

Quantum Computing & Quantum Mechanics [Foundations]

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Core Concepts:

- Classical vs. quantum information processing
- Quantum numbers and electron behavior
- Superposition and wave function collapse
- Quantum entanglement properties and applications
- Real-world quantum technologies

Why Should We Care About Quantum?

Imagine a computer that could break every password on Earth in minutes, discover new life-saving drugs by simulating molecules atom by atom, or solve traffic problems for entire cities simultaneously. This isn't science fiction—it's the promise of quantum computing. But to understand why these machines might

revolutionize everything, we first need to dive into one of physics' most mind-bending discoveries: quantum mechanics.

Part I: The Classical Foundation and Its Limits

What Classical Computers Do Well

Our current computers, even the most powerful supercomputers, operate on surprisingly simple principles. They use binary bits—information that's either 0 or 1, like a light switch that's either off or on. These classical machines excel at:

- Following precise, predictable rules
- Processing information sequentially (one calculation after another)
- Handling everyday problems with remarkable speed and accuracy

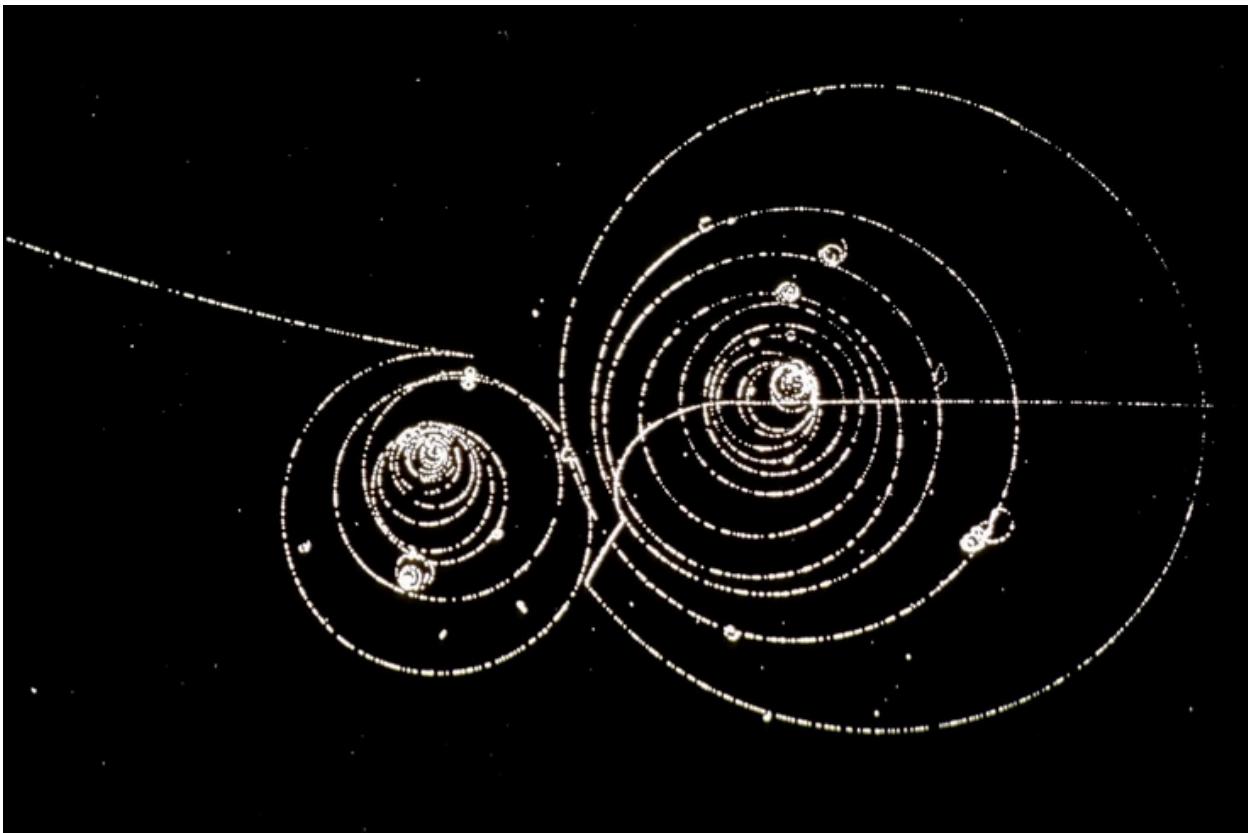
But here's where things get interesting: classical computers share more with quantum computers than you might expect. Both rely on printed circuit boards, electronic circuits, computer chips, and algorithm-based operations. The revolutionary difference lies not in their hardware foundations, but in how they process information.

Where Classical Physics Breaks Down

For centuries, Newton's classical mechanics seemed to explain everything. Objects followed predictable paths, cause and effect ruled supreme, and if you knew a system's initial conditions perfectly, you could predict its future with certainty. This worldview worked beautifully for everything we could see and touch.

Then scientists started looking closer—much closer. At the scale of atoms and subatomic particles, Newton's clockwork universe completely fell apart. Particles didn't follow predictable paths. They seemed to exist in multiple states simultaneously. Measuring them changed their behavior. The very act of observation altered reality.

This breakdown wasn't a failure of science—it was the discovery of something far stranger and more powerful than anyone had imagined.



Part II: Fundamental Quantum Mechanics Concepts

From Classical → Quantum Physics

The New Rules of Reality

Quantum mechanics emerged as the mathematical language needed to describe this bizarre microscopic world. Think of it as nature's instruction manual for photons, protons, neutrons, and electrons—particles that refuse to follow classical rules.

What makes quantum mechanics so counterintuitive? Richard Feynman, the Nobel laureate who helped develop the field, captured it perfectly:

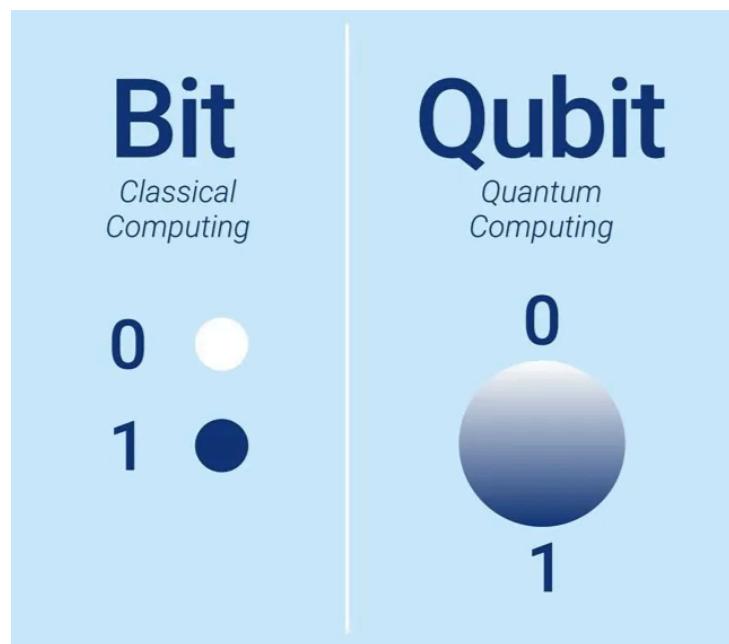
If you think you understand quantum mechanics, you don't understand quantum mechanics.

Even today, physicists can use quantum mechanics with incredible precision while still puzzling over what it all means.

The Quantum Bit Revolution

This is where quantum computing enters the picture. While classical computers use bits that are definitively 0 or 1, quantum computers use quantum bits—qubits—that can exist as 0, 1, or both simultaneously.

Rather than thinking of a classical bit as a coin lying flat (heads or tails), imagine a qubit as a coin spinning in the air. While it spins, it's neither heads nor tails—it's both possibilities at once. Only when it lands (when we measure it) does it "choose" a definite state.



Part III: Superposition - The Heart of Quantum Advantage

Wave Functions and Probability Clouds

Every quantum particle is described by something called a wave function—essentially a mathematical description of all the particle's possible states and the probability of finding it in each state. An unmeasured electron doesn't have a definite position or spin direction; instead, it exists as a probability cloud of all possible states.

This isn't just theoretical uncertainty—it's fundamental to how quantum systems work. The electron literally exists in superposition until something forces it to "collapse" into a definite state.

Wave Function Collapse: When Quantum Meets Classical

Here's where quantum mechanics gets truly strange. The moment you try to measure a quantum system—say, checking an electron's spin—the wave function collapses. The electron instantly transitions from being in all possible states simultaneously to having one definite state.

What triggers this collapse? Interaction with measurement apparatus, which essentially means any interaction with the classical, macroscopic world. This raises profound questions about the nature of observation and reality itself that physicists still debate today.

Computational Implications

For quantum computers, superposition means incredible parallel processing power. While a classical computer with three bits can represent one of eight possible combinations (000, 001, 010, etc.) at any given time, three qubits in superposition can represent all eight combinations simultaneously. As you add more qubits, this advantage grows exponentially—each additional qubit doubles the computational capacity.

Part IV: Quantum Numbers - Nature's Address System

Why Electrons Need Coordinates

Just as every house needs a unique address, every electron in an atom needs a unique set of coordinates. But instead of street addresses, electrons use quantum numbers. The Pauli Exclusion Principle ensures that no two electrons can have identical sets of all four quantum numbers—nature's way of preventing quantum traffic jams.

The Four Quantum Coordinates

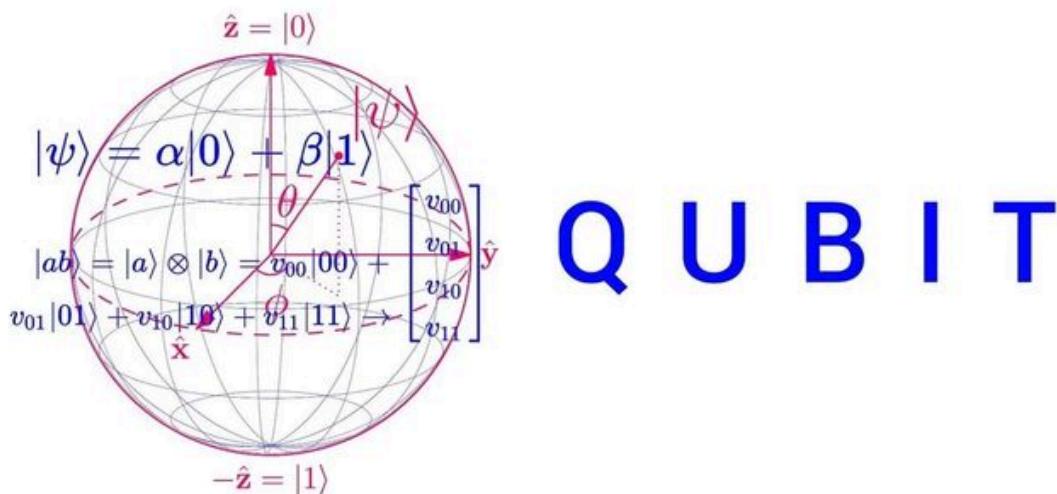
Principal Quantum Number (n): Think of this as the electron's "floor" in the atomic apartment building. Higher values mean the electron is farther from the

nucleus and has more energy.

Orbital Angular Momentum Quantum Number (ℓ): This determines the shape of the electron's "room"—whether it's spherical (s), dumbbell-shaped (p), or more complex geometries (d, f).

Magnetic Quantum Number (m_ℓ): This specifies which way the orbital points in space—like choosing which direction your room faces.

Electron Spin Quantum Number (m_s): The electron's intrinsic angular momentum, pointing either "up" (\uparrow) or "down" (\downarrow).



Connecting to Quantum Computing

Understanding these quantum numbers helps explain why quantum systems are so precisely controllable. Quantum computer designers manipulate these same fundamental properties—especially electron spin—to create and control qubits. The precision required is staggering: maintaining quantum states often requires temperatures colder than outer space and isolation from the tiniest vibrations.

Part V: Quantum Entanglement - The Ultimate Quantum Phenomenon

How Entanglement Forms

When two particles interact or are created together under specific conditions, something remarkable happens: their quantum properties become permanently linked. For electrons, this often occurs when they're generated in close proximity causing their spins to become entangled.

Once entangled, these particles remain connected in a way that defies classical intuition. They form what physicists call a correlated quantum system—a single entity described by one shared wave function, even when the particles are separated by vast distances.

The Properties That Shocked Einstein

Correlated Spins: Entangled electrons always exhibit opposite spins. If one spins up, the other spins down, guaranteed.

Maintained Superposition: Both electrons remain in superposition (spinning in all directions simultaneously) until one is measured.

Instantaneous Correlation: Here's the truly mind-bending part—measuring one electron immediately determines the other's state, regardless of distance. This happens faster than light could travel between them, which initially troubled Einstein so much he rejected the idea.

Distance Independence: Whether entangled particles are separated by millimeters or millions of light-years makes no difference. The correlation remains perfect and instantaneous.

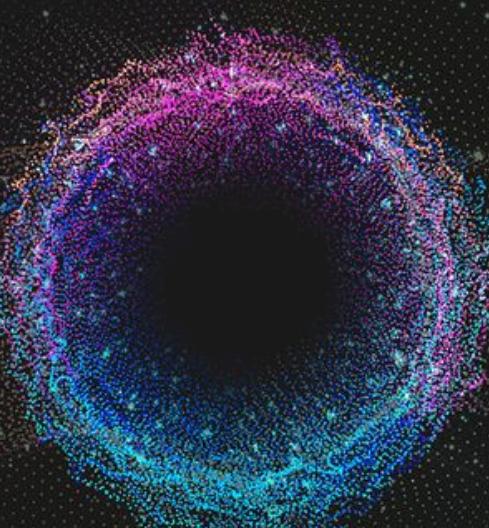
Why Einstein Called It "Spooky"

Einstein's discomfort with entanglement stemmed from its apparent violation of locality—the idea that objects are only influenced by their immediate surroundings. How could measuring an electron in New York instantly affect its partner near *Alpha Centauri*?

For decades, Einstein hoped that "hidden variables" would eventually explain away this spookiness. But experiments have repeatedly confirmed that entanglement is real, and there are no hidden variables. The universe really is this strange at its foundations.

QUANTUM ENTANGLEMENT AND THE SPOOKY ACTION AT A DISTANCE

Quantum entanglement is the physical phenomenon that occurs when a pair or group of particles is generated, interact, or share spatial proximity in a way such that the quantum state of each particle of the pair or group cannot be described independently of the state of the others, even when the particles are separated by a large distance.

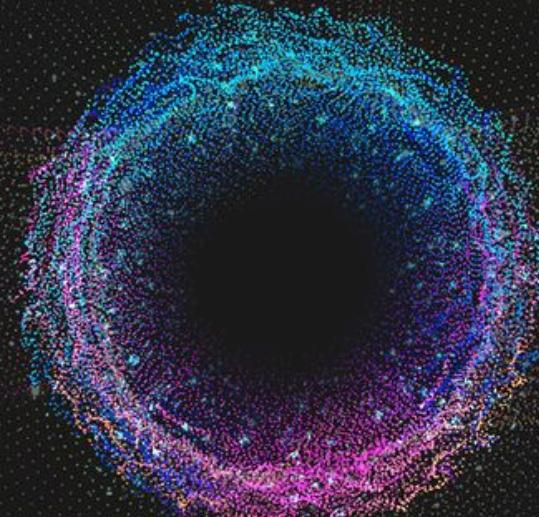


PARTICLE A

PHOTON

Quantum entanglement has been demonstrated experimentally with photons, neutrinos and electrons.

Measurements of physical properties such as position, momentum, spin, and polarization performed on entangled particles are found to be perfectly correlated.



PARTICLE B

THE EINSTEIN-PODOLSKY-ROSEN PARADOX

According to the theory of special relativity, instantaneous action at a distance violates the relativistic upper limit on speed of propagation of information. If one of the interacting objects were to suddenly be displaced from its position, the other object would feel its influence instantaneously, meaning information had been transmitted faster than the speed of light.

Einstein considered such behavior to be impossible, as it violated the local realism view of causality, thus referring to it as "spooky action at a distance".

OUTPUT 666

Part VI: Quantum Gates - The Building Blocks

From Classical to Quantum Logic

Classical computers use logic gates (AND, OR, NOT) to manipulate bits. Quantum computers use quantum gates that can create and manipulate superposition and entanglement. Unlike classical gates, quantum gates are reversible—you can always undo their operations, which is crucial for maintaining quantum information.

Common Quantum Gates

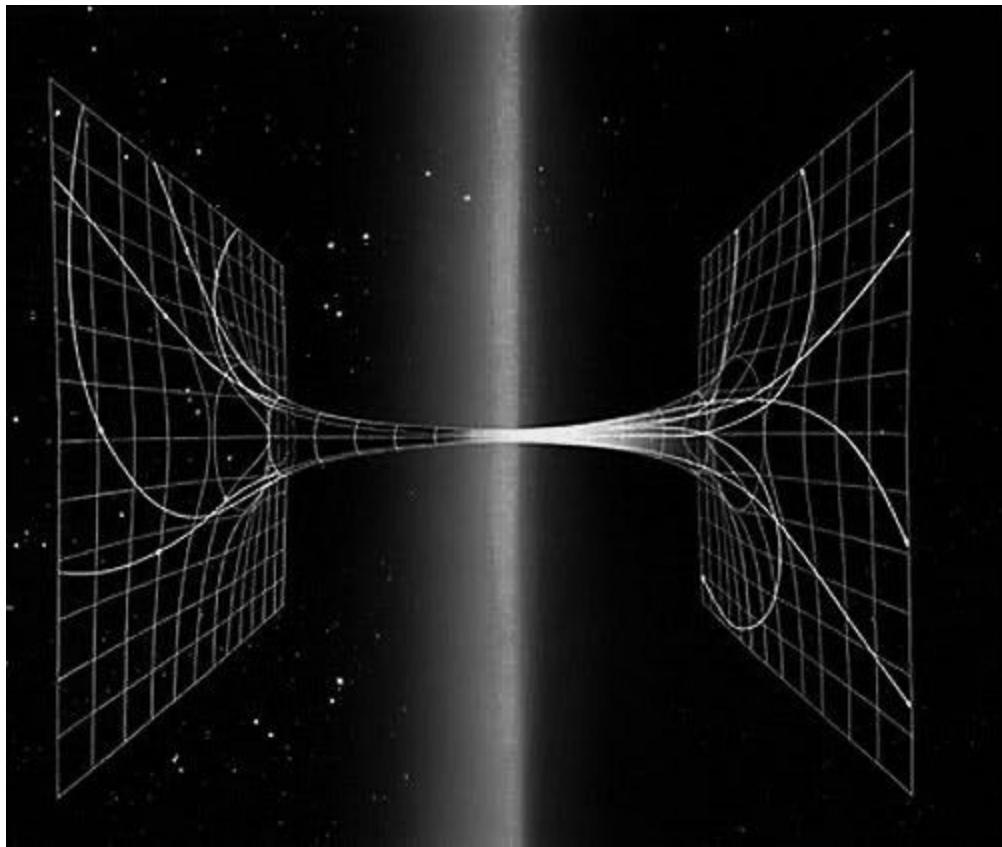
Pauli Gates: Flip qubit states or add phase shifts

Hadamard Gate: Creates superposition by putting qubits into equal probability states

CNOT Gate: Creates entanglement between qubits

Phase Gates: Manipulate the quantum phase without changing probabilities

These gates combine to form quantum circuits that can solve specific problems exponentially faster than classical approaches.



Part VII: Quantum Algorithms - Where Theory Meets Power

Shor's Algorithm: Breaking the Internet

Peter Shor's 1994 algorithm demonstrated that quantum computers could factor large numbers exponentially faster than classical computers. This matters because current internet security relies on the difficulty of factoring large numbers. A sufficiently powerful quantum computer running Shor's algorithm could break most current encryption in hours rather than millennia.

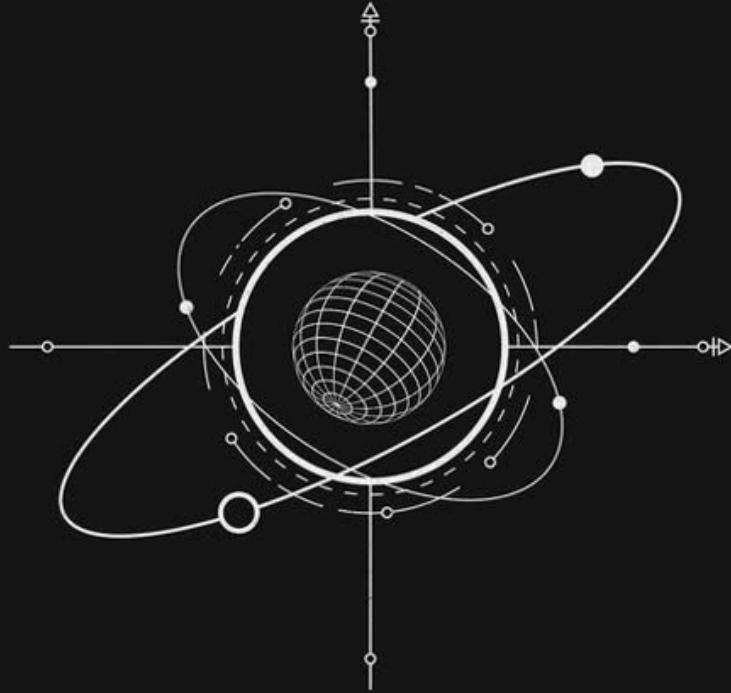
Grover's Algorithm: Searching the Unsearchable

Lov Grover's algorithm shows how quantum computers can search unsorted databases quadratically faster than classical computers. While this might sound modest, it represents a fundamental speedup for many optimization problems.

Current Limitations

Despite these theoretical advantages, we're still in quantum computing's early days. Current quantum computers are "noisy intermediate-scale quantum" (NISQ) devices that:

- Require extreme cooling (near absolute zero)
- Lose quantum coherence within milliseconds
- Have high error rates that increase with circuit complexity
- Can only run simple algorithms reliably



Part VIII: Real-World Applications and Current Progress

Quantum Cryptography in Action

The Switzerland case study from 2007 was just the beginning. Today, companies like ID Quantique, Toshiba, and others have deployed quantum key distribution networks for:

Government communications

Banking transactions

Critical infrastructure protection

Any attempt to eavesdrop on these quantum-encrypted channels immediately destroys the quantum states, alerting both parties to the security breach.

Beyond Communication

Drug Discovery: Quantum computers could revolutionize medicine by accurately simulating molecular interactions. Classical computers struggle with molecules containing just a few dozen atoms, but quantum computers could model complex proteins and design targeted therapies.

Financial Modeling: Portfolio optimization, risk assessment, and fraud detection all involve complex calculations that could benefit from quantum speedup.

Artificial Intelligence: Quantum machine learning algorithms might process and learn from data in entirely new ways, though this field is still largely theoretical.

The No-Cloning Theorem

One crucial limitation shapes all quantum applications, that is it's **impossible to create an exact copy of an arbitrary unknown quantum state**. In other words, you cannot build a quantum "photocopier" that perfectly duplicates any quantum information you feed into it.

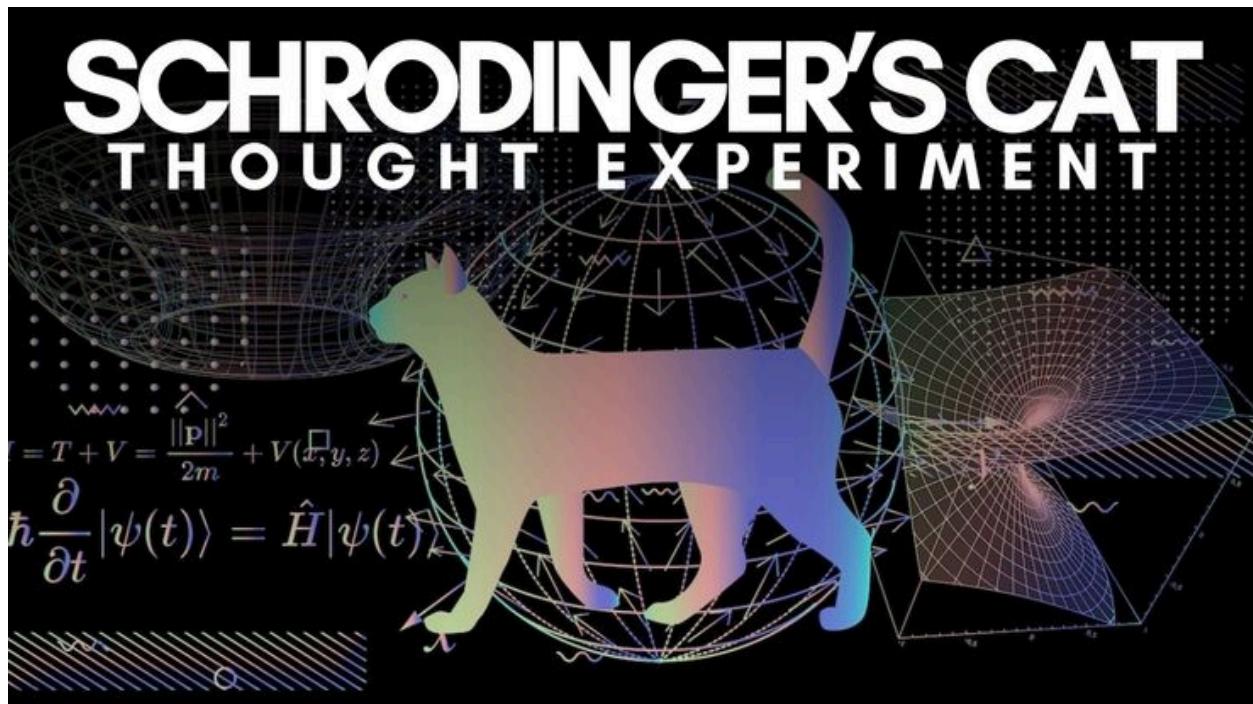
The theorem was proven by William Wootters and Wojciech Zurek in 1982. Here's the intuitive reasoning:

If you could perfectly clone a quantum state, you'd need to extract all the information about that state first. But quantum mechanics tells us that measuring a quantum system disturbs it—you can't read quantum information without changing it. Any attempt to "scan" the quantum state to copy it would destroy the original superposition. Although;

You CAN clone if you already know the state: If I tell you a qubit is in the $|0\rangle$ state, you can prepare as many copies as you want. The theorem only applies to *unknown* quantum states.

Classical information can still be copied: Once quantum information is measured and becomes classical (like the result "spin up"), that classical information can be copied normally.

Approximate cloning is possible: You can create imperfect copies, but never perfect ones.



Why This Matters?

The no-cloning theorem is what makes quantum cryptography unbreakable. Any eavesdropper trying to intercept and copy quantum-encrypted messages would necessarily disturb the quantum states, immediately alerting the legitimate parties.

Part IX: Quantum Decoherence - The Fragility Problem

Why Quantum States Don't Last

Quantum systems are incredibly fragile. The slightest interaction with the environment—a stray photon, a vibration, even cosmic radiation—can cause decoherence, destroying the delicate superposition and entanglement that quantum computers depend on.

Think of it this way: maintaining a quantum state is like trying to balance a pencil on its tip in a busy subway station. Every tiny vibration, air current, or bump threatens to knock it over. For quantum computers, that "pencil" is actually millions of quantum states that must remain perfectly balanced simultaneously.

The Scale of Environmental Threats

The sensitivity is almost unimaginable. Here's what can destroy quantum coherence:

Thermal Noise: At room temperature, particles move with enough energy to completely scramble quantum states within nanoseconds. This is why quantum computers operate at temperatures around 0.01 Kelvin—colder than the cosmic microwave background radiation of outer space.

Electromagnetic Interference: Even the Earth's magnetic field or radio waves from a cell phone miles away can disrupt quantum operations. The quantum processors must be shielded more thoroughly than military submarines.

Mechanical Vibrations: A truck driving past the building, footsteps in adjacent rooms, or even sound waves can shake the delicate quantum states apart. Some quantum computers are built on vibration-isolated platforms that can detect movements smaller than the width of a proton.

Cosmic Radiation: High-energy particles from space constantly bombard Earth. Even with atmospheric protection, these particles can randomly flip quantum states, introducing errors at unpredictable moments.

The Decoherence Timeline

Different quantum systems lose coherence at different rates:

- Superconducting qubits (used by IBM and Google): ~100 microseconds
- Trapped ion qubits: ~50 seconds
- Topological qubits (still experimental): potentially hours or days

To put this in perspective, 100 microseconds means quantum information survives about as long as it takes light to travel 30 kilometers. In computing terms, that's barely enough time for a few thousand quantum operations.

Why Quantum Computers Look So Strange

This environmental sensitivity explains why quantum computers look nothing like the sleek laptops or servers we're used to. Instead, they resemble bizarre scientific apparatus:

The Dilution Refrigerator: The heart of most quantum computers is a chandelier-like structure that gradually cools qubits through multiple stages. It looks like a golden chandelier because the copper components provide excellent thermal conductivity while the gold plating prevents oxidation that could introduce noise.

Massive Isolation Systems: The actual quantum processor—often smaller than a coin—sits at the center of a refrigeration system the size of a room. The bulk isn't for computing power; it's for protection. Layers of magnetic shielding, vacuum chambers, and vibration dampening surround the tiny quantum chip like a high-tech fortress.

Industrial Appearance: Quantum computers currently look more like experimental physics equipment than commercial computers because, essentially, that's what they are. Each machine requires:

- Industrial-grade cooling systems
- Specialized control electronics
- Extensive cabling for precise signal delivery
- Multiple layers of shielding and isolation

The Cabling Complexity: A single quantum computer might have thousands of carefully calibrated cables carrying microwave pulses to control individual qubits. These cables must be precisely temperature-controlled at each stage of the cooling system, creating the distinctive "quantum chandelier" appearance.

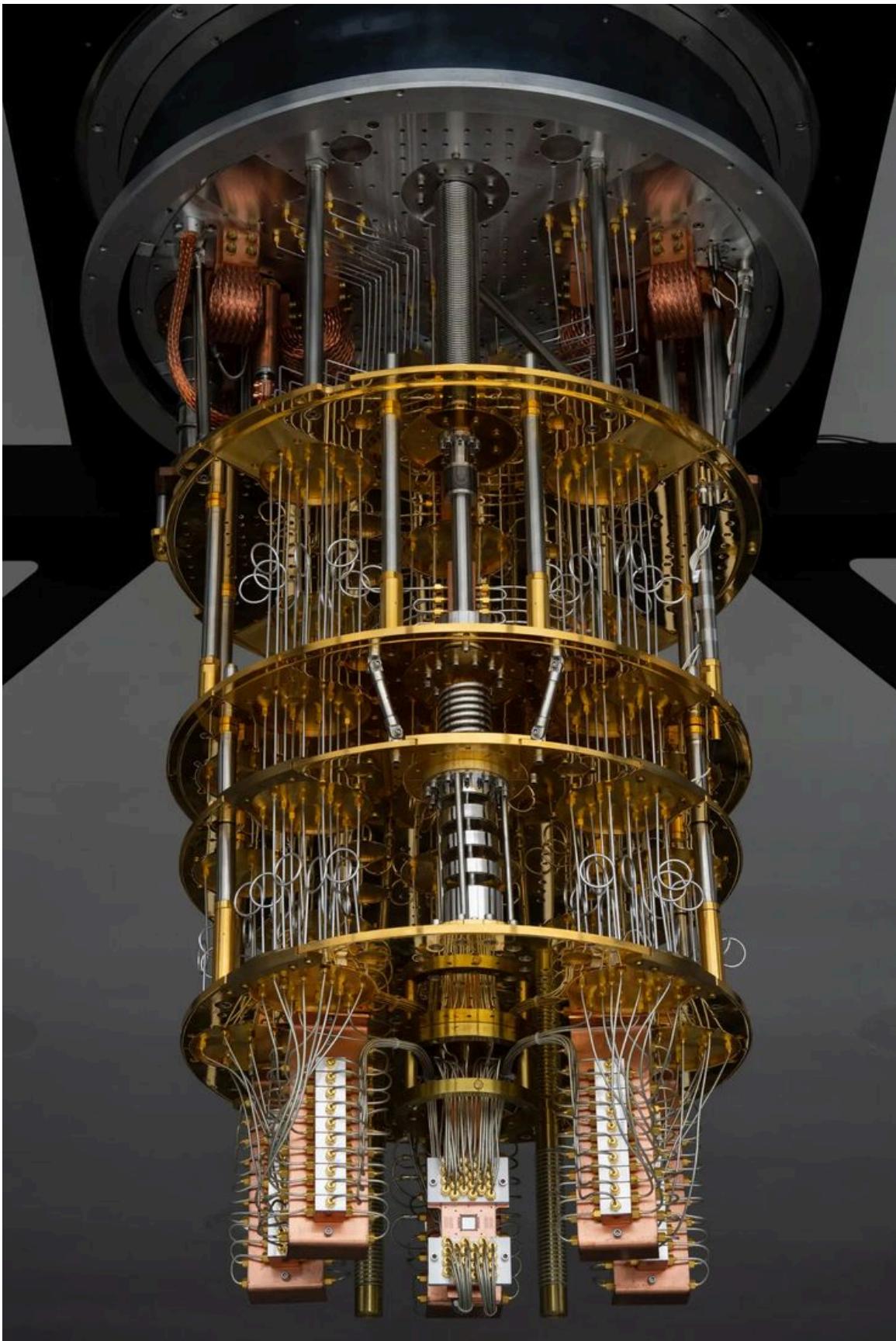
The Engineering Challenge

Maintaining quantum coherence isn't just about reaching extreme conditions—it's about maintaining them with incredible precision while still allowing for quantum operations. Engineers must:

- Cool systems to near absolute zero while precisely controlling microwave pulses

- Eliminate all electromagnetic noise while sending control signals
- Isolate from vibrations while allowing access for measurements
- Maintain vacuum conditions while running complex quantum circuits

This creates a fascinating paradox: to harness the most delicate quantum effects, we need some of the most robust and sophisticated classical engineering ever attempted.



Future Miniaturization

As quantum error correction improves and more stable qubit designs emerge, quantum computers will likely become smaller and more practical. But for now, the strange, room-sized appearance of quantum computers is a direct consequence of fighting against decoherence—nature's tendency to erase quantum information as quickly as possible.

Part X: Quantum Teleportation - Separating Fact from Fiction

What Quantum Teleportation Actually Does

Quantum teleportation doesn't transport matter—it transfers quantum information. Here's how it works:

1. Start with two entangled particles (Eminem has one, SlimShady has the other)
2. Eminem wants to send SlimShady the quantum state of a third particle
3. Eminem performs a special measurement on his particles
4. This measurement destroys the original quantum state but creates classical information
5. Eminem sends this classical information to SlimShady through normal channels
6. SlimShady uses this information to recreate the original quantum state in his particle

The original quantum state is destroyed in the process (satisfying the no-cloning theorem), but an exact copy appears at SlimShady's location. It's more like quantum cut-and-paste than Star Trek-style transportation.

Current Applications

Quantum teleportation enables secure quantum communication networks and is essential for distributed quantum computing, where multiple quantum processors work together on complex problems.

Part XI: The Bigger Picture and Future Outlook

Current State of the Field

We're in quantum computing's "transistor era"—similar to where classical computers were in the 1940s. Current quantum computers are proof-of-concept machines that demonstrate quantum effects but aren't yet practical for most real-world problems.

However, progress is accelerating. IBM, Google, IonQ, and others are building increasingly sophisticated quantum processors, while governments worldwide are investing billions in quantum research.

The Quantum Internet

Perhaps the most ambitious goal is a quantum internet—a network where quantum information can be transmitted globally while maintaining entanglement. This would enable:

- Unbreakable global communications
- Distributed quantum computing
- New forms of sensing and measurement
- Applications we haven't yet imagined

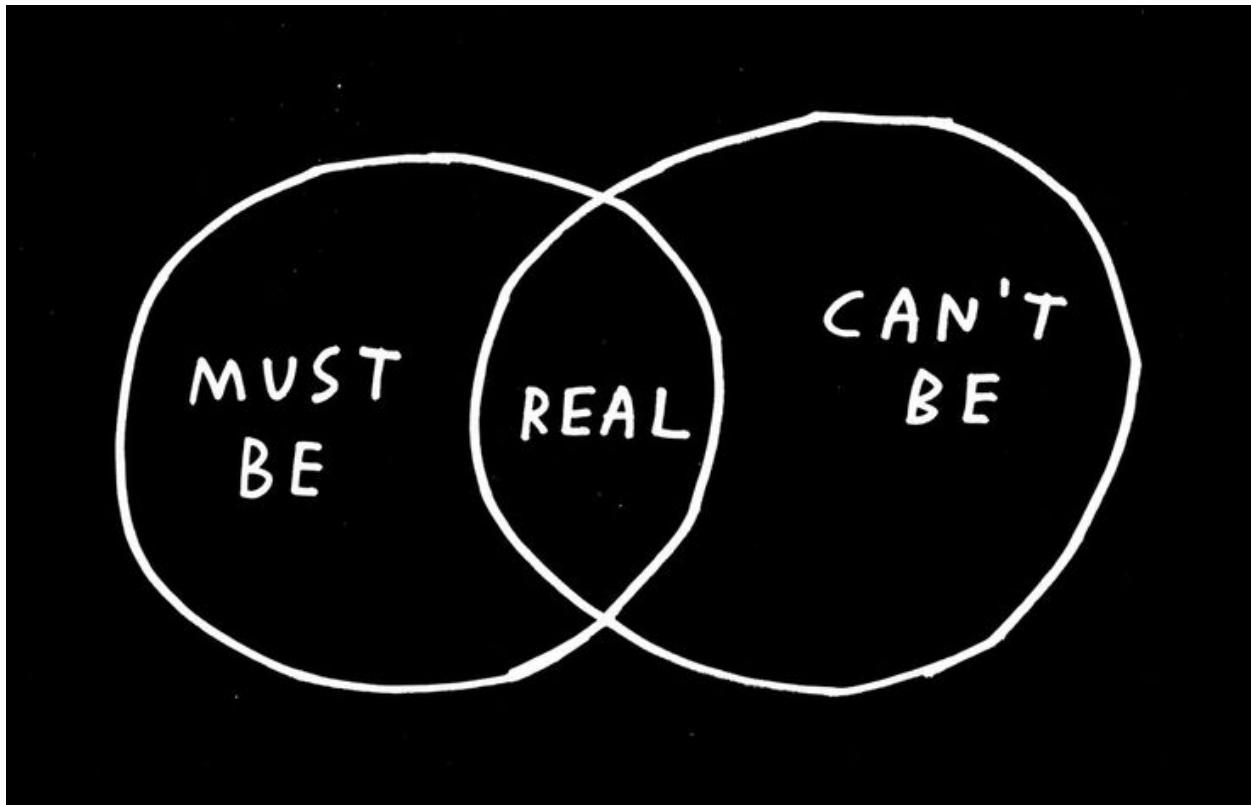
Why This Matters

Quantum mechanics challenges our fundamental assumptions about reality, causality, and information. Whether or not quantum computers eventually solve every problem we hope they will, they're already teaching us profound lessons about the nature of computation and the universe itself.

The field exemplifies something beautiful about science: the most practical technologies often emerge from the most abstract, seemingly useless discoveries. Who could have predicted that pondering the behavior of electrons would lead to technologies that might reshape cryptography, medicine, and artificial intelligence?

Final Reflection

As I've studied these concepts, what strikes me most is the elegant paradox at quantum mechanics' heart: the theories are mathematically precise and experimentally verified, yet they describe a reality that seems impossible. An electron really can be in multiple places simultaneously. Measurement really does change reality. Particles really can influence each other instantly across cosmic distances.



These aren't just abstract curiosities—they're the foundation for technologies that might define the next century. Understanding quantum mechanics doesn't just prepare us for future innovations; it expands our sense of what's possible in a universe far stranger and more wonderful than our everyday experience suggests.

The quantum world reminds us that reality is under no obligation to match our intuitions—and that's precisely what makes it so powerful.