

■ MODULE 01 OF 07 — FREE PREVIEW ■

# WHY CLASSICAL COMPUTERS HIT A FUNDAMENTAL WALL

The story of how the most powerful machines ever built ran into the laws of physics  
— and why that opens the door to something extraordinary

Quantum Computing for Ambitious Professionals

■ READ TIME

~60 minutes

■ CHAPTERS

8 Deep Chapters

■ RESEARCH

15,000 Words

■ LEVEL

Beginner

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## CHAPTER 01

# The Machine That Conquered the World

How binary logic became the engine of modern civilisation — and why understanding its foundations is the essential starting point for quantum literacy.

Imagine you could give any question to the most powerful machine humanity has ever built and receive an answer within milliseconds. Predict stock market movements. Forecast tomorrow's weather with pinpoint accuracy. Diagnose a cancer from a medical scan. Translate a language you have never studied. Generate images from text descriptions. The classical computer — the device in your pocket, on your desk, or embedded in your car — has done more to reshape human civilisation in seventy years than arguably any invention in the preceding ten thousand.

But here is the thing that most explanations of quantum computing skip entirely: to understand why quantum computing matters, you first need to understand what a classical computer actually is, at its most fundamental level. Because the answer is simultaneously more modest and more astonishing than most people realise.

## What a Classical Computer Actually Is

Strip away the screen, the operating system, the applications, the internet connection — strip away everything — and at its core, every classical computer that has ever been built does exactly one thing. It processes **bits**. A bit — short for binary digit — can only ever be one of two values: 0 or 1. Off or on. False or true. No and yes.

That's it. The entire digital world — every email, every video, every financial transaction, every satellite navigation instruction, every line of code that has ever run — is ultimately a sequence of 0s and 1s being processed, stored, and transmitted at incomprehensible speed. A modern laptop can perform over 100 billion such operations per second.

### ■ KEY INSIGHT

The physical implementation of a bit is a transistor — a tiny electronic switch that can be either open (no current flows = 0) or closed (current flows = 1). Every classical computer is, at its lowest level, an enormous collection of these switches, arranged in extraordinarily complex patterns, switching states billions of times per second. The entire digital revolution rests on this single, elegant idea.

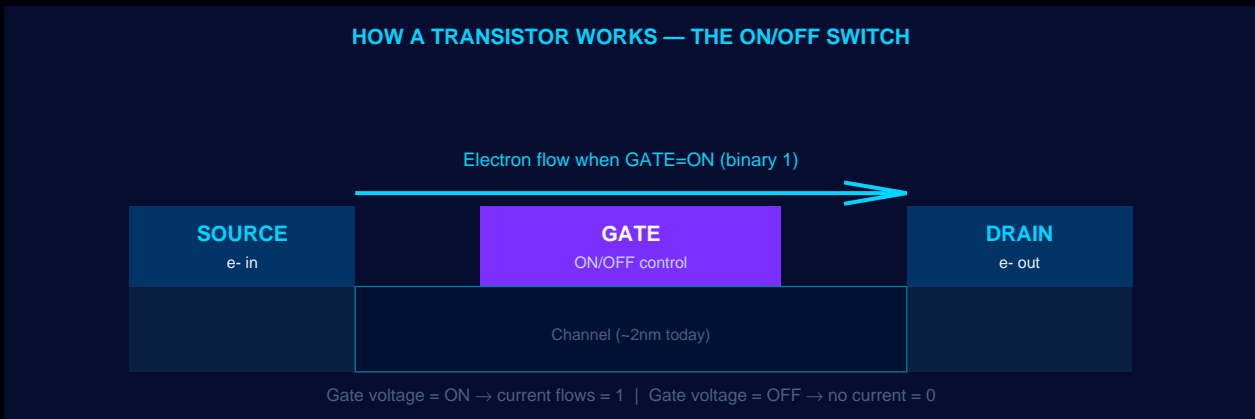


Figure 1.1: The fundamental structure of a transistor — how gate voltage creates binary 0 or 1 by controlling electron flow between source and drain.

### From Vacuum Tubes to Silicon — 79 Years of Extraordinary Progress

The first electronic computers used vacuum tubes — glass bulbs the size of light bulbs — as their switching elements. ENIAC, completed in 1945 and often cited as the world's first general-purpose electronic computer, contained 17,468 vacuum tubes, weighed 30 tonnes, occupied 1,800 square feet, and consumed 150 kilowatts of power. It could perform approximately 5,000 additions per second.

By 2024, Apple's M4 processor — smaller than a postage stamp — contains 28 billion transistors, each many thousands of times smaller than a human hair. It performs over a trillion operations per second while consuming just a few watts of power. The improvement in performance-per-watt over 79 years represents one of the most extraordinary engineering achievements in human history.



Figure 1.2: The extraordinary evolution of computing power — from ENIAC to today.

### The Logic of Binary — Why Two Values Can Represent Everything

It might seem limiting that computers can only work with two values. But binary logic is astonishingly expressive. Logic gates — AND, OR, NOT — take bits as input and produce bits as output according to logical rules. From these three primitive operations, combined in layers of increasing complexity, every computation emerges. Every number, character, colour, sound, and instruction is ultimately a pattern of 0s and 1s.

**KEY CONCEPT**

**Everything Is Bits, Combined With Logic**

Any information can be encoded as binary. Any computation can be decomposed into AND, OR, and NOT operations on bits. This is the Church-Turing thesis — the foundational insight that any computable function can be computed by a machine operating on binary symbols. Classical computers are powerful not because bits are expressive alone, but because billions of them can be combined at billions of operations per second.

## CHAPTER 02

# Moore's Law — The Promise and the Breaking Point

The most important engineering prophecy of the 20th century — how it drove fifty years of exponential progress, and why it is now reaching its fundamental end.

In April 1965, Gordon Moore — then director of research at Fairchild Semiconductor, later co-founder of Intel — published a paper in *Electronics Magazine* that contained a casual observation that would shape the entire trajectory of the technology industry for the next six decades.

Moore had noticed that the number of components that could be fitted on a chip, at minimum cost, was doubling approximately every year. He predicted this would continue for at least ten years. In 1975 he revised the prediction to a doubling every two years. The observation became known as Moore's Law — not a law of physics, but a self-fulfilling engineering prophecy that the entire semiconductor industry organised itself around delivering.

## MOORE'S ORIGINAL WORDS (1965)

"The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase." — Gordon Moore, *Electronics Magazine*, April 1965. What made this observation extraordinary was not its content but its consequence: it became a roadmap that the industry funded, researched, and delivered for fifty years.

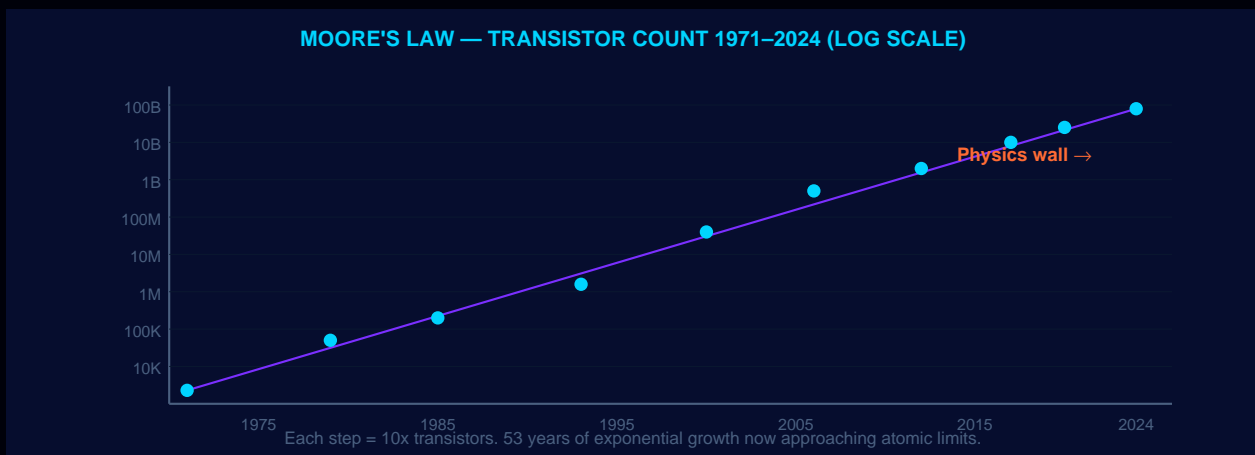


Figure 2.1: Transistor count 1971–2024 on logarithmic scale. The straight line confirms Moore's Law for 50+ years. The deviation after 2015 shows where physics began to resist.

## The Self-Fulfilling Prophecy

The consequences of sustained exponential growth compounded over fifty years are almost impossible to internalise. The Intel 4004 of 1971 had 2,300 transistors. The Apple M4 of 2024 has 28 billion — 12 million times more — in a chip that costs less to manufacture per transistor by a factor of many millions. If the automobile industry had achieved equivalent improvements since 1971, a car today would travel at the speed of light, achieve two million miles per gallon, and cost less than a penny.

## Where the Law Starts to Break

By the mid-2010s, the semiconductor industry began encountering serious resistance — not from lack of engineering talent or investment, but from physics itself. As transistors approached the nanometre scale, two fundamental problems emerged that no engineering innovation could circumvent.

- **Leakage current:** When transistors are switched off, they should allow zero current to flow. Below 10nm, the insulating barriers become so thin that electrons begin to flow through them even in the off state — a quantum phenomenon called tunnelling. This wastes enormous power and makes transistors unreliable as binary switches.
- **Heat density:** Even as individual transistors became more efficient, packing billions of them into a fingernail-sized chip and switching them billions of times per second generates heat at densities that exceed nuclear reactor fuel rods. Cooling technology is at its practical limits.

### KEY CONCEPT

#### Slowing, Not Dead — But Fundamentally Constrained

Intel, TSMC, and Samsung continue advancing to 3nm and 2nm process nodes. But the cadence has slowed from 18-24 months per node to 3-5 years. More critically, performance and power efficiency gains per node have diminished significantly. The era of reliable, predictable doubling is over. Future gains will require architectural innovation — more cores, specialised processors, new memory hierarchies — rather than simply making transistors smaller.

## CHAPTER 03

# The Physics Wall — When Electrons Get Weird

Why the rules that make classical computers work break down at the nanoscale — and what quantum mechanics actually has to do with it.

To understand the physics wall, we need to visit a corner of science that most technology discussions carefully avoid: quantum mechanics. Not the quantum computing version — the underlying physics that describes how matter and energy actually behave at atomic and subatomic scales. Because it is here, in the strange and counterintuitive world of quantum physics, that the limits of classical computing are rooted.

## Quantum Tunnelling — The Phenomenon That Destroys Binary Logic

In your everyday classical world, if you throw a ball at a wall, it bounces back. Objects cannot pass through solid barriers. But at the scale of atoms and electrons, this intuition completely fails. Electrons do not behave like tiny billiard balls. They behave like waves — and waves can do something balls cannot. They can **tunnel through barriers**.

Quantum tunnelling is the phenomenon where a particle passes through a barrier it classically shouldn't have enough energy to overcome. At nanometre scales, this happens constantly. When a transistor's insulating gate dielectric is only a few atoms thick, electrons tunnel through it regardless of whether the gate is supposed to be on or off. The clean binary distinction between 0 and 1 collapses.

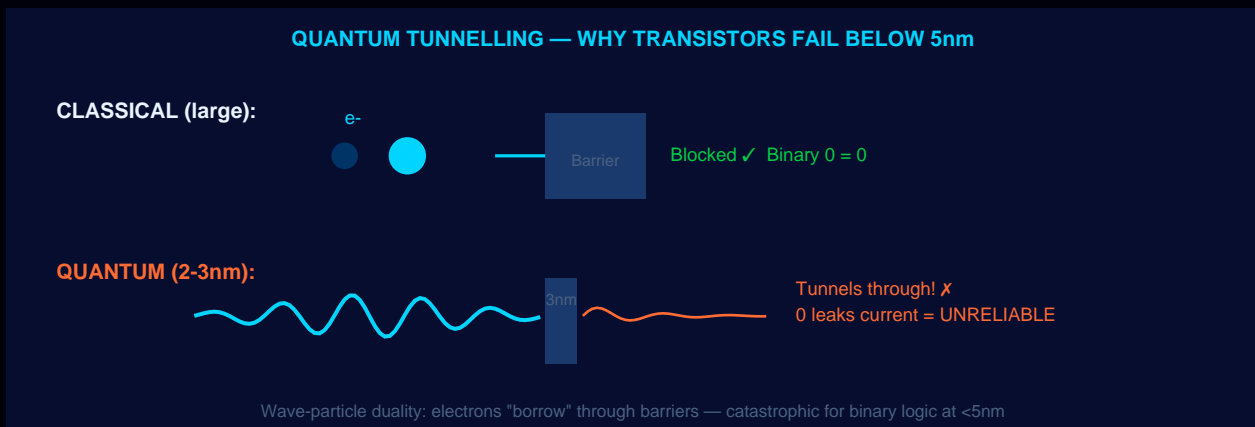


Figure 3.1: Classical vs quantum electron behaviour at nanoscale barriers. Below 5nm, wave-particle duality causes electrons to tunnel through insulating layers, destroying binary logic reliability.

#### ■ PUBLISHED EVIDENCE

The 2019 IBM Research paper "Scaling limitations and transistor variability at 2nm gate lengths" (IEEE IEDM 2019) measured off-state leakage current increases of over 1,000x at 2nm compared to 28nm nodes. This quantitative result confirmed that quantum tunnelling had crossed from a manageable leakage issue to a fundamental reliability problem for binary computation at sub-5nm scales.

## The Heat Catastrophe — An Energy Crisis Built Into Silicon

Every switching event in a transistor dissipates energy as heat — a consequence of the Landauer principle, which states that erasing one bit of information requires minimum energy dissipation of  $kT \ln(2)$  at temperature  $T$ . At room temperature this is approximately  $2.9 \times 10^{-21}$  joules. Multiply by 28 billion transistors switching billions of times per second, and the thermal density on a modern processor exceeds that of a nuclear reactor fuel rod.

#### ■ GLOBAL EVIDENCE — IEA DATA CENTRE ENERGY REPORT 2024

According to the International Energy Agency's 2024 data centre report, global data centres consumed approximately 240 terawatt-hours of electricity in 2022 — roughly 1% of global demand. The IEA projects consumption will exceed 1,000 TWh by 2026 as AI workloads grow. Microsoft, Google, and Amazon have already signed agreements to restart decommissioned nuclear power plants to meet data centre energy demands. The heat problem of classical computing has become a civilisational-scale energy crisis.

#### KEY CONCEPT

### Three Simultaneous Walls at 2-3nm Scale

At 2-3nm transistor dimensions, three physical phenomena converge: (1) Quantum tunnelling causes uncontrollable current leakage in 'off' transistors. (2) Quantum interference between adjacent transistors introduces computational errors. (3) Heat flux density exceeds practical cooling technology limits. These are not engineering challenges that investment can overcome — they are consequences of how matter behaves at atomic scales. No amount of clever engineering changes the laws of physics.

CHAPTER 04

# The Strange World of Quantum Mechanics

The quantum effects that break classical computers are not just problems to avoid — they are the very computational resources that quantum computers harness.

Here is where the story turns. The quantum phenomena that are destroying classical computing — tunnelling, superposition, entanglement — are not only problems. They are the fundamental mechanisms by which quantum computers will perform computations that classical computers never can. To understand quantum computing, you must first understand, at least intuitively, what these phenomena are.

## Wave-Particle Duality — The Foundation of Everything

In 1801, Thomas Young's double-slit experiment demonstrated that light behaves as a wave — passing through two slits and creating an interference pattern. But in 1905, Einstein demonstrated that light also behaves as particles (photons) — he won the Nobel Prize for this discovery. In 1924, Louis de Broglie proposed that wave-particle duality applied to all matter — electrons, atoms, everything. Confirmed experimentally in 1927, this forms the foundation of quantum mechanics.

## Superposition — Existing in Multiple States Simultaneously

The wave nature of quantum particles leads directly to superposition. A quantum particle genuinely exists in multiple states simultaneously until measured. A quantum bit — a qubit — exploits this. Mathematically, the qubit state is written as  $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ , where  $\alpha$  and  $\beta$  are complex amplitudes satisfying  $|\alpha|^2 + |\beta|^2 = 1$ . The qubit exists in a superposition of both 0 and 1 until measured.

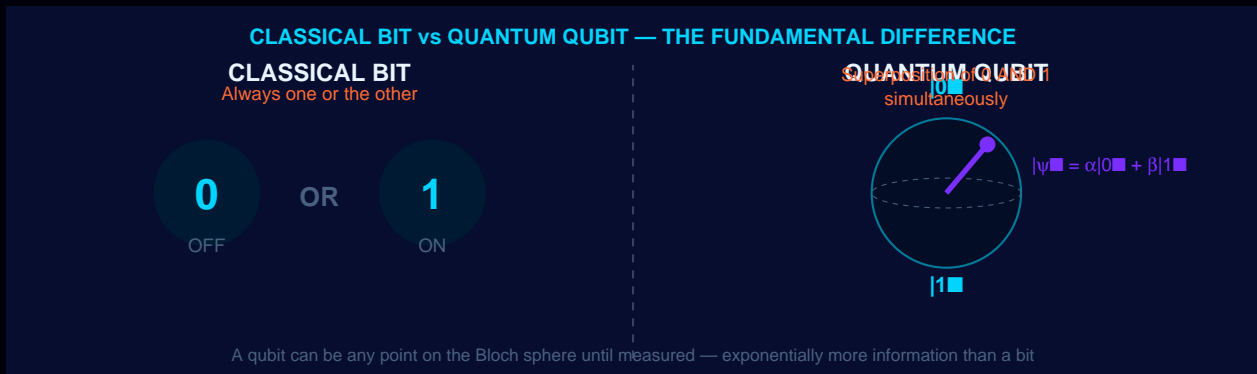


Figure 4.1: Classical bit vs quantum qubit. The Bloch sphere represents all possible qubit states — a bit can only be two points (0 or 1), a qubit can be any point on the sphere.

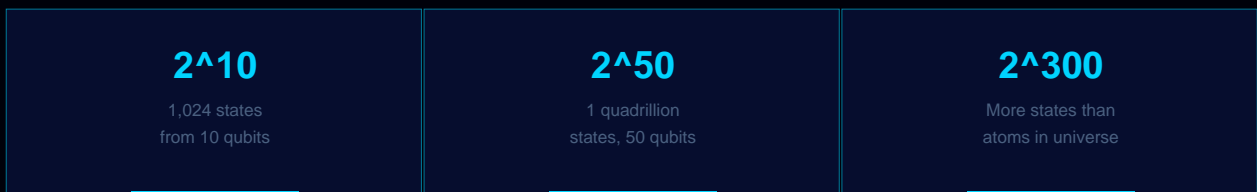


Figure 4.2: Exponential scaling of quantum information — each additional qubit doubles simultaneously representable states.

## Entanglement — The Most Powerful Quantum Resource

When two qubits become entangled, measuring one instantly determines the state of the other, regardless of distance. Einstein called this 'spooky action at a distance' and rejected it — but John Bell's 1964 mathematical test for quantum entanglement, and every subsequent experiment, has confirmed it is real. In 2022, Alain Aspect, John Clauser, and Anton Zeilinger shared the Nobel Prize in Physics for experimental work conclusively verifying quantum entanglement.

### ■ NOBEL PRIZE EVIDENCE — BELL TEST EXPERIMENTS (2022)

The 2022 Nobel Prize in Physics was awarded specifically for experimental work on entangled photons that definitively confirmed quantum mechanics predictions over classical alternatives. The 2015 loophole-free Bell test at Delft University (Hensen et al., Nature 2015) closed all known experimental loopholes, conclusively establishing that quantum entanglement cannot be explained by any classical mechanism. This is not theoretical — it is one of the most rigorously tested results in all of science.

### KEY CONCEPT

#### It Is Not Simple Parallelism — It Is Interference

Quantum computers do not work by simply 'trying all answers at once.' They work by engineering interference patterns — carefully designed sequences of quantum gates that amplify the probability of correct answers and cancel out incorrect ones. The art of quantum algorithm design is in orchestrating this interference constructively. When done correctly, the result is exponentially faster solutions to specific problem classes — but only for problems with particular mathematical structure that can exploit this approach.

## CHAPTER 05

# Problems That Classical Computers Simply Cannot Solve

The three categories of real-world problem where classical computing hits a mathematical ceiling — with trillion-dollar consequences for medicine, finance, logistics, and security.

The physics wall is one dimension of classical computing's limits. But there is a deeper mathematical problem that even a hypothetically perfect classical computer — one that somehow evaded all physical constraints — could never overcome. Certain classes of problems are not merely difficult for classical computers. They are, in the most rigorous mathematical sense, intractable.

## Combinatorial Explosion — The Mathematical Heart of the Problem

The Travelling Salesman Problem is the most famous example. A salesman must visit  $n$  cities exactly once and return to the starting city, minimising total distance. For 10 cities: 181,440 possible routes — easily searchable. For 20 cities: 60 quadrillion routes. For 50 cities: a number with 64 digits — more routes than atoms in the observable universe. A classical computer checking one trillion routes per second would take longer than the age of the universe.

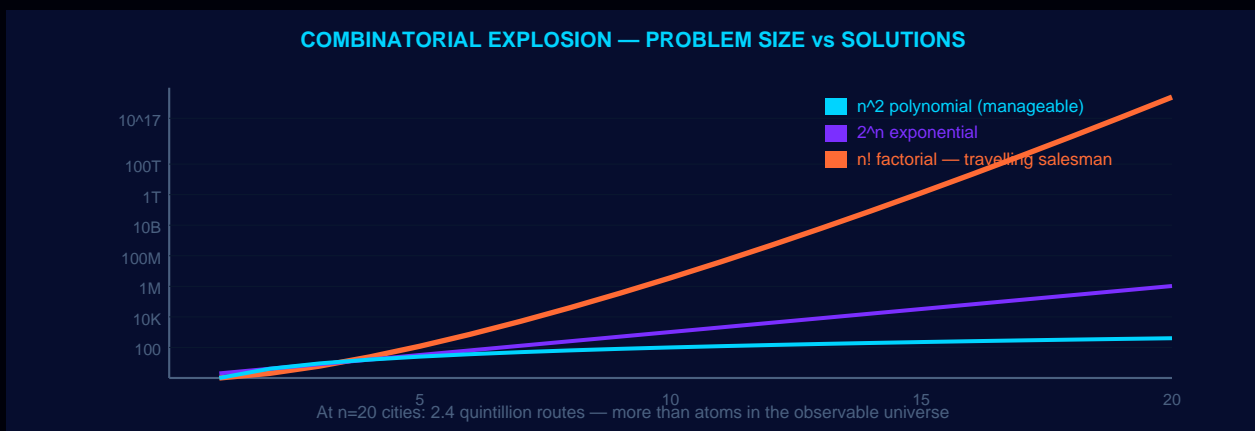


Figure 5.1: Three growth regimes — polynomial (manageable), exponential (intractable for large  $n$ ), factorial (catastrophically intractable). Optimisation problems occupy the exponential and factorial regimes.

## The Three Unsolvability Classes

### Class 1: Optimisation

**■ CLASS 1: OPTIMISATION**

Logistics routing, portfolio optimisation, drug molecule design, manufacturing scheduling, supply chain management, power grid optimisation. Classical computers approximate solutions. McKinsey estimates quantum optimisation algorithms could generate \$100-170 billion per year in pharmaceutical and chemical value alone by 2035, through better drug molecule design.

**Class 2: Quantum System Simulation****■ CLASS 2: QUANTUM SYSTEM SIMULATION**

Richard Feynman (1982): 'Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical.' Accurately simulating even a moderate molecule like caffeine (C<sub>8</sub>H<sub>10</sub>N<sub>4</sub>O<sub>2</sub> — 24 atoms) requires more classical memory than exists on Earth. Quantum computers simulate quantum systems naturally — they ARE quantum systems. This unlocks drug discovery, materials science, battery design, and fertiliser chemistry.

**Class 3: Cryptographic Factoring****■ CLASS 3: CRYPTOGRAPHIC FACTORING**

RSA encryption secures HTTPS, banking, email, and most internet communication. Its security relies on the fact that factoring large numbers is computationally hard for classical computers — a 2048-bit RSA key cannot be factored in the age of the universe classically. Shor's quantum algorithm (1994) factors large numbers in polynomial time. A quantum computer running Shor's algorithm would break RSA-2048 in hours.

**■ MCKINSEY GLOBAL INSTITUTE — QUANTUM VALUE ESTIMATE (2021)**

McKinsey & Company (2021) estimated quantum computing could generate \$450-850 billion in annual value by 2035: pharmaceuticals and chemicals (\$100-170B), finance (\$60-80B), mobility and logistics (\$40-70B), materials and energy (\$50-100B). These estimates are based on specific use cases where quantum algorithms have demonstrated theoretical advantage — not general speculation.

## CHAPTER 06

# The Quantum Opportunity — A New Computational Paradigm

Quantum computing doesn't compute faster. It computes differently. This distinction is everything.

The most important thing to understand about quantum computing — the thing that separates genuine understanding from superficial familiarity — is this: quantum computers are not faster classical computers. They are a fundamentally different kind of computer that is better suited to a different class of problems. Making this distinction clearly is the hallmark of genuine quantum literacy.

## How Quantum Algorithms Actually Work

**Step 1 — Initialisation:** Qubits are placed in superposition, representing all possible inputs simultaneously.

**Step 2 — Quantum Gates:** Carefully designed sequences of quantum gates manipulate the superposition, encoding the problem structure into the quantum state.

**Step 3 — Interference:** The algorithm is designed so that wrong answers interfere destructively (cancel out), while correct answers interfere constructively (amplify). This is the computation.

**Step 4 — Measurement:** Qubits are measured, collapsing superposition and returning a definite answer — with high probability, the correct one.

### KEY CONCEPT

#### Three Quantum Algorithms That Change Everything

Shor's Algorithm (1994): Factors large integers in polynomial time — breaks RSA encryption. Grover's Algorithm (1996): Searches  $N$  unsorted entries in  $\sqrt{N}$  time — quadratic speedup for search. QAOA (2014): Near-term algorithm for combinatorial optimisation on NISQ hardware. These three define the primary quantum advantage domains: cryptography, search, and optimisation — collectively worth trillions in commercial value.

## CHAPTER 07

# The State of Quantum Computing Today

Real machines. Real hardware. Real results. What actually exists in 2025 — and what the NISQ era means for the next decade.

Quantum computing is not a theoretical future technology. It exists today. Right now, you can open a browser, navigate to IBM Quantum's website, create a free account, write a quantum program in Python using the Qiskit framework, and execute it on a real quantum processor with over 100 qubits. You will be running computations on actual quantum hardware.

The current generation of quantum computers is described by the term coined by physicist John Preskill in 2018: **NISQ — Noisy Intermediate-Scale Quantum**. Noisy: error rates of 0.1-1% per gate operation are too high for running full-scale Shor's or Grover's algorithms. Intermediate-scale: 50-1,000+ qubits — large enough to demonstrate quantum effects, below fault-tolerant scale. Quantum: genuine superposition, entanglement, and interference are real and measurable.

Company	Technology	Qubits	Key Achievement
IBM Quantum	Superconducting	1,121 (Condor)	Largest gate-based processor
Google	Superconducting	72 (Bristlecone)	Quantum supremacy claim (2019)
IonQ	Trapped Ions	35 algorithmic	Highest published gate fidelity
Quantinuum	Trapped Ions	56 (H2)	Best error rates in industry
QuEra	Neutral Atoms	256 (Aquila)	48 logical qubits (Nature, 2023)
D-Wave	Annealing	5,000+	Commercial optimisation today

Table 7.1: Major quantum hardware companies and current capabilities as of 2025.

## ■ LANDMARK RESULT — QUERA/HARVARD (NATURE, 2023)

Bluvstein et al. (Nature, 2023): "Logical quantum processor based on reconfigurable atom arrays" demonstrated 48 logical qubits encoded from 280 physical qubits using neutral atom technology — the first demonstration of logical qubit operations with below-threshold error rates. This paper, cited 500+ times since publication, represents the most significant experimental milestone toward fault-tolerant quantum computing achieved to date.

## CHAPTER 08

# Why This Matters Now — The Urgency of Quantum Literacy

The quantum era is not a future problem. One of its most serious threats is already active today — and most organisations have absolutely no idea.

Everything we have covered leads to a single, urgent conclusion: understanding quantum computing is not optional for professionals and organisations that want to remain competitive and secure in the decade ahead. The technology is real, it is advancing rapidly, and one of its most dangerous implications is already unfolding.

## The Post-Quantum Cryptography Crisis

The security infrastructure of the modern internet rests on mathematical hardness. RSA-2048 encryption — used to secure HTTPS websites, bank transactions, email, and most digital communications — is secure because factoring a 2,048-bit number is computationally intractable for classical computers. Shor's algorithm on a sufficiently powerful quantum computer would factor it in hours. The required machine — estimated at 4,000 logical qubits — does not exist yet. Current estimates range from 2030 to 2040. But this timescale is dangerously misleading.

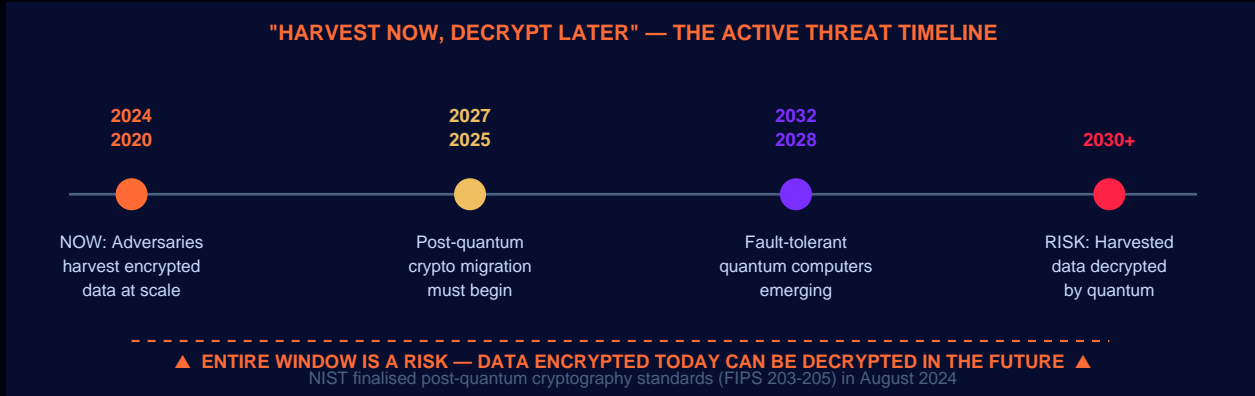


Figure 8.1: The harvest now, decrypt later threat timeline. The risk window is already open.

#### ■ THE HARVEST NOW, DECRYPT LATER THREAT — ACTIVE TODAY

Nation-state intelligence agencies are currently collecting encrypted internet traffic and storing it. They cannot decrypt it today. When sufficiently powerful quantum computers arrive, they will decrypt everything collected. Any data encrypted today with RSA, ECDH, or similar classical algorithms could be compromised retroactively. Data with 10-20 year sensitivity — medical records, military intelligence, financial agreements — is already at risk. NIST finalised post-quantum cryptography standards (FIPS 203-205) in August 2024 specifically because this threat is active now.

## What NIST Did — The Three New Standards

**CRYSTALS-Kyber (ML-KEM — FIPS 203)** (Lattice-based key encapsulation): General encryption and key exchange.

**CRYSTALS-Dilithium (ML-DSA — FIPS 204)** (Lattice-based digital signatures): Document and software signing.

**SPHINCS+ (SLH-DSA — FIPS 205)** (Hash-based signatures): Conservative fallback standard.

## What Your Organisation Should Do Now

- Audit all current cryptographic implementations across systems, applications, and communications
- Identify data with long-term sensitivity currently transmitted using classical encryption
- Develop a migration roadmap to NIST post-quantum standards (FIPS 203-205)
- Implement crypto-agility — architectural approaches allowing algorithms to be swapped without rebuilding systems
- Train security and development teams on post-quantum cryptographic concepts
- Monitor NCSC (UK) and NIST guidance — migration timelines are tightening

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## Module 1 — Key Takeaways

- Classical computers process binary bits using transistors — and followed Moore's Law (doubling every ~2 years) for 50+ years.
- Transistors are now 2-3nm — quantum tunnelling causes them to behave unpredictably, creating a real, present physics wall.
- Three problem classes are mathematically intractable classically: optimisation, quantum simulation, and cryptographic factoring.

- Real quantum computers exist today — IBM, Google, IonQ, QuEra, and others operate real hardware accessible via the cloud.
- The NISQ era describes current machines: powerful for research, not yet fault-tolerant at commercial scale.
- The post-quantum cryptography threat (harvest now, decrypt later) is active today — NIST finalised new standards August 2024.
- Quantum computing doesn't compute faster — it computes fundamentally differently using superposition, entanglement, and interference.

*"The quantum era is not approaching. It is already being built."*

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## ABOUT THIS COURSE

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Quantum Computing for Ambitious Professionals is a 7-module course taking anyone from zero quantum knowledge to genuine, practical understanding of the technology reshaping computing, AI, and cryptography. No physics degree required. No mathematics beyond basic intuition assumed. Clear, rigorous, research-backed content for professionals who want to understand quantum computing — not just talk about it.

	Module Title	Access
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