CSCI3350 Introduction to Quantum Computing (2026 Spring)

Intermezzo: A Philosophical Discussion

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(Nothing from this lecture will be tested on quizzes or exams!)

Why the Four Postulates?

— “You cannot keep asking why.”

Inherent Tension for CS-oriented Quantum Computing

Tension: limited time for underlying quantum mechanics.

- Pedagogical stance: adopt an axiomatic approach.
- Core idea: accept the four postulates as the foundation.

Why an Axiomatic Approach?

Reason 1: Breadth vs. Time

- Many quantum computing topics to cover.
- Finite lecture time prevents deep QM detours.

Reason 2: Limits of Understanding

- Humanity does not fully understand the "why" behind QM.
- Physicists (only) know what it predicts and how to apply it.
- But the postulates' ultimate justification remains an open question about reality's structure. (More discussion later: interpretations of quantum mechanics.)

Our Approach in This Course

The focus of this course:

- Provide "evidences"/"rationales" to make the four postulates feel reasonable.
- Goal: help you become comfortable working with the postulates.
- Honest boundary: this is the best we (and modern physics) can presently do.

Suggested Viewing: Feynman on Boundaries of Explanation

Watch: Interview with Richard Feynman (14:54–22:27)

- Theme: respecting the limits when probing "what really happened."
- Takeaway: why we accept the four postulates as foundational for quantum computing without demanding deeper "whys" in this course.

Who is Richard Feynman?

Richard P. Feynman (1918–1988) was an American theoretical physicist known for his path integral formulation of quantum mechanics, development of quantum electrodynamics (for which he shared the 1965 Nobel Prize in Physics), and the invention of Feynman diagrams. He was also a renowned educator, author of the Feynman Lectures on Physics, and a pioneer in articulating the idea of quantum computation.

Beyond the Clip

- The full one-hour interview is engaging and inspiring.
- Valuable for creativity, curiosity, and research in any field.
- Recommended if you have time: watch the entire interview.

Summary

In summary:

- We adopt the four postulates to build quantum computing rigorously.
- We will motivate and illustrate them as far as current understanding allows.
- Deeper “why” questions touch active frontiers of physics.

Interpretations of Quantum Mechanics

Acknowledgement: Materials presented here are mostly based on Lecture 12 of Scott Aaronson's Introduction to Quantum Information Science Lecture Notes.

Stepping Back

We are always wondering: *What is quantum mechanics telling us about reality?*

- No universal consensus; many positions evolved alongside breakthroughs in QM.
- Knowing the major viewpoints is useful (Bell inequality, quantum computing as examples).

The Weirdness of Measurement

Recall the following postulates:

- **Postulate 2:** $|\psi\rangle \mapsto U|\psi\rangle$.
- **Postulate 3:** upon measurement, state collapses to outcome $|i\rangle$ with probability $|\langle\psi|i\rangle|^2$.

A fundamental weirdness:

- QM seems deterministic, reversible, and continuous *most of the time* (Postulate 2).
- However, **Postulate 3** is an exception:
  - probabilistic, irreversible, discontinuous.

Interpreting Quantum Mechanics

Central Question

How does the universe know when to apply unitary evolution and when to apply measurement?

Different interpretations were proposed:

- Debates over the "correct" interpretation have persisted for over 100 years.
- Often compared to debates about consciousness: easy to talk in circles.[1]
- Nonetheless valuable to understand the main schools of thought.

[1] It is easy for the discussion to become repetitive and self-referential without making progress or reaching a clear conclusion. People keep revisiting the same points, often because key terms are not well-defined or there is no decisive evidence to settle the issue.

Outline

Today's agenda:

1. Copenhagen Interpretation
2. Thought Experiments
    - E.g., Schrödinger's Cat
3. Dynamical Collapse
4. Many-Worlds Interpretation

(1/4) Copenhagen Interpretation

Copenhagen Interpretation — Core Ideas

- Associated with Bohr, Heisenberg; hard to pin down precisely.
- Two domains:
  - Classical world: definite states, records, “we live here.”
  - Quantum world: superpositions, amplitudes, unitary dynamics.
- Measurement bridges domains; requires classical description to report outcomes.
- The “cut” (boundary) is fuzzy, context-dependent; don’t force classical concepts across it.

Copenhagen — Benefits and Critiques

Benefits:

- Pragmatic: aligns with lab practice; predicts experiments well.
- Conceptual caution: avoids reifying classical intuitions where they fail.

Critiques:

- Fuzzy, moving boundary; collapse not derived from dynamics.
- As macroscopic superpositions become feasible, "quarantining" QM becomes less viable.
- Rhetorical stance ("problem is you, not QM") doesn't satisfy scientific realism.

Copenhagen and "Shut Up and Calculate" (SUAC)

- Close cousin to Copenhagen; drop the philosophy, keep the predictions.
- Widely used by practitioners (physicists, chemists, engineers).
- Practical advantages clear—yet curiosity and scale-up pressure remain:
  - As QM impinges on everyday-scale phenomena, meaning matters.

(2/4) Thought Experiments

Schrödinger's Cat: Historical Context

- In the 1920s–30s, some physicists (notably Einstein and Schrödinger) rejected a rigid Copenhagen divide between quantum and classical worlds.
- They proposed thought experiments to show how untenable a sharp boundary is.
- The most famous: Schrödinger's Cat.

Macroscopic Systems as Quantum Superpositions

Einstein suggested modeling an inherently unstable system (e.g., gunpowder) as a quantum superposition:

$$\frac{|\text{intact}\rangle + |\text{exploded}\rangle}{\sqrt{2}}$$

Schrödinger's twist: what if we create a state that's a superposition where *one branch has a live cat and the other a dead cat*?

$$\frac{1}{\sqrt{2}}\left(|\text{cat alive}\rangle + |\text{cat dead}\rangle \right)$$

He isolates the cat from the environment by sealing it in a box (idealization).

Point of the Thought Experiments

The main point of these thought experiments:

- The formal rules of QM apply whenever there are distinguishable states, regardless of size.
- This means that, in principle, one can form arbitrary linear combinations (superpositions) of such states—even for macroscopic systems like cats.
- Therefore, Copenhagen's rigid boundary between the quantum and classical worlds is **untenable**.

Critiques to Schrödinger's Cat

The main critique:

- If we refuse to ascribe any pre-measurement reality, we approach extreme **solipsism** (e.g., "the cat only exists once we open the box").

Solipsism is the philosophical position that only one's own mind is certain to exist; everything else—other people, the external world, even the past—could be merely experiences or constructions within one's consciousness. In its strongest form, solipsism claims that there is no meaningful sense in which anything beyond the self exists independently.

(3/4) Dynamical Collapse Theories

Dynamical Collapse

Core Idea: Large systems undergo spontaneous, objective collapses to classical outcomes with Born probabilities.

$$\sum_i \alpha_i |i\rangle \longrightarrow |i\rangle \quad w.p. \quad |\alpha_i|^2.$$

- For example, cat-like superpositions rapidly become classical probability mixtures:

$$\frac{1}{\sqrt{2}}(|\text{alive}\rangle + |\text{dead}\rangle) \longrightarrow \begin{cases} w.p. \ \frac{1}{2} & |\text{alive}\rangle \\ w.p. \ \frac{1}{2} & |\text{dead}\rangle \end{cases}$$

Advantage: In principle, this theory is experimentally testable—making potentially falsifiable claims is what enables us to move these discussions from the realm of philosophy to science.

Collapse Triggers — Proposals and Tensions (1/2)

- Candidate triggers:
  - Number of atoms involved
  - Total mass threshold
  - "Complexity" threshold
- Reductionist worry: elementary dynamics should not depend on system size or complexity.
- Experimental trend: increasingly macroscopic superpositions (pushes thresholds upward).

Collapse Triggers — Proposals and Tensions (2/2)

Representative proposals to resolve the tensions:

- Ghirardi–Rimini–Weber (GRW) theory: more on subsequent slides.
- Penrose[2] Theory: collapse is due to general-relativity effects involving large mass and distance. (We will skip this theory.)

[2] Richard Penrose (b. 1931) is a British mathematical physicist known for foundational work in general relativity and cosmology—especially singularity theorems with Stephen Hawking, twistor theory, and contributions to black hole physics—for which he shared the 2020 Nobel Prize in Physics. He has also advanced ideas at the physics–philosophy–mathematics interface, including arguments that human consciousness and mathematical insight are non-algorithmic, and proposals (with Hameroff) linking quantum gravity–related objective reductions to consciousness.

Ghirardi–Rimini–Weber Theory (1/2)

Core Idea: Each microscopic constituent (e.g., an atom) has a tiny probability per unit time to collapse. A single collapse in an entangled macroscopic system can drive the **entire** system to a definite outcome.

- Consider the following entangled state:

$$\frac{|0\cdots 0\rangle + |1\cdots 1\rangle}{\sqrt{2}}$$

- Measuring just **one** qubit collapses <u>all</u> qubits to either $|0\cdots 0\rangle$ or $|1\cdots 1\rangle$.
- GRW uses spontaneous collapse (not a measurement) to produce a similar effect in macroscopic systems.

Ghirardi–Rimini–Weber Theory (2/2)

Scaling With System Size:

- Per-atom collapse probability is minuscule.
- But macroscopic objects contain $\sim 10^{23}$ atoms (e.g., a typical cat).
- Probability that **at least one** atom collapses soon becomes overwhelming.

Consequence

Larger systems have much **shorter** expected coherence times; Schrödinger's "cat states" are inherently unstable in GRW.

Experimental Pressure on Collapse Views

As scale grows, collapse theories must either predict deviations or risk ad hoc parameter tuning:

- Larger interference demos:
  - 1999: double-slit experiment with molecules with C_{60} atoms and hundreds of electrons.
  - 2019: same experiment with organic molecules with ~ 2000 atoms.
- Superconducting flux qubits: superpositions of clockwise vs. counterclockwise currents in micrometer loops (billions–trillions of electrons).

Favored by quantum computing skeptics?

- Dynamical Collapse seems to imply that a complex quantum computer would not work because quantum systems spontaneously collapse after they achieve "sufficient complexity" (whatever that means).

(4/4) Many-Worlds Interpretation

Many-Worlds Interpretation (MWI) — Core Picture

- Universal wavefunction $|\Psi\rangle$ evolves <u>only</u> unitarily; no fundamental collapse.
- Measurement = entanglement and amplification into environment/observer states:

$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\,|\text{You}\rangle \;\mapsto\; \frac{1}{\sqrt{2}}\big(\,|0\rangle\,|\text{You}_0\rangle + |1\rangle\,|\text{You}_1\rangle\,\big).$$

- "Branching": you and the environment split into effectively non-interfering histories; both branches are <u>equally real</u>.

Historical note: MWI was first proposed by Hugh Everett III in 1957, who was then a PhD student at Princeton working under John Archibald Wheeler. Wheeler told Everett to remove from his paper all references to the physical reality of parallel worlds, because Bohr and his friends had strenuously objected to the idea. Everett did so, and partly as a result it took 15 years for the rest of the physics community to rediscover Everett's proposal and understand what it meant.

Branching and Thermodynamics

MWI seems to be consistent with our current knowledge of thermodynamics:

- Constant proliferation of branches with near-zero recombination resembles the Second Law of Thermodynamics (i.e., entropy increase).
- If the universe had finitely many qubits (e.g., 10^{122}), branches could re-collide—but not for fantastically long times (e.g., $\gg 10^{100}$ years).
- In principle, "unmeasure" by $U^\dagger$; But practically infeasible (like unscrambling eggs), as it is disfavored by the Second Law of Thermodynamics.

Critiques for MWI (1/2)

If MWI is true, where do probabilities come from?

- We need $|\alpha|^2, |\beta|^2$ for $\alpha|0\rangle + \beta|1\rangle$—not just "sometimes 0, sometimes 1."

There are some modern efforts trying to answer this questions. but we will not go over them.

Critiques for MWI (2/2)

If MWI is true, in what basis does branching occur?

- $\{|\text{alive}\rangle, |\text{dead}\rangle\}$ vs. $\{\frac{|\text{alive}\rangle+|\text{dead}\rangle}{\sqrt{2}}, \frac{|\text{alive}\rangle-|\text{dead}\rangle}{\sqrt{2}}\}$.

Efforts to answer this question—Decoherence theory:

- environment selects stable "states" that are robust to interaction. E.g., if you poke an $|\text{alive}\rangle$ or $|\text{dead}\rangle$ cat, it will not change its status dramatically. But that's not true for a $(|\text{alive}\rangle + |\text{dead}\rangle)/\sqrt{2}$ cat.
- Similarly, an event has "definitely happened" only if there exist many records of the event spread through the environment, so that it's no longer feasible to erase them all.
- Like putting an embarrassing picture on Facebook: If only a few friends share it, you can still take it down. But if the picture goes viral, then it becomes impossible to delete all the copies.

Comparative Summary — Ideas and Critiques

Copenhagen/SUAC

- Ideas: Two domains; measurement bridges; classical descriptions necessary; operational success prioritized.
- Critiques: Fuzzy boundary; collapse primitive; rhetorical deflection; struggles as macroscopic superpositions proliferate.

Dynamical Collapse

- Ideas: Objective collapses for large systems.
- Critiques: Parameter tuning; reductionist tension; experiments keep pushing macroscopic coherence; need concrete, falsifiable scales.

Many-Worlds + Decoherence

- Ideas: Only unitary evolution; branching via entanglement; decoherence picks pointer basis; entropy growth explains effective irreversibility.
- Critiques: Born rule justification debated; preferred basis requires decoherence story; no distinct empirical signature (so far).

Just for Fun!

To further pique your interest, the film *Oppenheimer* in 2024 is (at least slightly) related to quantum mechanics. You are encouraged to watch it.

Here is a a short clip from that move,[3] where you will see a few familiar names we have just mentioned in this lecture.

[3] This link is password-protected so that only the instructor can play it during the lecture.