Proposal for a New Course on Quantum Algorithms

Proposer: Jens Palsberg (Professor of Computer Science)

Course number: 238B.

Course Catalog Title: Quantum Algorithms.

Short Title: Quantum Algorithms.

Units: 4.

Grading Basis: Letter grading.

Format: Lecture only.

GE or Major/Minor requirement: N/A.

Requisites: CS 238 Quantum Programming.

Description: Lecture, four hours; Discussion, two hours; outside study, eight hours. Quantum algorithms including quantum machine learning, Hamiltonian simulation, and quantum walk; quantum complexity classes, including BQP, QMA, and QIP; quantum verification, including instrumented simulation and quantum abstract interpretation; high-level quantum languages, including Silq, and big theorems in quantum computing including Gottesman-Knill and Solovay-Kitaev. Students will do a variety of projects.

Justification: Quantum computing is one of the most exciting technical topics of our time and our students deserve to have the option to take courses on this topic. The National Quantum Initiative, signed into law in December 2018, allocated more than $1 billion to research and training in quantum information science. My course is the second in a sequence that will provide the kind of training that is called for in the law.

My expertise on the topic: I have been a researcher and an instructor in the area of programming languages and compilers since the early 1990s. In 2018, I expanded my interests to also cover quantum computing and I saw an opportunity to teach quantum computing. Research-wise, I am a member of the $25 million NSF Quantum Leap Institute that was established in 2020 and is led by Berkeley. This institute will tackle far-reaching questions at the heart of general-purpose quantum computation. Additionally, I led the writing of a proposal that led to an NSF award of $750,000 for a Quantum Computing and Information Science Faculty Fellowship. This award supports the salary of a faculty member for three years. In 2023, I received the Eon Instrumentation Excellence in Teaching Award at UCLA for my courses on quantum computing.

Supplemental Information: None.

Extra resources required for the class: None. In the three previous course offerings, we used one of IBM's quantum computers.

Effective Date: Winter 2024.

Fall/Winter/Spring: I plan to offer the course every Winter quarter.

Syllabus:

Title of the course: Quantum Algorithms.

Course objectives: Learn advanced algorithms and big theorems of quantum computing; implement complex quantum algorithms and run them on a quantum computer.

Learning outcomes:

- *Knowledge outcomes:* a grasp of how advanced quantum algorithms work; insight into major quantum complexity classes and how they are related to classical complexity classes; understanding of the main techniques for verifying the correctness of quantum circuits; and knowledge of some big theorems in quantum computing and how they are proved.
- *Skills outcomes:* ability to map a paper on an advanced quantum algorithm to an experiment on a quantum computer; ability to prove and experimentally verify fundamental theorems in quantum computing.
- *Behavioral outcomes:* agency to contribute significantly to the development of new quantum algorithms.

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Weekly topics:

Week 1:	Gottesman-Knill	*Foundations*
	Surface code	*Error correction*
Week 2:	Data representation	*Algorithms*
	Amplitude amplification	
Week 3:	Hamiltonian simulation by Trotterization	
	Linear combination of unitaries	
Week 4:	Solving linear equations	
	Quantum linear regression	
Week 5:	Differentiable quantum programming	
	Silq	*Languages*
Week 6:	{CNOT,H,T} is universal	*Universality*
	Solovay-Kitaev	
Week 7:	Approximate quantum computing	
	Quantum complexity	*Complexity*
Week 8:	Five 2-qubits gates are necessary to impl. Toffoli	*Impossibility*

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Week 9:	Projections as assertions	*Verification*
	Quantum abstract interpretation	
Week 10:	Generalized Gottesman-Knill	
	Course evaluation	*Discussion*

Weekly discussion section: A weekly discussion section with a teaching assistant enables students with diverse backgrounds to apply what was learned from lectures in a hands-on way, to ask questions and get clarifications about the course material, and to obtain guidance on assigned homeworks and projects.

Course assignments:

- Grover's search with an unknown number of solutions
- Proof of Gottesman-Knill
- Number of SYC gates sufficient to implement CCNOT
- Run Hamiltonian simulation with a quantum simulator
- Approximate CCNOT
- QAOA in Silq
- Example of solving linear equations
- State of quantum machine learning

Grading structure:

- Assignments: 50%
- Final exam: 25%
- Quizzes: 10%
- Peer evaluation: 10%
- Participation: 5%

Reading list:

- Several papers, distributed via Bruinlearn.
- My lecture notes, distributed via Bruinlearn.

Enrollment and Student Evaluations from Previous Course Offerings: I have offered CS 239 Quantum Algorithms three times, in Spring 2021, in Spring 2022, and in Winter 2023; and I have attached the teaching evaluations. In summary, the evaluations are:

Spring 2021, instructor: 8.67, course 8.00 (21 responses out of 27).
Spring 2022, instructor: 8.78, course 8.56 (9 responses out of 11).
Winter 2023, instructor: 7.94, course 7.66 (35 responses out of 42).

In Spring 2021 and Spring 2022, the students were 80% Computer Science students, while the rest were from Physics, ECE, and Math. In the academic year 2023-2024, Physics started a new self-supporting degree program called Master of Quantum Science and Technology (MQST). The MQST students are required to take both of my quantum courses: CS 238 Quantum Programming and the CS 238B Quantum Algorithms that is the subject of this proposal. As a result, in the Winter 2023 offering of my course, 60% of the students were MQST students and 40% were Computer Science students. I am sensitive to the drop in my course evaluations and wonder whether the students from Physics tend to give lower scores.

Overlap: UCLA has no other permanent course that has any significant overlap with my course.