

# Classical vs Quantum Computing: A Structured Guide

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## 1. Fundamental Principles: How Information is Represented

### Classical Computing: The Binary Foundation

Classical computers operate like incredibly fast light switches, storing every piece of information as either 0 or 1—like a coin that's always either heads or tails. When your phone stores a photo, it breaks that image down into millions of these binary digits. This is analogous to describing a painting using only black and white dots.

This binary approach has served us well for decades, creating the deterministic, predictable computing environment we rely on daily.

### Quantum Computing: The Superposition Revolution

Quantum computers fundamentally change this paradigm. They're like having coins that can be heads, tails, OR spinning in the air all at once—a phenomenon called "superposition." A quantum bit (qubit) can be 0, 1, or both simultaneously.

Consider solving a maze: classical computers try one path at a time, while *quantum computers can explore all paths simultaneously* until they collapse into the correct answer.

### The Quantum Mechanics Behind the "Magic"

The quantum computer doesn't literally "try" all paths, as generally presumed by the general consensus. Instead, it creates a sophisticated mathematical phenomenon involving four key processes:

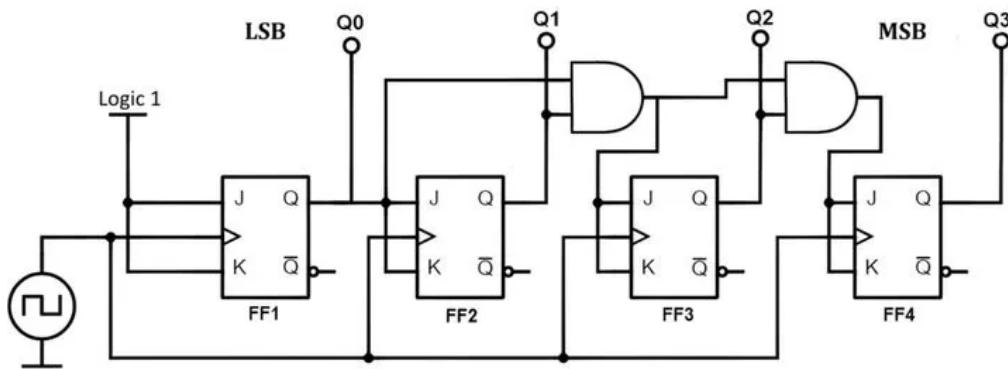
1. **Superposition:** The quantum system exists in a combination of all possible states simultaneously, like a wave with multiple peaks and valleys.
2. **Amplitude Assignment:** Each possible solution path receives a "probability amplitude"—a complex number determining the likelihood of that outcome when measured.
3. **Interference:** This is where quantum computing's true power emerges. The quantum algorithm manipulates these amplitudes so they interfere with each other:

- **Destructive Interference:** Wrong paths get amplitudes that cancel out, like waves perfectly out of sync
  - **Constructive Interference:** The correct path gets amplitudes that reinforce, creating a strong signal
4. **Measurement:** When you measure the result, you're most likely to get the correct answer because its amplitude is the largest after interference.

## 2. Algorithmic Thinking and Problem-Solving Approaches

### Classical Programming: Sequential Logic

Classical programming follows a familiar recipe-like structure: "First do this, then do that." It's sequential, logical, and deterministic. Run the same program twice with identical input, and you'll get identical output every time.



### Quantum Programming: Probabilistic Orchestration

Quantum programming is like conducting an orchestra where each musician plays all possible notes simultaneously until you listen—then they suddenly snap to a specific melody. Instead of instructions like "add A and B," you manipulate probability amplitudes and design interference patterns.

**Example:** Grover's algorithm for database searching doesn't check items sequentially like classical computers. Instead, it amplifies the probability amplitude of the correct answer while diminishing wrong answers, like tuning a radio to make one station clearer.

### Why Only Specific Problems Benefit from Quantum Computing?

This limitation is crucial and often overlooked. Quantum advantage requires specific mathematical structures:

**The Interference Requirement:** Problems must allow useful interference patterns where you can:

1. Represent all possible solutions as quantum states
2. Design operations that systematically reduce wrong answers' amplitudes
3. Exploit patterns in the "wrongness" of answers

#### Problems Well-Suited for Quantum Computing:

- **Database Search (Grover's Algorithm):** All wrong answers are equally wrong, enabling uniform amplitude reduction
- **Factoring (Shor's Algorithm):** Multiplication's mathematical structure creates exploitable patterns in quantum Fourier transforms
- **Optimization:** Solution quality can be encoded into amplitudes

#### Problems Poorly-Suited for Quantum Computing:

- **Sorting Lists:** No interference setup helps—elements must be compared individually

- **Sequential Text Processing:** Meaning emerges from order, not parallel amplitude manipulation
- **Everyday Computing Tasks:** Displaying pixels, handling user input, running apps—none benefit from superposition

The constraint is mathematical: interference only works when problems naturally translate into "waves with phases that can cancel or reinforce." Using quantum computing for unsuitable problems is like using a tuning fork to hammer nails.

### 3. The Probabilistic Nature: Why Run Algorithms Multiple Times?

Quantum computation's probabilistic nature requires multiple executions for reliable results.

#### The Probability Challenge

Even perfectly functioning quantum algorithms produce probabilistic outputs. For example, Grover's algorithm might yield:

- 85% chance of the correct answer
- 15% chance of wrong answers (distributed among all incorrect options)

#### Why Probabilities Persist

After interference, the correct answer has the largest amplitude, but rarely 100%. Some wrong answers retain small amplitudes that didn't perfectly cancel. Quantum measurement produces probabilities based on amplitude squares.

#### The Multiple Runs Strategy

- **Run 1:** Wrong answer (15% probability occurred)
- **Run 2:** Correct answer (85% probability occurred)
- **Run 3:** Correct answer again

After three runs, the answer appearing twice is likely correct.

#### Benefits of This Approach

- Confidence increases exponentially with repeated correct results
- Wrong answers appear randomly and won't repeat consistently
- The correct answer emerges most frequently
- Helps catch errors from environmental noise, imperfect quantum gates, and measurement errors

**Real Example:** Searching 1 million items:

- Classical: 500,000 operations (guaranteed)
- Quantum: 1,000 operations per run × 3 runs = 3,000 operations (still vastly superior)

### 4. Physical Implementation: Hardware Requirements

#### Classical Computing: Room Temperature Efficiency

Classical computers operate at room temperature using silicon chips where electrons flow through transistors like cars on highways. Modern processors contain transistors smaller than viruses, demonstrating decades of successful miniaturization.

#### Quantum Computing: Extreme Environmental Demands

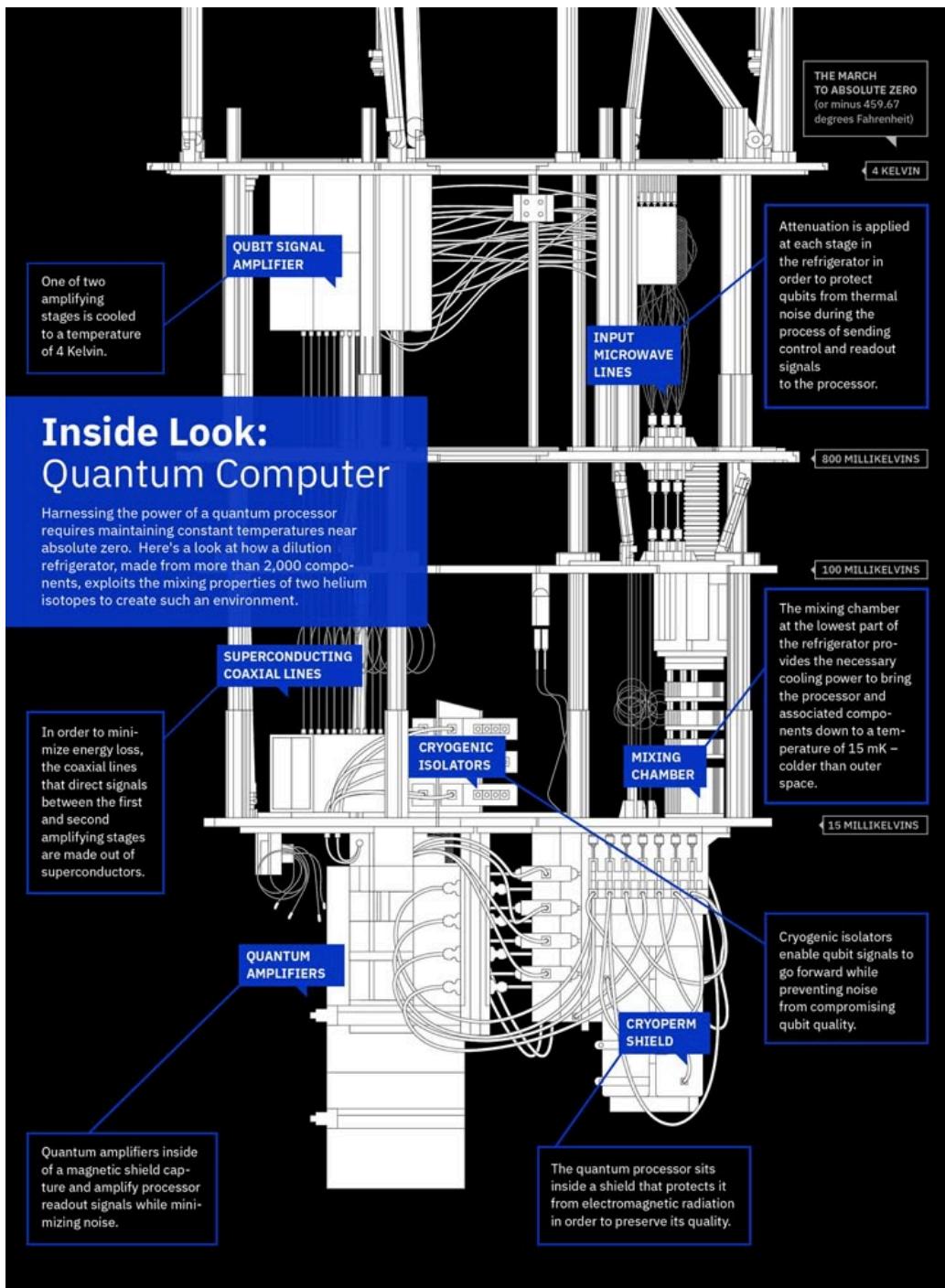
Quantum computers require temperatures colder than outer space—approximately -273°C, mere fractions above absolute zero.

## The Temperature Reality

- **Absolute Zero:** -273.15°C (0 Kelvin)—the theoretical lowest possible temperature
- **IBM's Quantum Computers:** ~0.015 Kelvin (-273.135°C), only 0.015 degrees above absolute zero
- **Google's Quantum Computers:** ~0.010 Kelvin (-273.140°C), even closer to absolute zero

These temperatures are:

- Colder than anywhere naturally occurring in the universe
- Colder than cosmic microwave background radiation
- Among the coldest places humans have ever created
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## Infrastructure Requirements

IBM's quantum computers operate within dilution refrigerators resembling golden chandeliers. Quantum states are so delicate that even a single heat photon can destroy computations. The quantum processor itself might be tiny, but the cooling system fills entire rooms—like needing a warehouse-sized air conditioner to keep an ice cube frozen.

*Extended Detail(s): The Apollo Guidance Computer (AGC) that took humans to the moon in 1969 had a 43 kHz processor (0.043 MHz), 32 KB RAM, and 72 KB storage, weighing 70 pounds and costing \$150,000 (\$1.2 million today). A modern smartphone has a 3.25 GHz processor (75,000x faster), 12-16 GB RAM (375,000x more), 256 GB-1 TB storage (2 millionx more), weighs 200 grams, and costs \$800-1,200. Even budget Android phones demolish the AGC's specifications.]*

## 5. Error Models and System Stability

### Classical Computing: Predictable and Correctable

Classical computer failures are generally understandable—memory exhaustion, software bugs, or rare cosmic radiation bit-flips. When errors occur, they can typically be detected and corrected through established methods.

### Quantum Computing: Fragile Quantum States

Quantum computers are like balancing pencils on their tips while blindfolded during earthquakes. Quantum states are extraordinarily fragile; simply observing them incorrectly destroys computations through "decoherence." Current quantum computers maintain quantum states for only microseconds before environmental noise disrupts everything.

**Error Correction Approach:** IBM employs error correction codes where multiple physical qubits collaborate to create one "logical" qubit with enhanced stability—like a choir where individual singers' mistakes don't destroy the overall harmony.

## 6. Scalability and Current Accessibility

### Classical Computing: Universal Accessibility

Classical computing has achieved remarkable scalability, from smartphones to supercomputers. The computing power in your pocket exceeds what NASA used for moon landings. Supply chains are mature, components standardized, and business models well-established.

### Quantum Computing: Exclusive and Experimental

Today's quantum computers resemble room-sized computers from the 1940s. IBM, Google, and others provide cloud access to quantum machines, but we're in the "cathedral" phase—expensive, specialized, and requiring PhD-level expertise.

**Current Reality:** IBM's largest quantum computer has approximately 1,000 qubits, but useful algorithms will require millions of error-corrected qubits.

## 7. Application Domains and Use Cases

### Classical Computing: Versatile Generalists

Classical computers are incredibly versatile Swiss Army knives, running Netflix, managing bank transactions, controlling traffic lights, and simulating weather. They excel at sequential tasks and user interfaces.

### Quantum Computing: Specialized Surgeons

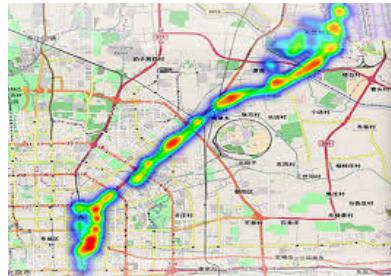
Quantum computers will excel in specific domains:

- **Drug Discovery:** Simulating molecular interactions (companies like Roche are already exploring this)
- **Cryptography:** Breaking current encryption methods
- **Financial Modeling:** Optimizing portfolios with thousands of variables
- **Logistics:** Solving complex routing problems

### Case Study: Volkswagen's Quantum Traffic Optimization

During Web Summit 2019 in Lisbon, Volkswagen successfully deployed quantum routing for nine public transit buses operating as "Quantum Shuttle," serving 26 stops between the airport and downtown conference venue. The quantum algorithm calculated the fastest route for each individual bus and optimized it in near real-time, assigning each bus an individual route to drive around traffic bottlenecks before they formed.

*[Extended Detail: Web Summit 2019 (November 4-8) brought tens of thousands of attendees to Lisbon, creating significant stress on the city's transit services. The quantum system used D-Wave quantum computers for calculations, with optimization delivered through tablets in every bus. This represented the first real-world demonstration of quantum computing for traffic optimization during a major international event, proving quantum algorithms could handle real-time logistics with dynamic variables including changing traffic conditions, passenger demand, and multiple optimization criteria.]*



## 8. Industry Economics and Investment Landscape

### Classical Computing: Mature Infrastructure

The classical computing industry operates on established trillion-dollar highways with mature supply chains, standardized components, and proven business models. Companies like Intel, AMD, and TSMC have perfected mass production of millions of identical chips.

### Quantum Computing: Modern Gold Rush

The quantum industry resembles the early internet era—abundant venture capital, bold promises, and uncertainty about eventual winners. Major investments include:

- **China:** \$15 billion national quantum initiative
- **European Union:** €1.1 billion Quantum Flagship program
- **United States:** National Quantum Initiative Act

**Investment Reality:** Despite massive funding, most quantum startups remain in the "research with potential" stage rather than delivering commercially viable products that outperform classical computers.

## 9. User Experience and Interface Design

### Classical Computing: Intuitive Human-Computer Interaction

Classical computers evolved to match human thinking patterns—desktop metaphors, files, folders, and clear cause-and-effect relationships. Click a button, see an immediate result.

### Quantum Computing: Alien Intuition Required

Quantum computers demand fundamentally different thinking in probabilities and parallel possibilities. Programs produce probabilistic outputs—run the same quantum program twice and receive different answers.

**Interface Challenge:** Tools like IBM's Qiskit attempt to make quantum programming accessible through visual circuit builders, but users must still think in terms of quantum gates and superposition—concepts with no classical analogs.

## 10. Philosophical Implications: Redefining Computation

### Classical Computing: Deterministic Universe

Classical computation embodies a deterministic worldview: given specific inputs and rules, outputs are predetermined. This represents computation as logical deduction, following paths established by Turing and von Neumann.

### Quantum Computing: Observer Effects and Probability

Quantum computation challenges fundamental notions of "computing." Is a quantum computer "computing" while in superposition, or only upon measurement? This parallels asking whether Schrödinger's cat is dead or alive before opening the box.

**Philosophical Insight:** Some researchers argue quantum computers aren't merely faster classical computers—they represent fundamentally different information processing that questions the boundary between observer and observed.



## 11. Security Paradigms: Locks, Keys, and Quantum Cryptography

### Classical Security: Digital Arms Race

Classical computer security operates like an evolving contest of locks and lock-picks. We encrypt data by making decryption computationally difficult—creating jigsaw puzzles with billions of pieces.

### Quantum Security: Breaking and Creating Ultimate Protection

Quantum computers present a security paradox:

- **Threat:** Shor's algorithm could break RSA encryption
- **Solution:** Quantum mechanics enables unbreakable communication through quantum key distribution

This creates conversations where eavesdropping automatically reveals itself—security guaranteed by physics laws, not mathematical complexity.

## 12. Resource Consumption and Environmental Impact

### Classical Computing: Efficient Workhorses

Modern classical computers demonstrate remarkable energy efficiency. Smartphones perform billions of calculations per second while consuming power comparable to small light bulbs. Data centers consume more energy but continue improving efficiency.

### Quantum Computing: Current Energy Intensity

Present quantum computers consume enormous energy maintaining operational temperatures. IBM's quantum systems use more electricity for cooling than small towns consume entirely. However, the computation itself uses minimal energy—overhead lies in maintaining quantum states.

**Future Potential:** Theoretical room-temperature quantum computers could become incredibly energy-efficient, performing certain calculations with far less energy than classical systems.

## 13. Standardization: Unity vs Fragmentation

### Classical Computing: Converged Standards

Classical computing has achieved standardization: binary representation, von Neumann architecture, common programming languages, and internet protocols. Python programs run similarly across different systems.

### Quantum Computing: Tower of Babel

The quantum landscape remains fragmented across different approaches:

- **Superconducting Qubits:** IBM, Google
- **Trapped Ions:** IonQ
- **Photonic Qubits:** Xanadu
- **Neutral Atoms:** QuEra

Each approach requires different programming models and offers distinct advantages. This resembles early personal computing when Apple, Commodore, and IBM machines were completely incompatible.

## 14. Historical Context and Development Narratives

### Classical Computing: Linear Evolution

Classical computing follows a logical progression: mechanical calculators → vacuum tubes → transistors → integrated circuits → personal computers → internet → smartphones. Each advancement built systematically on predecessors.

### Quantum Computing: Revolutionary Convergence

Quantum computing emerged from pure physics (Einstein, Bohr, Schrödinger) meeting computer science (Feynman, Shor, Grover). Rather than evolution, this represents revolution—transforming quantum mechanics' strangest aspects into computational advantages.

**Timeline:** Richard Feynman proposed quantum computers in 1981, but the first practical quantum algorithm (Shor's factoring algorithm) wasn't discovered until 1994, with useful quantum computers only appearing in the 2010s.



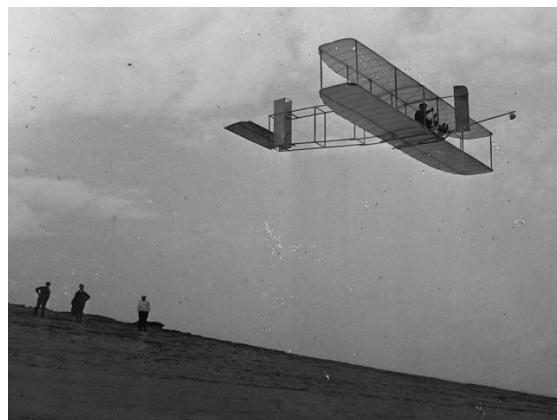
## 15. Current State and Future Outlook

### Classical Computing: Steady Innovation

Classical computers continue improving through new materials, architectures, and manufacturing processes. While Moore's Law may be slowing, innovation continues via specialized chips (AI accelerators, quantum processors) and new paradigms (neuromorphic computing).

### Quantum Computing: NISQ Era and Beyond

As physicist John Preskill noted, we're entering the "NISQ" era (Noisy Intermediate-Scale Quantum computers). These systems are imperfect and limited but potentially useful—like early airplanes that barely flew but hinted at aviation's future.



### Potential Future Scenarios

1. **Quantum Advantage:** Specialized quantum processors handle specific tasks while classical computers manage everything else
2. **Quantum Supremacy:** Large-scale quantum computers revolutionize entire industries
3. **Quantum Winter:** Technical challenges prove insurmountable, reducing investment and progress

**Expert Consensus:** Most specialists predict practical quantum advantage for commercially relevant problems within 10-20 years, but quantum computers replacing classical computers for general computing tasks remains unlikely.

## 16. The Quantum Supremacy Milestone

In 2019, Google's Sycamore quantum processor completed a specific calculation in 200 seconds that Google claimed would take a state-of-the-art supercomputer 10,000 years to finish. This demonstrated "quantum supremacy"—the first time a quantum computer provably outperformed classical computers on any task.



**Important Context:** Subsequent research by Chinese scientists showed they could perform the same computation on classical computers much faster than Google initially estimated, illustrating the ongoing debate about quantum supremacy claims.

## 17. Cultural Impact and Public Perception

### Classical Computing: The Familiar Evolution

Classical computers transformed from mysterious room-sized monsters into familiar tools. We understand them intuitively through metrics like processing speed, memory, and storage capacity.

### Quantum Computing: Mystique and Mythology

Quantum computing captures public imagination like science fiction made real. Movies employ quantum computers as plot devices for time travel and parallel universes. The "quantum" prefix has become marketing gold, leading to "quantum" vitamins and yoga.

**Cultural Note:** The phrase "quantum leap" in popular usage means a large jump, but in physics, it represents the smallest possible energy change. This disconnect illustrates how quantum concepts become mythologized in public consciousness.



## 18. The Beautiful Partnership: Classical AND Quantum

The future isn't classical OR quantum computing—it's classical AND quantum working together. Classical computers excel at logical, sequential tasks and user interfaces, while quantum computers master exploring vast possibility spaces and solving optimization problems.

Your future smartphone might contain a classical processor for apps and interfaces alongside a quantum coprocessor for specialized tasks, potentially all cooled by room-temperature quantum effects yet to be discovered.

This represents computation's evolution toward hybrid systems where each paradigm handles what it does best, solving problems neither could tackle alone.

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**Note:** Technical specifications for modern smartphones and quantum computer operating temperatures sourced from manufacturer documentation (Apple, Samsung, IBM, Google Quantum AI).