@umd.edu)
7. Graduate PCC Chair (jfarman@umd.edu)
8. Dean of the Graduate School (jfarman@umd.edu; sroth1@umd.edu)
9. Senate PCC Chair (mcolson@umd.edu; wstickle@umd.edu)
10. University Senate Chair (mcolson@umd.edu)
11. President (mcolson@umd.edu)
12. Board of Regents (mcolson@umd.edu)
13. MHEC (mcolson@umd.edu)
14. Provost Office (mcolson@umd.edu)
15. Graduate Catalog Manager (bhernand@umd.edu; fantsao@umd.edu)

Approval Path

1. Mon, 15 May 2023 13:16:19 GMT
   Jessica Crosby (jcrosby): Approved for D-CHPH PCC Chair
2. Wed, 13 Sep 2023 21:26:12 GMT
   Wendell Hill (wth): Approved for D-CHPH Chair
3. Thu, 14 Sep 2023 22:29:31 GMT
   John Fourkas (fourkas): Approved for CMNS PCC Chair
4. Wed, 20 Sep 2023 13:18:10 GMT
   Robert Infantino (rinfanti): Approved for CMNS Dean
5. Mon, 16 Oct 2023 21:06:33 GMT
   Michael Colson (mcolson): Approved for Academic Affairs Curriculum Manager
6. Tue, 05 Dec 2023 18:12:59 GMT
   Jason Farman (jfarman): Approved for Graduate School Curriculum Manager
7. Tue, 05 Dec 2023 18:21:48 GMT
   Jason Farman (jfarman): Approved for Graduate PCC Chair
8. Tue, 05 Dec 2023 20:37:04 GMT
   Stephen Roth (sroth1): Approved for Dean of the Graduate School
9. Thu, 07 Dec 2023 18:17:02 GMT
   Wendy Stickle (wstickle): Approved for Senate PCC Chair

New Program Proposal

Date Submitted: Thu, 27 Apr 2023 14:24:06 GMT

Viewing: 913 : Quantum Computing
Last edit: Mon, 16 Oct 2023 20:24:27 GMT

Changes proposed by: Konstantina Trivisa (trivisa)

Program Name

Quantum Computing

Program Status

Proposed

Effective Term

Spring 2024

Catalog Year

2023-2024

Program Level

Graduate Program

Program Type

Master's

Delivery Method

On Campus

Departments

Department
Institute for Physical Sciences & Technology

Colleges

College
Computer, Mathematical, and Natural Sciences

Degree(s) Awarded

Degree Awarded
Master of Science

Proposal Contact

Konstantina Trivisa, Amy Chester

Proposal Summary

This proposal is to convert the approved MPS in Quantum Computing to an MS in Quantum Computing. No curriculum changes proposed to the approved program.
CIP Code: 27.0304 Computational and Applied Mathematics

(PCC Log Number 23048)

Program and Catalog Information

Provide the catalog description of the proposed program. As part of the description, please indicate any areas of concentration or specializations that will be offered.

The Masters of Science in Quantum Computing provides participants with foundational, practical and theoretical topics of quantum computing. Participants will discover current state-of-the-art quantum computing technology and areas of application, while also exploring its origins, evolution, and possible future states of this technology.

Experiential learning is at the core of the program with courses that provide ample opportunity for the participant to apply concepts on current-day commercial quantum computing hardware.

Special topics include quantum networks, quantum thermodynamics, quantum machine learning, quantum information theory, quantum Monte Carlo and simulations, and quantum computing hardware.

Catalog Program Requirements. Please click on the help bubble for more specific information about formatting requirements.

The Master of Science in Quantum Computing requires 30 credits including 7 core courses and 3 electives.

Course	Title	Credits
Core courses		
MSQC601	Course MSQC601 Not Found (Mathematics and Methods of Quantum Computing)	3
MSQC602	Course MSQC602 Not Found (The Physics of Quantum Devices)	3
MSQC603	Principles of Machine Learning	3
MSQC604	Course MSQC604 Not Found (Quantum Computing Architectures and Algorithms)	3
MSQC605	Course MSQC605 Not Found (Advanced Topics in Quantum Computing)	3
MSQC606	Course MSQC606 Not Found (Practical Quantum Computing)	3

MSQC607	Course MSQC607 Not Found (Advanced Topics in Quantum Computing)	3
Elective courses		**9**
MSQC610	Course MSQC610 Not Found (Quantum Machine Learning- elective)	
MSQC611	Course MSQC611 Not Found (Quantum Networks- elective)	
MSQC612	Course MSQC612 Not Found (Quantum Computing Hardware- elective)	
MSQC613	Course MSQC613 Not Found (Quantum Monte Carlo and Applications- elective)	
MSQC614	Course MSQC614 Not Found (Quantum Information Theory- elective)	
MSQC615	Course MSQC615 Not Found (Quantum Thermodynamics- elective)	
Total Credits		**30**

Sample plan. Provide a term by term sample plan that shows how a hypothetical student would progress through the program to completion. It should be clear the length of time it will take for a typical student to graduate. For undergraduate programs, this should be the four-year plan.

Full time:

First Year					
Semester 1	**Credits**	**Semester 2**	**Credits**	**Semester 3**	**Credits**
MSQC601 (The Mathematics and Methods of Quantum Computing)	3	MSQC604 (Quantum Computing Architectures and Algorithms)	3	MSQC612 or MSQC613 (Quantum Computing Hardware or Quantum Monte Carlo and Applications)	3
MSQC602 (Physics of Quantum Devices)	3	MSQC606 (Practical Quantum Computing)	3		
MSML/MSQC603 (Principles of Machine Learning)	3	MSQC608 or MSQC610 (Quantum Information Theory or Quantum Machine Learning)	3		
	9		**9**		**3**

Second Year	
Semester 1	**Credits**
MSQC605 (Advanced Quantum Computing and Applications)	3
MSQC607 (Advanced Topics in Quantum Computing)	3
MSQC609 or MSQC611 (Quantum Thermodynamics or Quantum Networks)	3
	9

Total Credits 30

Sample Plan of Study (Part time)

Semester 1 (fall)

MSQC601 The Mathematics and Methods of Quantum Computing (core)
MSQC602 Physics of Quantum Devices (core)

Semester 2 (spring)

MSQC604 Quantum Computing Architectures and Algorithms (core)
[choose any one of the following]
MSQC608 Quantum Information Theory (elective)
MSQC610 Quantum Machine Learning (elective)

Semester 3 (summer)

[choose any one of the following]
MSQC612 Quantum Computing Hardware (elective)
MSQC613 Quantum Monte Carlo and Applications (elective)

Semester 4 (fall)

MSQC603 Principles of Machine Learning (core)
MSQC605 Advanced Quantum Computing and Applications (core)

Semester 5 (spring)
MSQC606 Practical Quantum Computing (core)

Semester 6 (fall)

MSQC607 Advanced Topics in Quantum Computing (core)
[choose any one of the following]
MSQC609 Quantum Thermodynamics (elective)
MSQC611 Quantum Networks (elective)

List the intended student learning outcomes. In an attachment, provide the plan for assessing these outcomes.

Learning Outcomes
Explain principles of quantum physics as they apply to quantum computing.
Develop quantum computing programs and implement them on quantum computing platforms.
Distinguish the elements of a quantum computing algorithm and differentiate it from a classical algorithm.
Describe current quantum computing hardware, and examine the effects of its current state of maturity on the design of quantum computing algorithms.
Discuss and implement quantum computing paradigms to solve problems in quantum networks and quantum machine learning.
Compare quantum thermodynamics and quantum information theory and how they relate to classical information theory.

New Program Information

Mission and Purpose

Describe the program and explain how it fits the institutional mission statement and planning priorities.

The Master of Science in Quantum Computing aims to provide training and advanced knowledge in the area of quantum computing with a focus on practical education for working professionals. This program will contribute to the development of the emerging labor market of quantum computing scientists and engineers in the state of Maryland, and the nation. Other countries, such as China, have invested greatly recently in these scientific and technological sectors. The potential benefits of early discoveries and implementation of technological solutions that use quantum computing promise to generate important societal and economical benefits in the long term. For these reasons, the Master of Science in Quantum Computing is aligned with the mission of the University of Maryland to provide excellent teaching, research and education in service of the needs of the citizens of Maryland, and the nation.

Program Characteristics

What are the educational objectives of the program?

The main educational objective of the Master of Science in Quantum Computing is to prepare the individual to be ready to apply the principles and techniques of quantum computing to the solution of a variety of problems in optimization, secure communications, encryption, materials discovery and any such problems that require considerable computing resources.
Moreover, the participant should be able to differentiate the many technologies currently used to implement quantum computers and compare their intrinsic strengths and limitations.
Finally, the individual will gain the ability to make appropriate business decisions now to be set up for success when quantum technologies reach maturity in the future.

Describe any selective admissions policy or special criteria for students interested in this program.

A four-year baccalaureate degree from a regionally accredited U.S. institution, or an equivalent degree from a non-U.S. institution

A 3.0 GPA (on a 4.0 scale) in all prior undergraduate and graduate coursework
Official copy of transcript for all post-secondary work

Curriculum vitae/resume

Personal statement including such elements as relevant experience and interests in engineering, mathematics, and natural sciences

Prior programming experience (Python preferred)

Quantitative abilities including coursework in Linear Algebra and Advanced Calculus

Summarize the factors that were considered in developing the proposed curriculum (such as recommendations of advisory or other groups, articulated workforce needs, standards set by disciplinary associations or specialized-accrediting groups, etc.).

In recent years, the federal government and private sector have substantially increased funding for research and development of quantum technologies, including quantum computing.
This new area of economic activity requires a highly trained and skilled labor force to take advantage of this technological era and contribute to the solution of problems at the local, regional, and national levels.
Conversations with experts at the National Institute for Standards and Technology (NIST), as well as the Universities Space Research Association (USRA), have confirmed that there are skills gaps in the current workforce and more trained experts in these areas are required.
The University of Maryland has seen an exponential growth in investments and the creation of multiple centers, institutes and departments bringing in research talent and economic resources in quantum physics and quantum computing.This program will take advantage of this ecosystem of quantum expertise on campus, and complement UMDs development by adding an educational component.
Therefore, the proposed program is aligned with the university mission to promote interdisciplinary and cross sector partnerships to advance science and technology for the benefit of the state and the nation.

Select the academic calendar type for this program (calendar types with dates can be found on the Academic Calendar). Please click on the help bubble for more specific information.

Traditional Semester

For Master's degree programs, describe the thesis requirement and/or the non-thesis requirement.

Non-thesis requirement: complete all courses, 30 credits, with a 3.0 cumulative GPA or better.

Identify specific actions and strategies that will be utilized to recruit and retain a diverse student body.

The primary recruitment activities will be via the CMNS Science Academy. The Science Academy uses a diverse, targeted approach when recruiting students. This digital strategy focuses on UMD alumni, current UMD graduating seniors, and working professionals in the DMV area, including senior scientist personnel in NIST, NASA, and NIH. The admissions review process reviews for not only academic readiness but also diversity in experiences, industries, backgrounds, and career aspirations to recruit a diverse student body.

To attract a diverse student population, we will engage in the following activities:
• Representing the program in educational fairs, conferences and events, e.g. the National Leadership Conference of the National Society of Black Engineers, GEM Grad Labs.
• Advertising the program to the National Society of Black Engineers (NSBE), the Society of Women Engineers (SWE), and the Association for Women in Computing (AWC).
• Direct mailing and email campaigns to domestic and international colleges
• Outreach to UMD Campus organizations and clubs
• Holding online (virtual) open houses, information sessions and career panels
• Outreach to US Military to attract veterans
• Social media and online advertising
• Establishing graduate scholarships to provide financial aid to underrepresented minority applicants

Once enrolled, the Science Academy staff, and faculty are committed to creating and fostering a supportive environment for all students to thrive. We regularly share resources and opportunities for counseling, support, and funding. All students are expected to complete and honor the TerrapinSTRONG orientation and initiatives. Students are encouraged to take part in Grad School programs that address diversity and inclusion in higher education, build communities of support and success, and create meaningful dialogue among graduate students. Such programs include"Cultivating Community Conversations" and the "Annual Office of Graduate Diversity and Inclusions Spring Speaker Services." Faculty that are involved in the Science Academy represent many departments, have a diversity of appointments (both tenure track, professional track, and adjunct) exposing students to many future career paths. The Science Academy and faculty provide student advising, academic support, and career guidance to students to retain all students and support timely graduation.

Our student retention efforts will consist of:
• Holding "Women in Engineering, Computing and STEM" seminars to addresses the obstacles faced by women in today's technical workplace and guide our women students to maneuver through the internship and job application process
• Requiring students to attend mandatory advising sessions with the program adviser to ensure that the students' study plans are in line with their interests and career goals, and that the students make satisfactory progress toward meeting the degree requirements
• Implementing an early warning system that detects students struggling with core courses and alerts the academic advisor, who meets with the students and designs a study plan to get them back on track

Relationship to Other Units or Institutions

If a required or recommended course is o#ered by another department, discuss how the additional students will not unduly burden that department's faculty and resources. Discuss any other potential impacts on another department, such as academic content that may significantly overlap with existing programs. Use space below for any comments. Otherwise, attach supporting correspondence.

One course is shared across existing programs in the Science Academy, DATA/MSML 603: Principles of Machine Learning. Other courses will be new courses and should not burden department's faculty or resources. New courses will be developed and delivered by a combination of tenure-track or professional-track faculty teaching on overload and adjuncts.

Accreditation and Licensure. Will the program need to be accredited? If so, indicate the accrediting agency. Also, indicate if students will expect to be licensed or certified in order to engage in or be successful in the program's target occupation.

No accreditation or licensure is required for the program.

Describe any cooperative arrangements with other institutions or organizations that will be important for the success of this program.

MSQC604 Quantum Computing Architectures and Algorithms and MSCQ605 Advanced Quantum Computing and Applications will be developed in collaboration with the Universities Space Research Association (USRA).

USRA will contribute industry perspective on in-demand skills and competencies, create real world problem sets/simulations/projects, identify prospective participants from government labs and private industry, and market the program.

Faculty and Organization

Who will provide academic direction and oversight for the program? In an attachment, please indicate the faculty involved in the program. Include their titles, credentials, and courses they may teach for the program. Please click on the help bubble for a template to use for adding faculty information.

Konstantina Trivisa Ph. D., Director of Institute for Physical Science and Technology, Professor of Mathematics Pratyush Tiwary Ph. D., Associate Professor IPST and Chemistry and BioChemistry
Alfredo Nava-Tudela Ph.D., Director of Scientific Computing, IPST
Charles Clark Ph.D., JQI Fellow and IPST
Maria Cameron Ph.D., Associate Professor of Mathematics
Nicole Yunger Halpern Ph.D., Adjunct Assistant Professor QuICS and IPST
Avik Dutt Ph.D., Assistant Professor Mechanical Engineering and IPST
Franz Klein Ph.D., Office of Academic Computing Services
Aaron Lott Ph.D., Universities Space Research Association (USRA)
Alejandra Mercado Ph.D., Associate Director ECE

Indicate who will provide the administrative coordination for the program

The Science Academy in the College of Computer, Mathematics and Natural Science will provide administrative coordination for the program, in collaboration with the Office of Extended Studies. The Office of Extended Studies provides program development support (budget development and projections, market research, preparation of PCC document), program management (UMD policies and procedures
compliance, program website, data requests), student and program services (admission support, scheduling, registration, billing and payment, graduation, appeals), and financial management (faculty contracts, payment processing, course charge processor, net revenue distribution).

Resource Needs and Sources

Each new program is required to have a library assessment prepared by the University Libraries in order to determine any new library resources that may be required. This assessment must be done by the University Libraries. Add as an attachment.

The University of Maryland at College Park subscribes to substantial journal holdings and index databases, as well as additional support services and resources, to support teaching and learning in the Master of Science in Quantum Computing, per the University of Maryland Libraries assessment. These materials are supplemented by a strong monograph collection. Additionally, the Libraries Scan & Deliver and Interlibrary Loan services make materials that otherwise would not be available online, accessible to remote users. As a result, the University of Maryland Libraries are able to meet the curricular and research needs of the proposed Master of Science in Quantum Computing. This assessment stems from the assessment that the University of Maryland Libraries provided for the Professional Masters in Quantum Computing, which applies exactly to the curriculum of this new Masters of Science in Quantum Computing.

Discuss the adequacy of physical facilities, infrastructure and instructional equipment.

No additional physical facilities, infrastructure and instructional equipment is required for this program. Existing facilities (e.g., classrooms) and resources (e.g., instructional equipment) will be used. It is anticipated that most of the instruction will be in the evenings, to accommodate the working professional’s schedule.

Discuss the instructional resources (faculty, staff, and teaching assistants) that will be needed to cover new courses or needed additional sections of existing courses to be taught. Indicate the source of resources for covering these costs.

The Master of Science in Quantum Computing will not use any state resources since all funding will come from tuition.
The instructors and course designers will include faculty members from the Institute of Physical Science and Technology, which consists of applied mathematicians, physicists, and engineers with the required expertise. We will also count with adjunct faculty from NIST and USRA, and other units within the College of Computer, Mathematical and Natural Sciences, as well as units within the J. Clark School of Engineering.

Discuss the administrative and advising resources that will be needed for the program. Indicate the source of resources for covering these costs.

The CMNS Science Academy will provide the academic and advising oversight to incoming and admitted students. Revenue generated from the program will be used to support administrative and advising resources including a Program Manager. No state resources will be used to support the program

Use the Maryland Higher Education Commission (MHEC) commission financial tables to describe the program's financial plan for the next five years. See help bubble for financial table template. Use space below for any additional comments on program funding. Please click on the help bubble for financial table templates.

Based on the attached proposed budget the program projects to bring in revenue during the first year and to cover all start up costs. This program will not use any state funds and will be revenue generating. All expenses will be paid for by the tuition revenue for this program. See attached document.

Implications for the State (Additional Information Required by MHEC and the Board of Regents)

Explain how there is a compelling regional or statewide need for the program. Argument for need may be based on the need for the advancement of knowledge and/or societal needs, including the need for "expanding educational opportunities and choices for minority and educationally disadvantaged students at institutions of higher education." Also, explain how need is consistent with the Maryland State Plan for Postsecondary Education. Please click on the help bubble for more specific information.

The National Institute of Standards and Technology has made substantial investments on campus to pursue research in quantum physics and technology over the past decades taking into account the vast faculty expertise in quantum physics and engineering. Campus has seen the creation of the Joint Quantum Institute (JQI), the Joint Center for Quantum Information and Computer Science (QuICS), and the Quantum Technology Center (QTC). This, combined with the need to create a skilled professional workforce in quantum computing, makes UMD a natural choice to create an educational offering for this workforce development. In particular NASA Goddard Space Flight Center personnel have expressed interest in courses like the ones proposed in this MS degree.

Present data and analysis projecting market demand and the availability of openings in a job market to be served by the new program. Possible sources of information include industry or disciplinary studies on job market, the USBLS Occupational Outlook Handbook, or Maryland state Occupational and Industry Projections over the next five years. Also, provide information on the existing supply of graduates in similar programs in the state (use MHEC's Office of Research and Policy Analysis webpage for Annual Reports on Enrollment by Program) and discuss how future demand for graduates will exceed the existing supply. As part of this analysis, indicate the anticipated number of students your program will graduate per year at steady state.) Please click on the help bubble for specific resources for finding this information.

A market research study shows that there are very few (2) programs with comparable focus and scope to the proposed certificate. No similar programs exist in the state of Maryland. A labor market study shows that participants in this program will have access to well remunerated jobs. See both market analysis documents attached.

Identify similar programs in the state. Discuss any di#erences between the proposed program and existing programs. Explain how your program will not result in an unreasonable duplication of an existing program (you can base this argument on program di#erences or market demand for graduates). The MHEC website can be used to find academic programs operating in the state. Please click on the help bubble for specific information on finding similar programs within the state.

No similar programs exist in the state of Maryland. Ref. market analysis by OES.

Discuss the possible impact on Historically Black Institutions (HBIs) in the state. Will the program affect any existing programs at Maryland HBIs? Will the program impact the uniqueness or identity of a Maryland HBI?

No impact as there are no similar programs in the state of Maryland. See above.

Supporting Documents

Attachments

Faculty List Template- Quantum.docx
PGP_Benchmark_Quantum_Computing_MPS 2023.xlsx
Collection_Assessment_MPS_QuantumComputing_2022.docx
MS in Quantum Computing Budget.xlsx
Quantum Learning Outcomes and Assessment.pdf
Quantum- Curriculum- MS in Quantum Computing.pdf

Key: 913

Faculty Information- Quantum Computing

The following faculty members are projected to teach in the program. All faculty are full-time unless otherwise indicated.

Name	**Highest Degree Earned, Program, and Institution**	**UMD Title (indicate if part-time)**	**Courses**
Babak Azimi-Sadjadi	Ph.D., ECE, UMD	Visiting Lecturer	DATA/MSML/BIOI/MSQC 603: Principles of Machine Learning
Maria Cameron	Ph.D., Mathematics, University of California - Berkeley	Associate Professor	Curriculum Advisor
Charles Clark	Ph.D., Physics, University of Chicago	Adjunct Professor	MSQC 602: Physics of quantum devices
Avik Dutt	Ph.D., Electrical and Computer Engineering, Cornell University	Assistant Professor	Curriculum Advisor
Nicole Yunger Halpern	Ph.D., Physics, California Institute of Technology	Adjunct Asst. Professor	Curriculum Advisor
Franz Klein	Ph.D., Physics, University of Bonn (Germany)	Engineer	MSQC 606: Practical Quantum Computing
Aaron Lott	Ph.D., AMSC, UMD	Adjunct Assoc. Professor	MSQC 604: Quantum Computing Architectures and Algorithms MSQC605: Advanced Quantum Computing and Applications
Alejandra Mercado	Ph.D., ECE, UMD	Associate Director	DATA/MSML/BIOI/MSQC 603: Principles of Machine Learning
Alfredo Nava-Tudela	Ph.D., AMSC, UMD	Director	MSQC 601: The Mathematics and Methods of Quantum Computing
Pratyush Tiwary	Ph.D., Materials Science, California Institute of Technology	Associate Professor	Curriculum Advisor
Konstantina Trivisa	Ph.D., Applied Mathematics, Brown University	Professor	MSQC 601: The Mathematics and Methods of Quantum Computing

OES In-House Market Research: Other Institution Comparison Quantum Computing -Masters										
Institution	**Website**	**Delivery Method**	**Degree Name & Type (MPS, MA, MS, MPH, etc.)**	**# of Credits**	**Program Duration**	**Tuition (course or credit)** **Resident**	**Non-Resident**	**Target Population**	**Prior Education/ Pre-Requisites**	**Notes**
Big Ten Institutions										
Indiana University Bloomington	https://qis.iu.edu/academics/index.html	F2F	Quantum Informational Science (QIS), MS	30 credits	In as little as one year, (two full semesters and one summer session	$10,630/year	$30,704/year	Our MS degree program is designed to bridge students from a wide variety of BS degree-level backgrounds with the knowledge and skills needed to join this new field. Although many of the advances in QIS came from people with PhD-level backgrounds in math/chemistry/physics and similar areas, in the near future, companies foresee that the QIS field will require people who can combine an understanding of QIS concepts with significant knowledge from a variety of fields. Our MS degree program can be used to prepare you for jobs in the developing QIS industry or for other degree programs.	Must have a bachelor's degree, minimum GPA of 3.0 on a 4.0 scale for undergraduate coursework. Demonstrate proficiency in the English language. Do offer a non-credit "bootcamp" before the start of the program to help bring entrants into the program with a common point of understanding	Specialized courses provide you with opportunities to apply quantum concepts and/or to learn about the science and technology where quantum processes are hosted. Specializations include: Quantum Information and Simulation: including mathematical and computational models of quantum computation and simulation, and complexity theory. Quantum Materials and Sensing: including topological electron systems, strange metals, superconductors, theoretical physics and chemistry, photonics, nano-engineering, and quantum measurement. Quantum Applications and Operations: including optimization problems, quantum algorithms, logistics, operations research, and machine learning.
Northwestern University	https://www.mccormick.northwestern.edu/electrical-computer/academics/graduate/masters/electrical-engineering/quantum-computing-and-photonics.html	F2F	Electrical and Computer Engineering -Quantum Computing and Photonics Specialization	12 Unit (Courses)	not noted	$19,978/term		This track will prepare you for a career in the full range of fields in quantum information sciences to meet the challenges of this cutting-edge technology. In this multi-disciplinary field, you will acquire foundational skills in four key areas including quantum computation, quantum communication, quantum sensing, and fundamental quantum science. Additionally, you will also learn how to apply both theoretical and practical knowledge to design quantum algorithms, circuitry, cryptography, optical systems, communication protocols, and more.	For its master of science in electrical engineering program, the Department of Electrical and Computer Engineering looks for students who have a solid undergraduate background in electrical engineering and a desire to progress further into the field. A typical applicant is expected to have a Bachelor of Science in Electrical Engineering, Computer Engineering, or a related discipline from a recognized institution. Highly qualified candidates with other academic backgrounds may also be considered.	Have 3 degree options: Thesis Degree, Project Degree, and Course Degree
Penn State University Park	https://bulletins.psu.edu/graduate/programs/majors/engineering-science-mechanics/#text	F2F	Engineering Science and Mechanics, MS (research opportunities in Quantum Computation and Informational Sciences)	32 credits	Intense 1 year program	$1,086/credit	$1,803/credit	The Master of Science in Computer Science and Engineering programs requires the completion of 30 credits. Students interested in an M.S. in CSE should have already successfully completed Operating Systems Design and Construction, Introduction to Computer Architecture, Programming Language Concepts, Data Structures and Algorithms, and Logical Design of Digital Systems or Introduction to the Theory of Computation	Applicants who hold a baccalaureate degree in engineering, the sciences, mathematics, engineering science, and materials who present at least a 3.00 grade-point average will be considered for admission	There is a non-thesis track for the same program: The one-year intensive master's degree program is meant to prepare students for work in industry. As such, there is no thesis required, although a final paper is required during the last semester of the program.
University of Wisconsin–Madison	https://www.physics.wisc.edu/graduate/mspqc-prospective-students/	F2F	Physics: Quantum Computing, MS (MSPQC)	30 credits	Accelerated 1 year program (Fall, Spring, Summer)	$1600 per credit		The program provides students with a thorough grounding in the new discipline of quantum information and quantum computing. This begins with a study of the relevant parts of quantum theory, and proceeds to quantum gates, measurements, algorithms, quantum error correction and decoherence. Quantum communication theory and the secure transmission of information are also covered. The supporting areas of statistical mechanics, solid-state physics, and atomic physics will form part of the classroom training. Just as important, the program gives students a mastery of the advanced lab skills involved in quantum computation. Finally, all students have the opportunity to get involved in original research.	Admissions Materials: Three letters of recommendation; Official transcripts; Resume/CV; Statement of Purpose: Address relevant experiences and future research/industry interests and goals. Communicate motivations for pursuing the MSPQC, and convey how interests/experiences align with the strengths of the UW– Madison program. NOTE: GRE scores are NOT required and will not be considered.	Degree began in 2019, claims to be the first.
State of Maryland System Institutions: Overseen by MHEC (http://mhec.maryland.gov/publications/Pages/research/index.aspx)										
Capitol Technology University	https://www.captechu.edu/degrees-and-programs/doctoral-degrees/quantum-computing-phd	Online	Quantum Computing, PhD	60 credits	not noted	$933 per credit		The PhD in Quantum Computing is a unique doctoral program designed to meet the immediate industry need for innovative researchers and practitioners. Professionals will graduate with the skills necessary to become key leaders in the advancement, expansion, and support of the this rapidly growing industry.	All students interested in applying for a doctoral degree need a master's degree in a relevant field, a resume showing a minimum of 5 years of directly related work experience plus 2 completed recommendation forms.	The PhD program offers 2 degree completion requirement options. 1. Thesis Option: The student will produce, present, and defend a doctoral dissertation after receiving the required approvals from the student's Committee and the PhD Review Boards. 2. Publication Option: the student will produce, present and defend their original doctoral research and produce three published as articles in high-impact journals identified by the university and the student's Committee. Students must receive the required approvals from the student's Committee and the PhD Review Board prior to publication.
Morgan State University	https://www.morgan.edu/advanced-computing-ms/ms_advancedcomputing	F2F/Online	Advanced Computing, MS	30	Can be completed in 12 months and 16 months for the thesis option	$464/credit	$912/credit	This new program is designed for students who have recently completed a bachelor's degree program in Computer Science or a related field and wish to enhance their career, explore research opportunities in Computer Science, and apply their acquired skills in multi-disciplinary teams or for specific focus. The program also meets the needs of students who are already in the workforce and wish to update or improve their knowledge of current computer science.	Only students with an undergraduate cumulative grade point average of 3.0 will be considered for admission. Students with an undergraduate cumulative GPA of between 2.5 and 2.99 may be considered for conditional admission. Post-bachelor's undergraduate credits will not be used to enhance G.P.A. requirements for admission to graduate study.For admission to graduate study an applicant must: Have earned a bachelor's degree from a regionally accredited college or university. The undergraduate record must be of such quality as to promise successful achievement at the graduate level.	
Colleges & Universities in the Washington DC - Baltimore MD area										
No Washington DC-Baltimore MD area Quantum Computing Masters Programs										
Other Major Institutions Offering Similar Programs										
Duke University	https://ece.duke.edu/masters/study/quantum-computing	F2F	Master of Science in Electrical and Computer Engineering with a Quantum Computing Concentration (MS)	30 credits	3 semesters	$31,310 fulltime per semester, after 3 semesters charged $3,478 per credit		Duke ECE is home to international leaders in information physics research, embodied in pathbreaking programs in metamaterials, quantum devices, and optical systems. Master's students will learn from faculty team with deep interdisciplinary research strengths and a track record of entrepreneurship and innovation.	Three letters of recommendation, Statement of Purpose, GRE optional	The ECE Quantum Computing MS has two tracks: 1. **The Software Track** prepares students to program and control quantum information devices and builds off the well-established Software Development Concentration 2. **The Hardware Track** focuses on the design, fabrication and testing of quantum devices
University of California, Los Angeles, UCLA	https://qst.ucla.edu/	F2F	Masters of Quantum Science and Technology (MQST)	36 units (9 courses)	1 year (Fall, Winter, Spring)	$51,174 program cost		The UCLA Master of Quantum Science And Technology is a professional degree program designed to prepare students for careers in research and development of quantum technologies. The degree addresses the needs of both students and industry, tailored to those who wish to pursue technical positions that require a unique combination of specialized knowledge and skills. The program consists of a rigorous interdisciplinary course curriculum, a year-long program of laboratory skills development, and an industry-relevant capstone internship.	Bachelor's degree, 3 letters of recommendation, Statement of Purpose, and a Personal Statement	The UCLA Master of Quantum Science and Technology is a one-year, full-time program that begins in Fall and concludes at the end of the following Summer quarter. The program consists of nine courses (36 units), an internship, and a capstone presentation on the internship. The core courses are designed specifically for the MQST program. The MQST curriculum emphasizes breadth and laboratory work and will equip students to apply their skills in diverse settings.

Five-Year Enrollment Trends		
Year	Capitol Technology University	Morgan State University
	Quantum Computing, PhD	Advanced Computing, MS
2016	N/A	N/A
2017	N/A	N/A
2018	N/A	N/A
2019	N/A	N/A
2020	2	2
2021	7	10
Projected		

Five-Year Degree Recaps		
Year	Capitol Technology University	Morgan State University
	Quantum Computing, PhD	Advanced Computing, MS
2017	N/A	N/A
2018	N/A	N/A
2019	N/A	N/A
2020	N/A	N/A
2021	0	0
2022	0	2

http://mhec.maryland.gov/publications/Pages/research/index.aspx

Enrollment Trends: Go to "Enrollment Reports" then "Trends in Fall Enrollment by Program"

Degree Recaps: Go to "Student Outcomes" then "Trends in Degrees and Certificates by Program"

OES In-House Market Research: Projected Employment Information				
Quantum Computing				
Occupation	**# of Jobs in the Field**	**Where Professionals are Employed**	**Professional Salary Information**	**Projected Job Growth**
Information from U.S. Bureau of Labor Statistics' Occupational Outlook Handbook (https://www.bls.gov/ooh/)				
Physicists and Astronomers	25,200	Astronomers held about 2,200 jobs in 2021. The largest employers of astronomers were as follows: Research and development in the physical, engineering, and life sciences-41% Colleges, university, and professional schools; state, local, and private-24% Federal government, excluding postal service-22% hysicists held about 23,000 jobs in 2021. The largest employers of physicists were as follows: Scientific research and development services-44% Federal government, excluding postal service-15% Colleges, universities, and professional schools; state, local, and private-12% Ambulatory healthcare services-2%	$147,450/year $70.89/hour	Job Outlook, 2021-31: 8% (Faster than average)
Computer and Information Reseach Scientists	33,500	Federal government, excluding postal service-31% Computer systems design and related services-20% Research and development in the physical, engineering, and life sciences -16% Software publishers-6% Colleges, universities, and professional schools; state, local, and private-5%	$131,490/year $63.22/hour	Job Outlook, 2021-31: 21% (much faster than average)
Information from State of Maryland's Occupational and Industry Projections				
Physicists and Astronomers	2,010	Maryland is the highest employment level in Physicists and the third highest concentration of jobs.	$134,648/year	8% (as fast as average)
Computer and Information Reseach Scientists	2,220	Maryland is the third highest emloyement level and is the state with the highest concentration of jobs.	$123,324/year	4.9% (slower than average)

UNIVERSITY OF MARYLAND
UNIVERSITY LIBRARIES

McKeldin Library
7649 Library Lane
College Park, MD 20742
Phone: (301) 405-0800

DATE: September 16, 2022

TO: Alfredo Nava-Tudela , Director of Scientific Computing, ant@umd.edu,
Institute for Physical Science and Technology

FROM: On behalf of the University of Maryland (UMD) Libraries:
Sarah Weiss, STEM and Open Science Librarian, srweiss@umd.edu
Maggie Saponaro, Director of Collection Development Strategies, msaponar@umd.edu
Daniel Mack, Associate Dean, Collection Strategies & Services, dmack@umd.edu

RE: Library Collection Assessment to support a new program – Masters of Professional Studies in Quantum Computing

We are providing this assessment in response to a proposal by the Institute for Physical Science and Technology in the College of Computer, Mathematical, and Natural Sciences (CMNS) to create Masters of Professional Studie in Quantum Computing. The Institute for Physical Science and Technology asked that we at the University of Maryland Libraries assess our collection resources to determine how well the Libraries support the curriculum of this proposed program.

Serial Publications

The University of Maryland Libraries currently subscribe to a large number of scholarly journals—almost all in online format—that focus on quantum computing.

The Libraries subscribe to most of the top ranked journals, based on Journal Impact Factor (JIF), that are listed in the Quantum Science and Technology category in the 2021 Science Edition of *Journal Citation Reports.*[1]

The Libraries subscribes to top journals in this category, which are available online:

- *Progress in Quantum Electronics* (#2)
- *IEEE Journal of Selected Topics in Quantum Electronics* (#9)
- *Classical and Quantum Gravity* (#10)
- *Optical and Quantum Electronics (#11)*
- *IEEE Journal of Quantum Electronics* (#12)

[1]Note: *Journal Citation Reports* is a tool for evaluating scholarly journals. It computes these evaluations from the relative number of citations compiled in the *Science Citation Index* and *Social Sciences Citation Index* database tools.

- *International Journal of Quantum Chemistry* (#13)
- *Quantum Information Processing* (#14)
- *Quantum Electronics (#15)*

Some of the journals are open access and available online:

- *npj Quantum Information* (#1)
- PRX Quantum (#3)
- *EPJ Quantum Technology* (#4)
- *npj Quantum Materials* (#5)
- *Quantum* (#7)
- *Quantum Topology (last 2 years are OA)* (#16)

Articles in journals that we do not own will likely be available through Interlibrary Loan/Document Delivery.

Databases

The Libraries' *Database Finder* (https://lib.guides.umd.edu/az.php) offers online access to databases that provide indexing and access to scholarly journal articles and other information sources. Many of these databases cover subject areas that would be relevant to this proposed program. Databases that would be useful in the field of quantum computing include *ACM Digital Library, ArXiv, IEEEXplore, and NTIS (National Technical Reports Library).* Also, three general/multidisciplinary databases, *Academic Search Ultimate (EBSCO)*, *Web of Science (Clarivate Analytics)* and *ScienceDirect (Elsevier)* are good sources of articles relevant to this topic.

In many—and likely in most—cases, these indexes offer full text copies of the relevant journal articles. In those instances in which the journal articles are available only in print format, the Libraries can make copies available to students through the Libraries' Interlibrary Loan (ILL) service (https://www.lib.umd.edu/find/request-digital/ILL/how-article). (Note: See ILL section below.)

Monographs

The Libraries regularly acquire scholarly monographs in quantum computing and allied subject disciplines. Monographs not already part of the collection can usually be added upon request. Most monographs in this subject area are available as e-books. Relevant eBook collections for this program include*: Morgan & Claypool Synthesis Digital Library, IEEE/Wiley eBooks, IET Digital Library*, and *SIAM* *eBooks*. Even in instances when the books are only available in print, students will be able to request specific chapters for online delivery through the Interlibrary Loan program.[2]

A search of the University of Maryland Libraries' WorldCat UMD catalog was conducted, using a variety of relevant subject terms. For example, using the search string <kw:("quantum computing") OR kw:("quantum information theory")> resulted in the citations of almost 700 books that we own here at UMD. A further search revealed that the Libraries' membership in the Big Ten Academic Alliance (BTAA) dramatically increases these holdings and citations as the same search string returns upwards of 2,000 results. As with our own materials, students can request that chapters be copied from these BTAA books if the books are not available electronically.

Interlibrary Loan Services

Interlibrary Loan services (https://www.lib.umd.edu/find/request/ILL) provide online delivery of bibliographic materials that otherwise would not be available online. As a result, remote users who take online courses may find these services to be helpful. Interlibrary Loan services are available free of charge.
The article/chapter request service scans and delivers journal articles and book chapters within three business days of the request--provided that the items are available in print on the UM Libraries' shelves or in microform. In the event that the requested article or chapter is not available on campus, the request will be automatically forwarded to the Interlibrary Loan service (ILL). Interlibrary Loan is a service that enables borrowers to obtain online articles and book chapters from materials not held in the University System of Maryland.

Additional Materials and Resources

In addition to serials, monographs and databases available through the University Libraries, students in the proposed program will have access to a wide range of media, datasets, software, and technology. Media in a variety of formats that can be utilized both on-site and via ELMS course media is available at McKeldin Library. GIS Datasets are available through the GIS Data Repository (https://www.lib.umd.edu/research/services/gis) while statistical consulting and additional research support is available through the Research and Learning department (https://www.lib.umd.edu/research) and technology support and services are available through the Terrapin Learning Commons Tech Desk (https://www.lib.umd.edu/visit/libraries/mckeldin/techdesk) and the STEM Library (https://www.lib.umd.edu/visit/libraries/stem).

The subject specialist librarian for the discipline, *Sarah Weiss*, also serves as an important resource to programs such as the one proposed. Through departmental partnerships, subject specialists actively

[2] Note: Please note that one limitation of these services that might create some challenges for online students is that the Libraries are not allowed to make online copies of entire books. The only way that a student can get access to a print copy of an entire book is to physically come to the Libraries and check out that book.

develop innovative services and materials that support the University's evolving academic programs and changing research interests. Subject specialists provide one-on-one research assistance online, in-person, or via the phone. They also provide information literacy instruction and can provide answers to questions regarding publishing, copyright and preserving digital works.

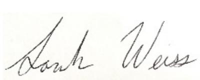
Other Research Collections

Because of the University's unique physical location near Washington D.C., Baltimore and Annapolis, University of Maryland students and faculty have access to some of the finest libraries, archives and research centers in the country vitally important for researchers in quantum computing. These include the National Institute of Technology, the National Library of Medicine, the Library of Congress, the National Archives to name just few.

Conclusion

With our substantial journals holdings and index databases, as well as additional support services and resources, the University of Maryland Libraries have resources to support teaching and learning in Masters of Professional Studies in Quantum Computing. These materials are supplemented by a strong monograph collection. Additionally, the Libraries Scan & Deliver and Interlibrary Loan services make materials that otherwise would not be available online, accessible to remote users. As a result, our assessment is that the University of Maryland Libraries are able to meet the curricular and research needs of the proposed Masters of Professional Studies in Quantum Computing.

Respectfully submitted:



Maggie Saponaro *Daniel C. Mack*

Sarah Weiss Maggie Saponaro Daniel Mack

MS in Quantum Computing					
Five-Year Program Budget					
Tuition Revenue	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
A. Total enrolled students	9	19	20	21	23
First year enrollment	9	10	10	11	12
Second year enrollment		9	10	10	11
B. Total # of 3-credit Courses (by enrollment year)	8	10	10	10	10
# of courses offered for students in year one of the program	8	8	8	8	8
# of courses offered for students in year two of the program		2	2	2	2
C. Per Course Rate	$4,000	$4,120	$4,244	$4,371	$4,502
Total Tuition Revenue	$288,000	$403,760	$424,360	$472,058	$531,240
Direct Expenses	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
A. Instructor Salaries and Fringe	$157,556	$173,936	$179,154	$184,529	$190,065
1. Subtotal: Instructor salaries	$121,290	$133,900	$137,917	$142,055	$146,316
Average 3-credit course salary	$13,000	$13,390	$13,792	$14,205	$14,632
Program specific courses (100% FTE)	9	9	9	9	9
Shared courses (33% FTE)	1	1	1	1	1
2. Fringe Benefits: 29.9%	$36,266	$40,036	$41,237	$42,474	$43,749
Total Direct Expenses	$157,556	$173,936	$179,154	$184,529	$190,065
Total Annual Tuition Revenue	$288,000	$403,760	$424,360	$472,058	$531,240
Total Annual Direct Expenses	$157,556	$173,936	$179,154	$184,529	$190,065
Total Annual OES Administrative Fee	$28,800	$40,376	$42,436	$47,206	$53,124
Annual Distributable Revenue	$101,644	$189,448	$202,770	$240,323	$288,051

Indirect Expenses					
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Administrative Salaries and Fringe	$53,692	$55,303	$56,962	$58,671	$60,431
1. Administrative Salaries	$39,596	$40,784	$42,007	$43,268	$44,566
Director (20% FTE)	$25,846	$26,621	$27,420	$28,243	$29,090
Faculty Director Stipend	$15,000	$15,450	$15,914	$16,391	$16,883
Program Manager (33% FTE)	$13,750	$14,163	$14,587	$15,025	$15,476
2. Fringe Benefits: 35.6%	$14,096	$14,519	$14,955	$15,403	15,865
Hourly Wages	$38,736	$51,648	$52,552	$53,474	$54,414
1. Hourly Wages	$36,000	$48,000	$48,840	$49,697	$50,571
Graders for program specific courses ($6K per course)	30,000	42,000	42,840	43,697	44,571
Graders for shared courses ($2K per course)	6,000	6,000	6,000	6,000	6,000
2. Hourly Wages Benefits: 7.6%	$2,736	$3,648	$3,712	$3,777	$3,843
Marketing	$2,500	$2,575	$2,652	$2,732	$2,814
1. Marketing	2,500	2,575	2,652	2,732	2,814
Equipment	$1,500	$1,545	$1,591	$1,639	$1,688
1. Equipment	1,500	1,545	1,591	1,639	1,688
Travel & Recruitment	$1,500	$1,545	$1,591	$1,639	$1,688
1. Travel & Recruitment	$1,500	$1,545	$1,591	$1,639	$1,688
Total Indirect Expenses	$97,928	$112,616	$115,349	$118,155	$121,035

Net Revenue	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
OES Distribution to CMNS	$101,644	$189,448	$202,770	$240,323	$288,051
Indirect Expenses	$97,928	$112,616	$115,349	$118,155	$121,035
Balance	**$3,716**	**$76,832**	**$87,421**	**$122,169**	**$167,016**

Learning Outcomes and Assessment

Learning Outcomes

Explain principles of quantum physics as they apply to quantum computing.
Develop quantum computing programs and implement them on quantum computing platforms.
Distinguish the elements of a quantum computing algorithm and differentiate it from a classical algorithm.
Describe current quantum computing hardware, and examine the effects of its current state of maturity on the design of quantum computing algorithms.
Discuss and implement quantum computing paradigms to solve problems in quantum networks and quantum machine learning.
Compare quantum thermodynamics and quantum information theory and how they relate to classical information theory.

Assessment for Learning Outcomes

Assessment for learning outcomes will be done via graded quizzes, exams, and assignments. Assignments will include a variety of professional focused work products where students will be applying learning to real life examples, such as quantum encryption and quantum key distribution, quantum chemistry, discrete combinatorial optimization, and quantum telecommunications. These applied learning and experiential opportunities will consist of case studies, simulations and oral presentations. To create this body of work students will need to demonstrate proficiency writing code in cloud quantum computing environments such as Amazon Braket, IBM Quantum, Azure Quantum, or similar cloud options.

MSQC601: The Mathematics and Methods of Quantum Computing

Learning objectives
The aim of quantum mechanics is to describe the movement of the atomic particles that matter is composed of. It is a mechanical theory that replaces classical mechanics in the domain of the microscopic world. Its origin dates back to the works of Heisenberg and Schrödinger. This theory has borne many technological advancements of which its latest ramification has been the development of quantum computers. This course will provide the student with the necessary mathematical tools and background knowledge to understand, model, and conceptualize quantum computing building blocks and systems.

Course outline - (under revision, see working copy of course)
Elements of real and complex analysis
Linear Algebra Review
Probability Review
Numerical Optimization
Elements of Differential Equations
Introductory Functional Analysis
Basic Notions of Quantum Mechanics
Elements of Theory and Practice of Computation
Quantum Gates and Circuits for Elementary Calculations

Prerequisites
Advanced calculus, linear algebra.

Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC602: Physics of Quantum Devices

Learning objectives
An introduction to quantum physics with emphasis on topics at the frontiers of research, and developing understanding through exercises.
The Physics of the very small course aims to build a bridge between natural principles such as light and atoms and a variety of modern applications.
This course will provide the student with the necessary physical intuition and background information on quantum physics so that to be able to understand and appreciate a variety of applications in quantum computing such as quantum currency, encryption, random number generation. A **quantum money** scheme is a quantum cryptographic protocol to create and validate banknotes which are impossible to forge. Encryption is a means **of securing digital data using one or more mathematical techniques**, along with a password or "key" used to decrypt the information. **Random number generation** is a process by which, often by means of a **random**

number generator (**RNG**), a sequence of numbers or symbols that cannot be reasonably predicted better than by random chance is generated. This means that the particular outcome sequence will contain some patterns detectable in hindsight but unpredictable to foresight.

Course outline
The Schrödinger equation
Probabilities and probability amplitudes
Qubits
Waves: $c = \lambda v$
Interference and polarization of light
Quantization of light: $E = hv$
Projective measurement: optical polarization
Superposition principle: optical polarization
State preparation/analysis with polarizers and beamsplitters
Quantum random number generation
Quantum money
Quantum cryptography
Parametric down conversion/correlated photons
Recent photon Einstein-Podolsky-Rosen experiments
Optical and material qubits (spins)
Quantum gate operations

Prerequisites
Advanced calculus, algebra, linear algebra, elements of differential equations, complex numbers.

Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

<u>MSQC603/MSML603: Principles of Machine Learning</u>

Learning objectives
Machine learning aims to make computer systems learn from experience. Learning systems are not manually programmed to solve a problem, but instead they are based on examples of how they should behave, or from trial-and-error experience trying to solve the problem. This requires learning algorithms to specify how the system should change its behavior as a result of experience. Machine learning is an interdisciplinary field, with historical roots in computer science, statistics, pattern recognition, and even neuroscience and physics. This course will focus on the classic machine learning methods that have been valuable and successful in practical applications. This course will cover various methods, with the aim of explaining the circumstances under which each is most appropriate. We will also discuss more advanced deep neural networks.

Course outline
Decision Tree
Linear regression
Logistic regression
SVM
Boosting
Clustering
Dimensionality reduction
Autoencoders (standard, denoising, contractive, etc etc)
Variational Autoencoders
Convolutional Neural Networks
Adversarial Generative Networks
Generative models and Discriminative models
Generative models with different data representations
Dynamical systems: RNNs
Attention and Memory Models
Applications with supervised and unsupervised learning

Prerequisites
Linear Algebra, Analysis, Probability, some notions of Signal Processing, and Numerical Optimization.

Grading
Homework (25%)
--Presentation including demonstration of running results with code
--Presentation about paper reviewing

Final project (15%)
--Project proposal in your own area with deep learning (middle term presentation)
--Final presentation to show your results

Final exam (60%)

MSQC604: Quantum Computing Architectures and Algorithms

Learning objectives
Quantum computing aims to utilize quantum properties of matter to efficiently solve problems that classical computing systems would take too long to solve. This course reviews modern noisy-intermediate scale quantum (NISQ) quantum computing architectures and algorithms for these platforms. We focus on mapping of optimization and machine learning problems onto NISQ architectures and also discuss how to leverage state-of-the-art classical simulation methods for these quantum-inspired algorithms. We review several NISQ architectures and associated software interfaces, we analyze performance for optimization and statistical sampling. We survey current literature to review and implement methods for mapping optimization and machine learning problems onto NISQ architectures and modern simulators and use them to solve and study example problems.

Course outline

Introduction to quantum computing (QC)

- Introduction to key mathematical concepts and notations for quantum computation
- Mathematical description of qubit mechanics
- Mathematical description of qubit controls and quantum gates
- Quantum logic gates

Overview of basic concepts and vocabulary of QC

- FTQ - Fault tolerant QC
- NISQ - Noisy intermediate scale QC
- Architecture types (superconducting, ion-trap, photon, neutral atom, annealing)
- Quantum computing extensions of key linear algebra operations
- Quantum computing extensions to key probability concepts

Algorithms & Analysis

- Mapping problems onto Ising model/Boltzmann Machines
- Overview of quantum algorithms landscape
- Optimization & Sampling methods
- Quantum Annealing
- QAOA (Quantum Approximate Optimization Algorithm)
- Trainability of quantum neural networks and barren plateaus

Software tools for QML & Optimization

- Tensorflow/PyTorch
- Cirq, Qiskit, Forrest, Ocean
- Tensorflow Quantum

Quantum Machine Learning

- Boltzmann machines
- Born machines
- Support Vector Machines
- Boosting
- Energy-based models
- Variational Autoencoders
- GANs

Prerequisites

MSQC601 The Mathematics and Methods of Quantum Computing,
MSQC602 The Physics of the Very Small and its Technological Ramifications

Grading

Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC605: Advanced Quantum Computing and Applications

Learning objectives

When Richard Feynman first introduced the concept of quantum computers it was posed for the purpose of simulating nature. Today quantum simulation remains one of the likely first applications to benefit from quantum computers. This course introduces key concepts required for quantum simulation, and builds tools for performing quantum simulation using state-of-the-art architectures. We introduce classical schemes, like tensor networks, and machine learning approaches, that can be used for these simulations on CPU/GPU architecture. We survey current literature to review and implement methods of quantum simulation and use them to solve and study example problems.

Course Outline

Introduction to quantum simulation (QC)
- Introduction to quantum chemistry & materials

Quantum simulation algorithms
- Quantum Fourier Transform
- Quantum Phase Estimation
- Variational Quantum Eigensolver
- Hamiltonian simulation
- Quantum Monte Carlo

Methods for Quantum Simulation
- Tensor networks
- Matrix Product States
- Density matrix renormalization group
- Machine learning approaches for simulation

Prerequisites

MSQC604 Quantum Computing Architectures and Algorithms

Grading

Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC606: Practical Quantum Computing

Learning objectives

Quantum computation is a rapidly growing field at the intersection of physics and computer science, electrical engineering and applied math. While instrumentation of quantum computers is in its infancy, quantum algorithms are being developed to provide efficient solutions to various computational problems.
This course covers basic quantum computing, including quantum circuits, significant quantum algorithms, and hybrid quantum-classical algorithms, with focus on applying the concepts to

programming existing and near-future quantum computers. Example codes, homework assignments, and class projects will employ Python modules to handle the data exchange with quantum computers.

Course Outline

Single-qubit systems: properties, representations, basic operations
Tutorial (optional): basics of Python programming language using Jupyter notebooks. [Franz, make this part of the course, don't mark it as optional - Alfredo comment]
Multi-qubit systems: superposition, entanglement, controlled operations.
Applications: teleportation, quantum repeater (entanglement swapping).
Basic quantum algorithms:
- Grover’s algorithm; Quantum Amplitude Amplification
- Quantum Fourier Transform
- Quantum Phase Estimation
- Shor’s algorithm: factoring and period finding
- Hamiltonian simulation

State of instrumentation:
- Superconductors, photonic networks, quantum dots, neutral atoms traps, ion traps; (optional: visit of IonQ headquarters)
- Quantum error correction and mitigation methods

Near-term algorithms:
- Quantum annealing
- Quantum approximate optimization algorithm
- Variational quantum eigensolver
- SLE solver: HHL and derived algorithms
- Quantum Machine Learning: qSVM, qPCA, qGAN

Prerequisites

MSQC601 The Mathematics and Methods of Quantum Computing
MSQC602 The Physics of the Very Small and its Technological Ramifications

Grading

Homework (50%)
- Programming exercises: application of introduced concepts and methods

Final project (20%)
- Worked-out project using a near-term quantum algorithm

Midterm exam (15%)
Final exam (15%)

<u>MSQC607: Advanced Topics in Quantum Computing</u>

Learning objectives

This course will showcase a variety of topics from which students can select one, or come up with one of their own, and proceed to study it in depth. The students will make presentations of their findings to class by citing literature and code implementations where appropriate, and culminate with the writing of a scholarly paper on the topic chosen.

Course Outline

Prerequisites
All previous core courses

Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC610: Quantum Machine Learning

Learning objectives
In this course we explore what quantum computing can contribute to data mining and machine learning. We focus on exploring what kind of speedups are possible using quantum computing as well as the storage capacity of quantum associative memories, for example.

Course Outline
Prerequisites
Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC611: Quantum Networks

Learning objectives
The need to communicate in a network the quantum states of qubits will necessitate the existence of a “quantum Internet.” Quantum signals are weak and very fragile and in general cannot be copied or amplified. The area of quantum networking explores how to combine well established networking techniques with quantum repeaters to transmit quantum information over long distances. In this course we explore quantum repeaters and their applications to telecommunications.

Course Outline
Prerequisites
Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC612: Quantum Computing Hardware

Learning objectives
There are a variety of technologies that implement qubits. In this course we explore these technologies.

Course Outline
Prerequisites
Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC613: Quantum Monte Carlo and Applications (course still under revision)

Learning objectives
In this course we study the quantum Monte Carlo method and explore applications in diverse areas ranging from correlated systems, chemistry, quantum mechanic systems simulations.

Course Outline
Prerequisites
Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC614: Quantum Information Theory

Learning objectives
Quantum information theory synthesizes three major themes: quantum physics, computer science, and information theory. At the core of information theory lies the work of Claude E. Shannon, which we review in this course, and we present and study three problems related to his work and subsequent extension to quantum computing. These are, compressing quantum

information, transmitting classical and quantum information through noisy quantum channels, and quantifying, characterizing, transforming, and using quantum entanglement.

Course Outline
Prerequisites
Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)

MSQC615: Quantum Thermodynamics

Learning objectives
Quantum thermodynamics is an emerging field that offers fundamental insights into energy, information, and their relationship. Thermodynamics originally described "classical" systems—everyday objects formed from many particles. The theory has recently extended to the quantum domain of single electrons and few atoms, which behave in ways impossible for everyday objects. For example, quantum particles correlate strongly through "entanglement," which gives one particle a surprisingly large amount of information about others. We will explore how scientists are leveraging such quantum phenomena in technologies such as quantum computers.

Course Outline
Prerequisites
Grading
Quizzes (20%)
Homework (40%)
Midterm exam (20%)
Final exam (20%)