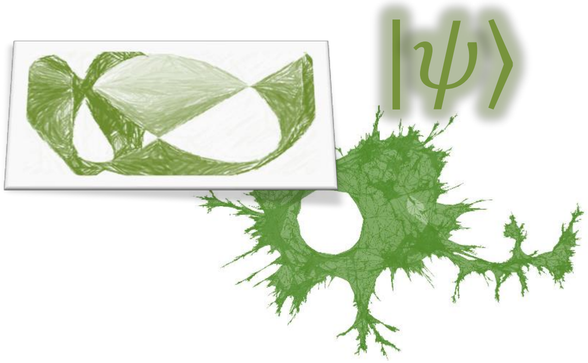
CSE 599Q: Intro to Quantum Computation



Instructor (me): James R. Lee
TA: Kasper Lindberg
Course info: https://homes.cs.washington.edu/~jrl/cse599Q/

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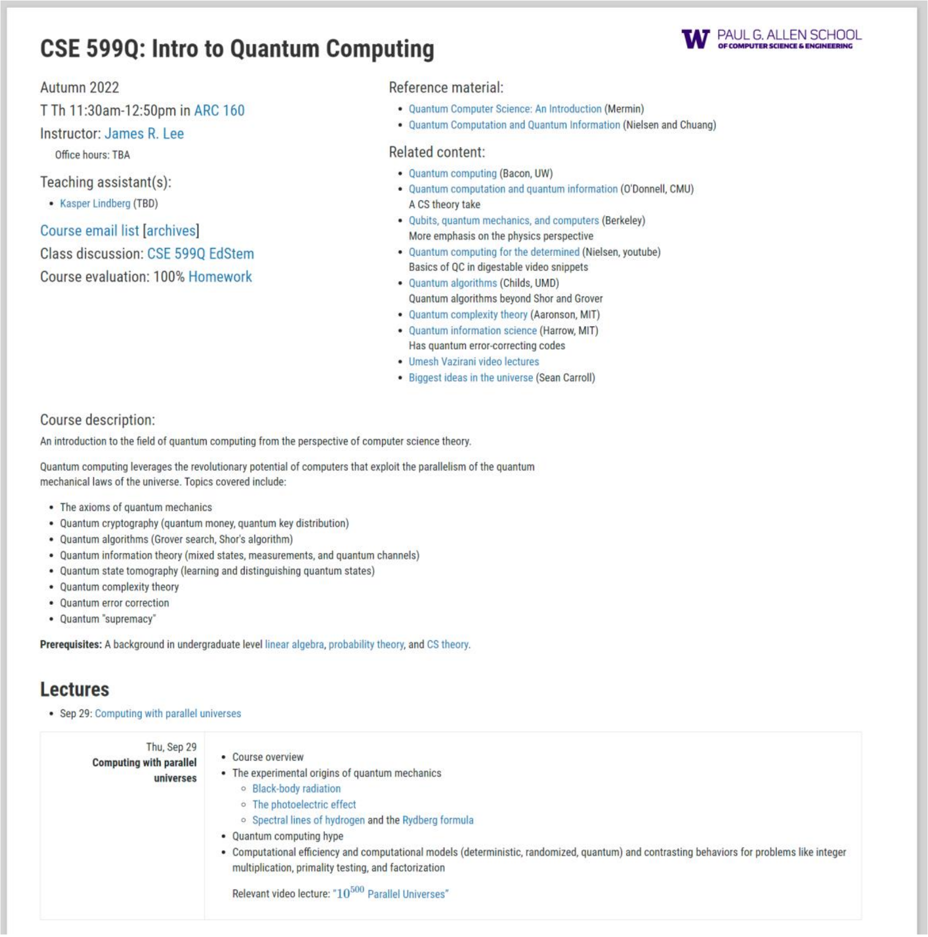


CSE 599Q: Intro to Quantum Computing

PAUL G. ALLEN SCHOOL OF COMPUTER SCIENCE & ENGINEERING

Autumn 2022
T Th 11:30am-12:50pm in ARC 160
Instructor: James R. Lee
Office hours: TBA

Teaching assistant(s):
- Kasper Lindberg (TBD)

Course email list [archives]
Class discussion: CSE 599Q EdStem
Course evaluation: 100% Homework

Reference material:
- Quantum Computer Science: An Introduction (Mermin)
- Quantum Computation and Quantum Information (Nielsen and Chuang)

Related content:
- Quantum computing (Bacon, UW)
- Quantum computation and quantum information (O'Donnell, CMU)
  A CS theory take
- Qubits, quantum mechanics, and computers (Berkeley)
  More emphasis on the physics perspective
- Quantum computing for the determined (Nielsen, youtube)
  Basics of QC in digestable video snippets
- Quantum algorithms (Childs, UMD)
  Quantum algorithms beyond Shor and Grover
- Quantum complexity theory (Aaronson, MIT)
- Quantum information science (Harrow, MIT)
  Has quantum error-correcting codes
- Umesh Vazirani video lectures
- Biggest ideas in the universe (Sean Carroll)

Course description:
An introduction to the field of quantum computing from the perspective of computer science theory.

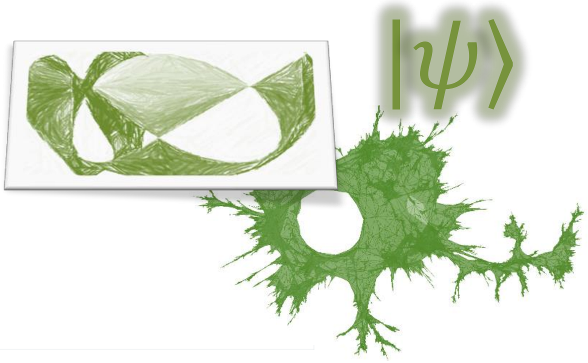
Quantum computing leverages the revolutionary potential of computers that exploit the parallelism of the quantum mechanical laws of the universe. Topics covered include:

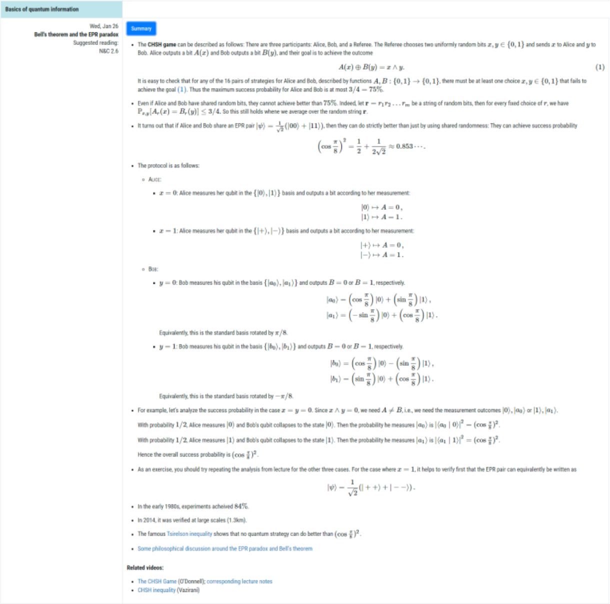
- The axioms of quantum mechanics
- Quantum cryptography (quantum money, quantum key distribution)
- Quantum algorithms (Grover search, Shor's algorithm)
- Quantum information theory (mixed states, measurements, and quantum channels)
- Quantum state tomography (learning and distinguishing quantum states)
- Quantum complexity theory
- Quantum error correction
- Quantum "supremacy"

Prerequisites: A background in undergraduate level linear algebra, probability theory, and CS theory.

Lectures
- Sep 29: Computing with parallel universes

Thu, Sep 29 **Computing with parallel universes**	• Course overview
	• The experimental origins of quantum mechanics
	  ◦ Black-body radiation
	  ◦ The photoelectric effect
	  ◦ Spectral lines of hydrogen and the Rydberg formula
	• Quantum computing hype
	• Computational efficiency and computational models (deterministic, randomized, quantum) and contrasting behaviors for problems like integer multiplication, primality testing, and factorization
	Relevant video lecture: "10^{500} Parallel Universes"





Basics of quantum information

Wed, Jan 26
Bell's theorem and the EPR paradox
Suggested reading:
N&C 2.6

Summary

- The **CHSH game** can be described as follows: There are three participants: Alice, Bob, and a Referee. The Referee chooses two uniformly random bits $x, y \in \{0,1\}$ and sends x to Alice and y to Bob. Alice outputs a bit $A(x)$ and Bob outputs a bit $B(y)$, and their goal is to achieve the outcome
$$A(x) \oplus B(y) = x \wedge y. \quad (1)$$
It is easy to check that for any of the 16 pairs of strategies for Alice and Bob, described by functions $A, B : \{0,1\} \to \{0,1\}$, there must be at least one choice $x, y \in \{0,1\}$ that fails to achieve the goal (1). Thus the maximum success probability for Alice and Bob is at most $3/4 = 75\%$.
- Even if Alice and Bob have shared random bits, they cannot achieve better than 75%. Indeed, let $\mathbf{r} = r_1 r_2 \dots r_m$ be a string of random bits, then for every fixed choice of r, we have $\mathbb{P}_{x,y}[A_r(x) = B_r(y)] \leq 3/4$. So this still holds where we average over the random string $\mathbf{r}$.
- It turns out that if Alice and Bob share an EPR pair $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, then they can do strictly better than just by using shared randomness: They can achieve success probability
$$\left(\cos\frac{\pi}{8}\right)^2 = \frac{1}{2} + \frac{1}{2\sqrt{2}} \approx 0.853\cdots.$$
- The protocol is as follows:
  - Alice:
    - $x = 0$: Alice measures her qubit in the $\{|0\rangle, |1\rangle\}$ basis and outputs a bit according to her measurement:
    $$|0\rangle \mapsto A = 0, \quad |1\rangle \mapsto A = 1.$$
    - $x = 1$: Alice measures her qubit in the $\{|+\rangle, |-\rangle\}$ basis and outputs a bit according to her measurement:
    $$|+\rangle \mapsto A = 0, \quad |-\rangle \mapsto A = 1.$$
  - Bob:
    - $y = 0$: Bob measures his qubit in the basis $\{|a_0\rangle, |a_1\rangle\}$ and outputs $B = 0$ or $B = 1$, respectively.
    $$|a_0\rangle = \left(\cos\frac{\pi}{8}\right)|0\rangle + \left(\sin\frac{\pi}{8}\right)|1\rangle, \quad |a_1\rangle = \left(-\sin\frac{\pi}{8}\right)|0\rangle + \left(\cos\frac{\pi}{8}\right)|1\rangle.$$
    Equivalently, this is the standard basis rotated by $\pi/8$.
    - $y = 1$: Bob measures his qubit in the basis $\{|b_0\rangle, |b_1\rangle\}$ and outputs $B = 0$ or $B = 1$, respectively.
    $$|b_0\rangle = \left(\cos\frac{\pi}{8}\right)|0\rangle - \left(\sin\frac{\pi}{8}\right)|1\rangle, \quad |b_1\rangle = \left(\sin\frac{\pi}{8}\right)|0\rangle + \left(\cos\frac{\pi}{8}\right)|1\rangle.$$
    Equivalently, this is the standard basis rotated by $-\pi/8$.
- For example, let's analyze the success probability in the case $x = y = 0$. Since $x \wedge y = 0$, we need $A \neq B$, i.e., we need the measurement outcomes $|0\rangle, |a_0\rangle$ or $|1\rangle, |a_1\rangle$.
  With probability $1/2$, Alice measures $|0\rangle$ and Bob's qubit collapses to the state $|0\rangle$. Then the probability he measures $|a_0\rangle$ is $|\langle a_0 \mid 0\rangle|^2 = (\cos\frac{\pi}{8})^2$.
  With probability $1/2$, Alice measures $|1\rangle$ and Bob's qubit collapses to the state $|1\rangle$. Then the probability he measures $|a_1\rangle$ is $|\langle a_1 \mid 1\rangle|^2 = (\cos\frac{\pi}{8})^2$.
  Hence the overall success probability is $(\cos\frac{\pi}{8})^2$.
- As an exercise, you should try repeating the analysis from lecture for the other three cases. For the case where $x = 1$, it helps to verify first that the EPR pair can equivalently be written as
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|++\rangle + |--\rangle).$$
- In the early 1980s, experiments acheived 84%.
- In 2014, it was verified at large scales (1.3km).
- The famous Tsirelson inequality shows that no quantum strategy can do better than $(\cos\frac{\pi}{8})^2$.
- Some philosophical discussion around the EPR paradox and Bell's theorem

Related videos:
- The CHSH Game (O'Donnell); corresponding lecture notes
- CHSH inequality (Vazirani)

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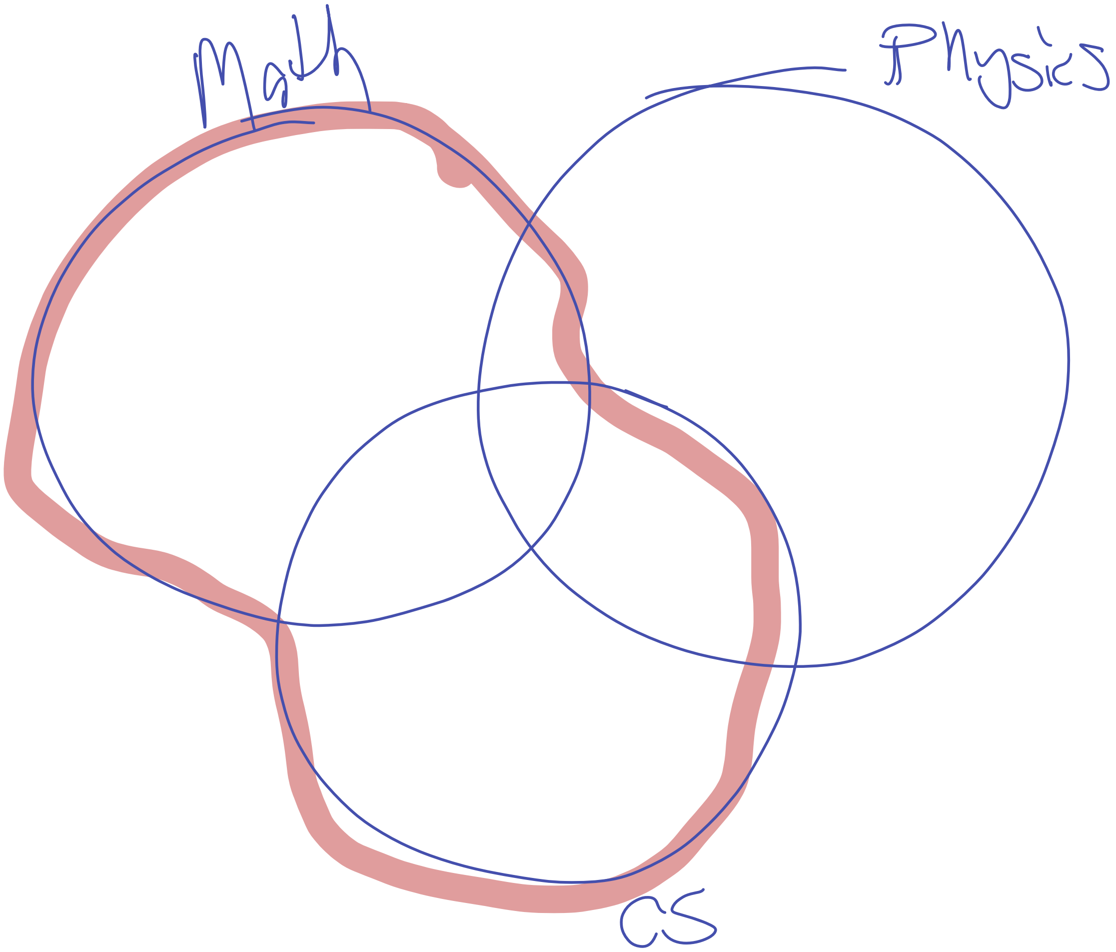
computing with parallel universes

"Quantum computing is… nothing less than a distinctively new way of harnessing nature… it will be the first technology that allows useful tasks to be performed in collaboration between parallel universes."

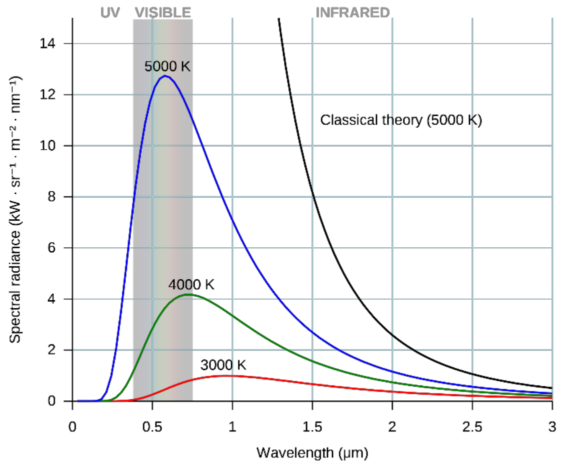
"When a quantum factorization engine is factorizing a 250-digit number, the number of interfering universes will be of the order of 10^{500}. This staggeringly large number is the reason why Shor's algorithm makes factorization tractable. I said [earlier in the book] that the algorithm requires only a few thousand [or maybe a million] operations. I meant, of course, a few thousand parallel operations in each universe that contributes to the answer. All those computations are performed in parallel, in different universes, and share their results through interference."

Quotes from David Deutsch (cofounder of quantum computing)

Math ∩ CS ∩ Physics

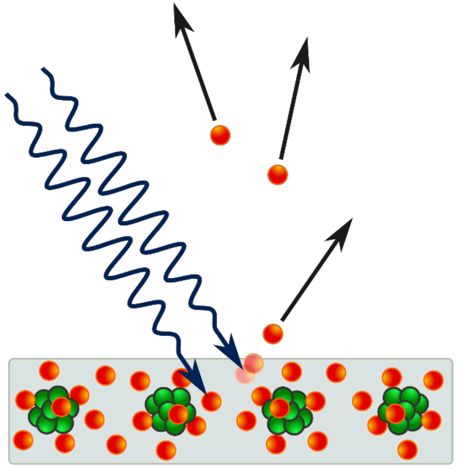


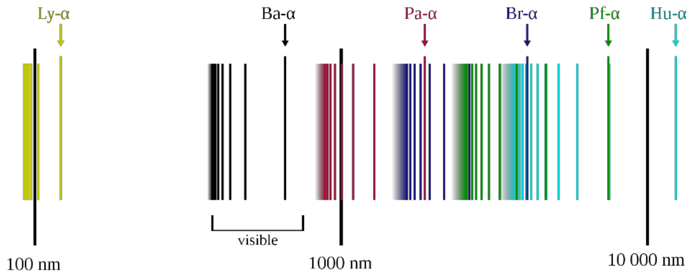
quantum mechanics arose from observations



Blackbody radiation problem

Photoelectric effect



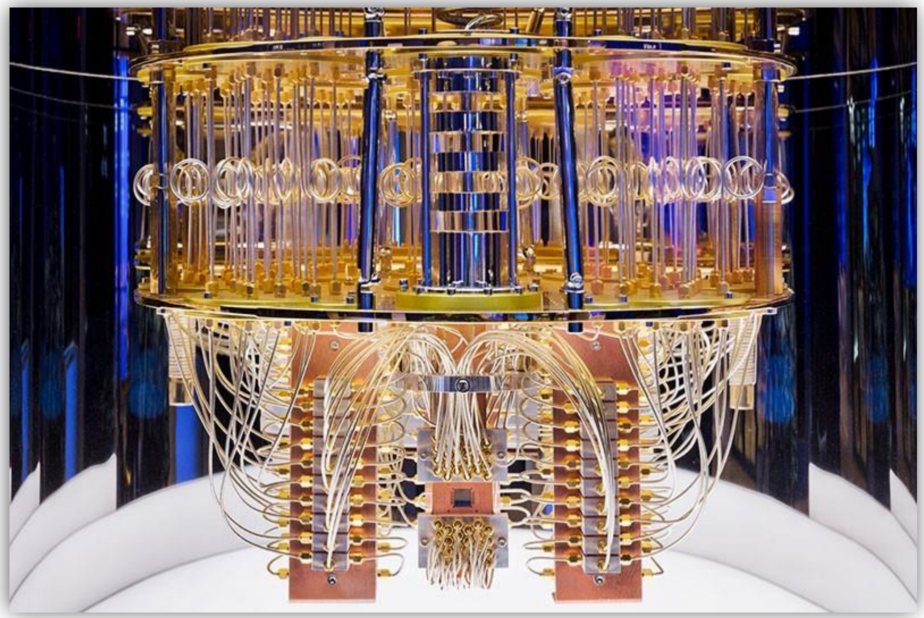


Spectral lines

Foundations of quantum mechanics: 1900—1925

Quantum computation: 1980+

(Benioff, Feynman, Manin, Deutsch, …)



all aboard the hype train