Exeter College Oxford Summer Programme
Quantum Computer Science: an introduction

Course Description

This is an introduction to quantum computer science, intended primarily for computer scientists, physicists, electrical engineers and mathematicians. It will introduce a large number of ideas with an emphasis on building familiarity with the main concepts, and some general knowledge of terminology and methods. Mathematical methods will be employed in a practical way, on a 'need-to-know' basis. The aim is to give a grounding which will facilitate entry into this subject for anyone who wishes, eventually, either to join the research effort or to join the engineering and commercial workforce with a well-informed background. The main reference text is David Mermin's *Quantum Computer Science: An Introduction*. John Preskill's lecture notes may also be useful.

Syllabus Overview

1. Classical bits and classical information

The notion of data compression; Shannon information and noiseless coding theorem.

2. Classical computer science

Turing machine and universality, von Neumann architecture, logic gates, complexity classes, the halting problem.

3. Mathematical background: linear algebra

Vectors of complex numbers, eigenvalues, Hermitian and unitary, commutators, the Pauli matrices, Dirac notation

4. The basic quantum observation: superposition, entanglement, measurement

Two-path quantum interference experiments, Young's slits, which-path information, simple theory of measurement (projection), Schrodinger's equation

5. Quantum bits, quantum states, gates and measurement

The two-state quantum system, single- and two-qubit logic gates, Hadamard transform, Clifford gates, Gottesman-Knill theorem, universal set of gates.

6. Experimental methods

Outline of ion trap quantum computing and optical lattice (Rydberg gate) quantum computing: laser cooling, optical pumping, microwave and optical pulses. Outline of superconducting circuit methods: Josephson junction, cryostat, flux, charge and phase.

7. No-cloning, Bell states, dense coding and quantum teleportation

The no-cloning theorem, the Bell basis and its stabilizers, quantum dense coding, the quantum teleportation protocol

8. Quantum cryptography

BB84 protocol, entanglement-based key distribution

9. Quantum algorithms: Deutsch-Jozsa, Grover, Simon

The Deutsch-Jozsa algorithm, Grover's search algorithm, Simon's problem and Simon's algorithm

10. Period-finding, factoring and cryptography

The quantum Fourier transform, Shor's algorithm, relevance to public-key cryptography

11. Communication in the presence of noise: classical error correction

Binary vector, binary vector space, parity check, distance, linear code, Hamming codes, Hamming bound, Gilbert-Varshamov bound

12. Quantum error correction

Bit-flip and phase errors, error syndrome, parity check network, Shor code, Steane code, self-dual classical codes, CSS codes

The course comprises 12 lectures, 6 seminars, and 4 tutorials. It requires the students to read in advance to gain an understanding of the contents to be discussed. The course will help you to sharpen your analytical skills, improve your abilities to critically interpret primary scientific data, improve your confidence in academic debate, and develop your presentation skills. It will also give you a chance to learn to write clearly and advocate ideas for our debates (tutorials). This course is suitable for students who have a strong interest in and curiosity about the intersection of quantum physics and computer science. No prior knowledge of quantum physics or computer science is needed, but it is a prerequisite that students are familiar with the mathematical methods of vector spaces and linear algebra, matrices and eigenvalues, to the level of a first year undergraduate course in physics, chemistry, engineering, computer science, or similar. Some knowledge of logic gates or elementary quantum ideas would be an advantage. The course will require that you read in advance of each lecture and will aim to be interactive and stimulate you to debate the ideas presented.

Teaching Methods and Assessment
• 12 .25hr Lectures 15hrs)
• 6 x 1.25hr Seminars7.5hrs)
• 4 .25hr Tutorials 5hrs)

Twice weekly lectures will present the key points of the topics. Students will be expected to have completed the readings before the relevant lecture. A weekly seminar will focus in-depth study of lecture themes and provide opportunities to read, interpret, discuss and critique scientific literature. In addition, students will be expected to give a short oral presentation on a particular primary research article relevant to the topics discussed in the course.

Assessments: Final assessment: An essay of no more than 3,000 words (50%), a final three-hour written examination (40%), oral presentation (10%).

Lecture Schedule and required reading

Lecture 1: Introduction; classical bits and classical information

Andrew Steane, Quantum computing, Rep. Prog. Phys. **61** (1998) 117–173, sections 1 and 2. Mermin 1.1—1.4

Lecture 2: Classical computer science

Steane section 3.

Lecture 3: Mathematical background: linear algebra

Mermin Appendix A

Lecture 4: The basic quantum observation; superposition, entanglement, measurement

Feynman R, Leighton R B and Sands M L 1965 *The Feynman Lectures on Physics*, volume III, chapter 1.

Lecture 5: Quantum bits, quantum states, gates and measurement

Mermin 1.5 – 1.12

Lecture 6: Experimental methods

Steane section 8

Lecture 7: No-cloning, Bell states, dense coding and quantum teleportation

Steane section 5.1—5.5, Mermin 6.1, 6.3—6.6

Lecture 8: Quantum cryptography

Steane section 5.7, Mermin 6.2

Lecture 9: Quantum algorithms: Deutsch-Jozsa, Grover, Simon

Mermin chapter 2

Lecture 10: Period-finding, factoring and cryptography

Mermin chapter 3

Lecture 11: Communication in the presence of noise: classical error correction

Andrew M. Steane, *A Tutorial on Quantum Error Correction,* sections 1—5 [Proceedings of the International School of Physics "Enrico Fermi", course CLXII, "Quantum Computers, Algorithms and Chaos", G. Casati, D. L. Shepelyansky and P. Zoller, eds., pp. 1–32 (IOS Press, Amsterdam 2006).]

Lecture 12: Quantum error correction; Conclusion

Mermin chapter 5, Steane sections 5—8

GENERAL READING:
There are various textbooks on quantum computing available in bookstores, and plentiful lecture notes on the web. The trick is to find material at the right level. Preskill's notes are too advanced for a reader with little mathematics, but will suit those ready for mathematical detail. Mermin's book is a good way in. The Wikipedia article gives a brief survey of ideas, perhaps worth a look before you plunge into a book.