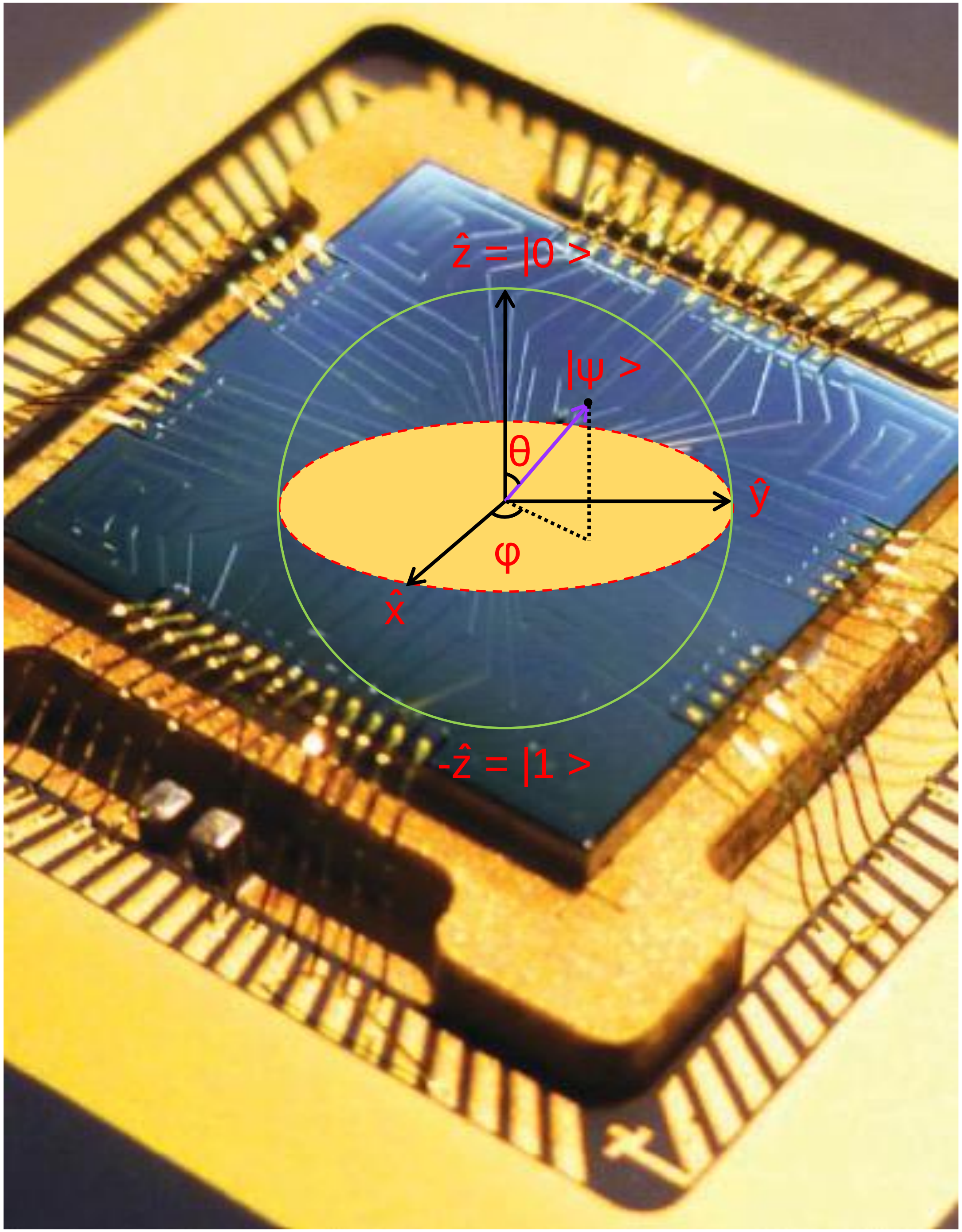
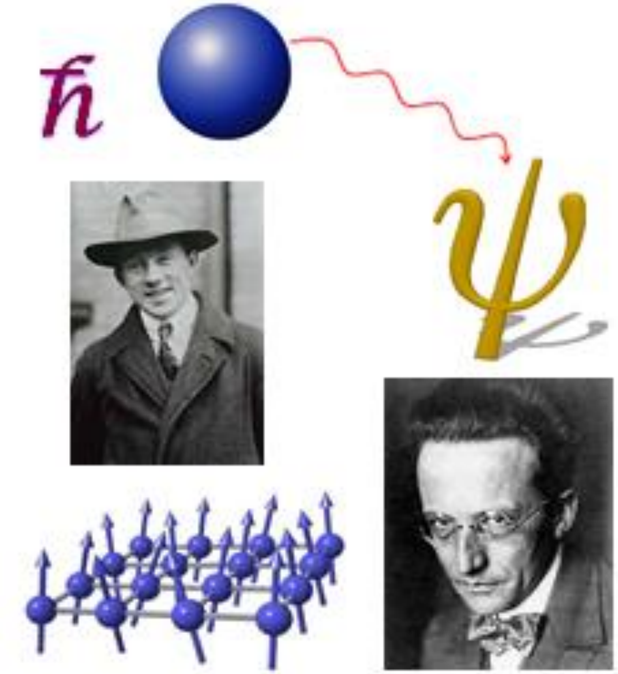


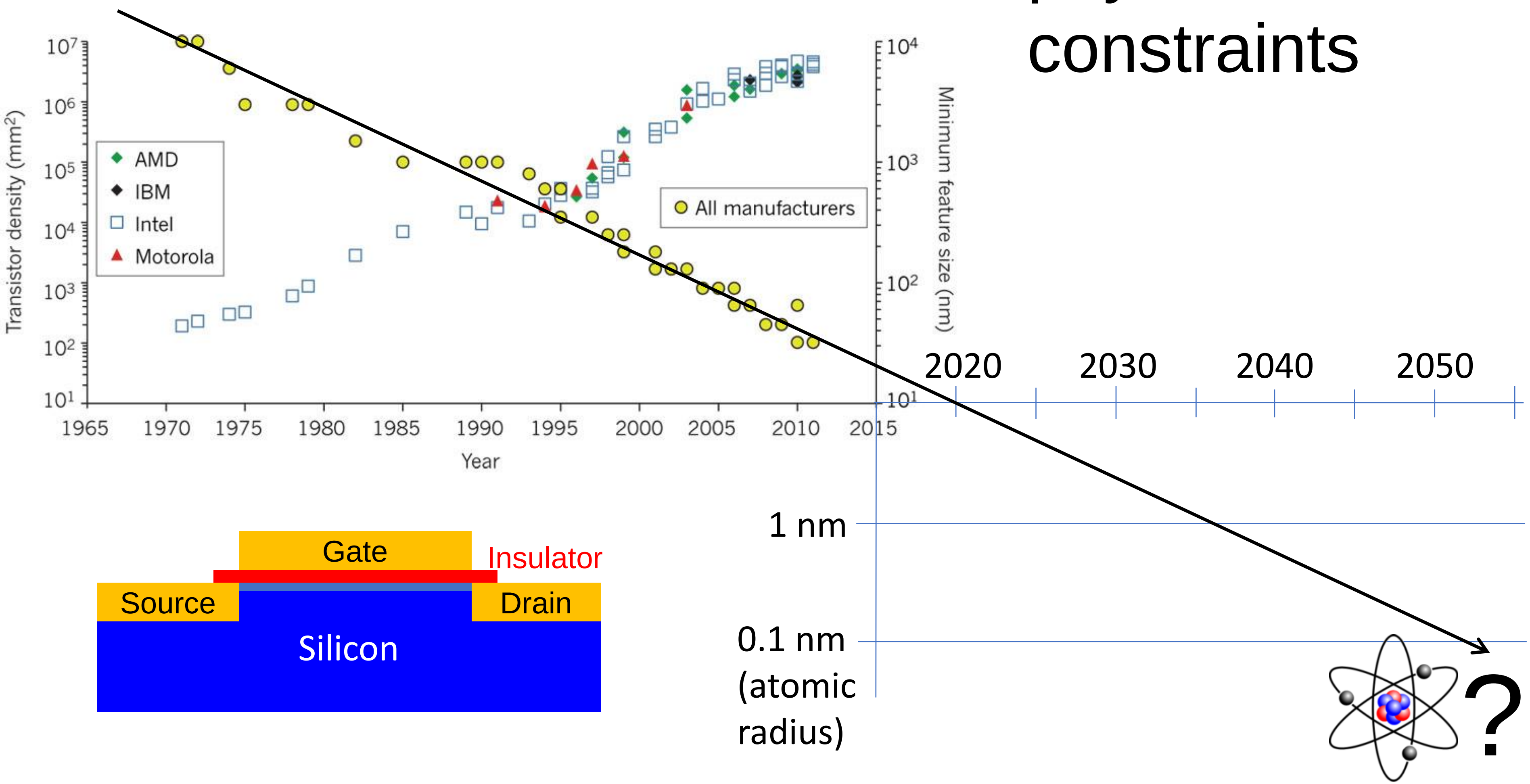


Quantum Computing

Computers in 1950

Motivation: Future of Computers

Moore's law …will soon run into major physical constraints



Moore, G. E. *Electronics* **8**, 114–117 (1965).
Image from: Ferain, I. *et al*., *Nature* **479**, 310–316 (2011).

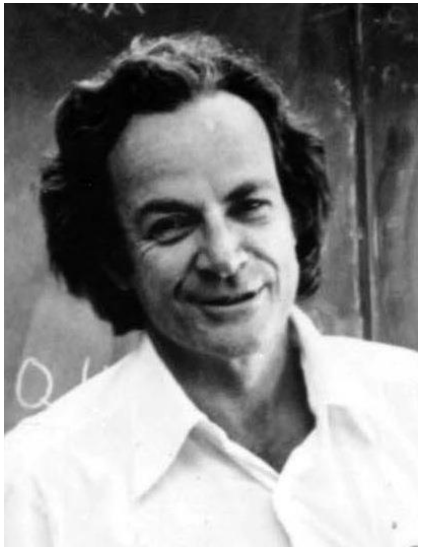
Problems …

- Current technology is not having difficulty adding more transistors….
- At current rate transistors will be as small as an atom.
- If scale becomes too small, Electrons tunnel through micro-thin barriers between wires corrupting signals.

Limitations of Classical Computers

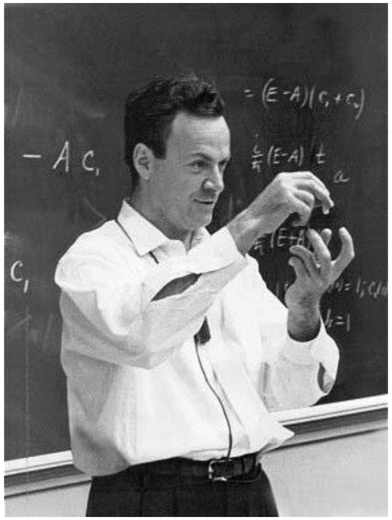
Unsolved problem in computer science:
Can integer factorization be solved in polynomial time on a classical computer?

- RSA encryption (2048-bit)
  - 100,000 computers in parallel
  - 3 GHz processors
  - Factoring would take longer than the age of the universe
- Quantum Simulation: inefficient with classical computers
  - Feynman: why not use quantum mechanics for computation?

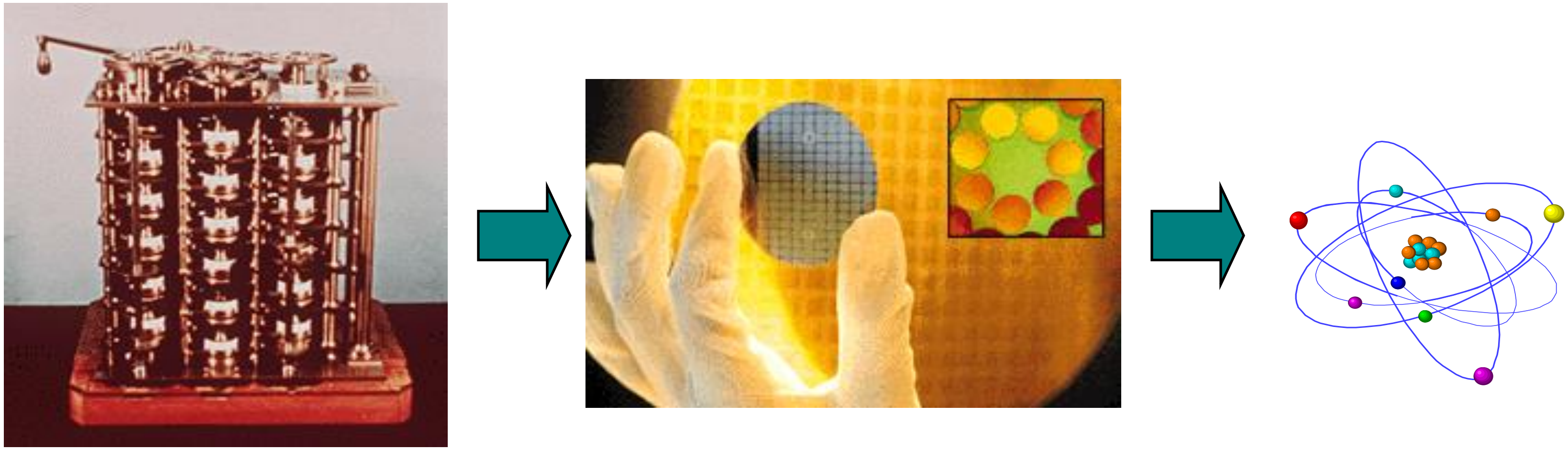


Introduction

- 1982 - Feynman proposed the idea of creating machines based on the laws of quantum mechanics instead of the laws of classical physics.



- 1985 - David Deutsch developed the quantum Turing machine, showing that quantum circuits are universal.
- 1994 - Peter Shor came up with a quantum algorithm to factor very large numbers in polynomial time.
- 1997 - Lov Grover develops a quantum search algorithm.



Computer technology is making devices smaller and smaller…

…reaching a point where classical physics is no longer a suitable model for the laws of physics.

Physics and Computation

In a classical computer, tiny electronic switches called bits take values of either 0 or 1. Programs that run on them use this binary logic to perform operations.

- Information is stored in a physical medium, and manipulated by physical processes.
- The laws of physics dictate the capabilities of any information processing device.
- Designs of "classical" computers are implicitly based in the *classical* framework for physics
- Classical physics is known to be wrong or incomplete… and has been replaced by a more powerful framework: *quantum mechanics*.

The nineteenth century was known as the machine age, the twentieth century will go down in history as the information age. I believe the twenty-first century will be the quantum age. Paul Davies, Professor Natural Philosophy – Australian Centre for Astrobiology

The design of devices on such a small scale will *require* engineers to control quantum mechanical effects.

Allowing computers to take advantage of quantum mechanical behaviour allows us to do *more* than cram increasingly many microscopic components onto a silicon chip…

What we tend to treat as "particles" of matter — molecules, atoms and subatomic entities such as electrons — have hidden depths, with inherently undefined properties. An electron's position, for instance, can be impossible to pin down precisely. Quantum computing manipulates these undefined properties.

… it gives us a whole new framework in which information can be processed in *fundamentally new ways.*

What is a quantum computer?

It helps to first understand the basics of classical computers

Computation with coherent atomic-scale dynamics

- A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behavior of particles at the sub-atomic level.

Nobody understands Quantum Mechanics

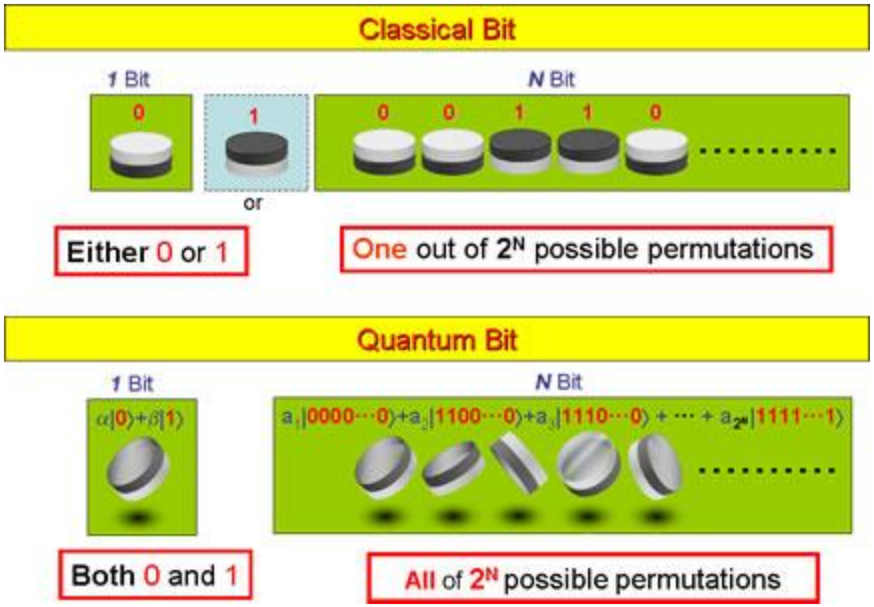
“No, you’re not going to be able to understand it. . . . You see, my physics students don’t understand it either. That is because I don’t understand it. Nobody does. ... The theory of quantum electrodynamics describes Nature as absurd from the point of view of common sense. And it agrees fully with an experiment. So I hope that you can accept Nature as She is -- absurd.

Richard Feynman

Representation of Data

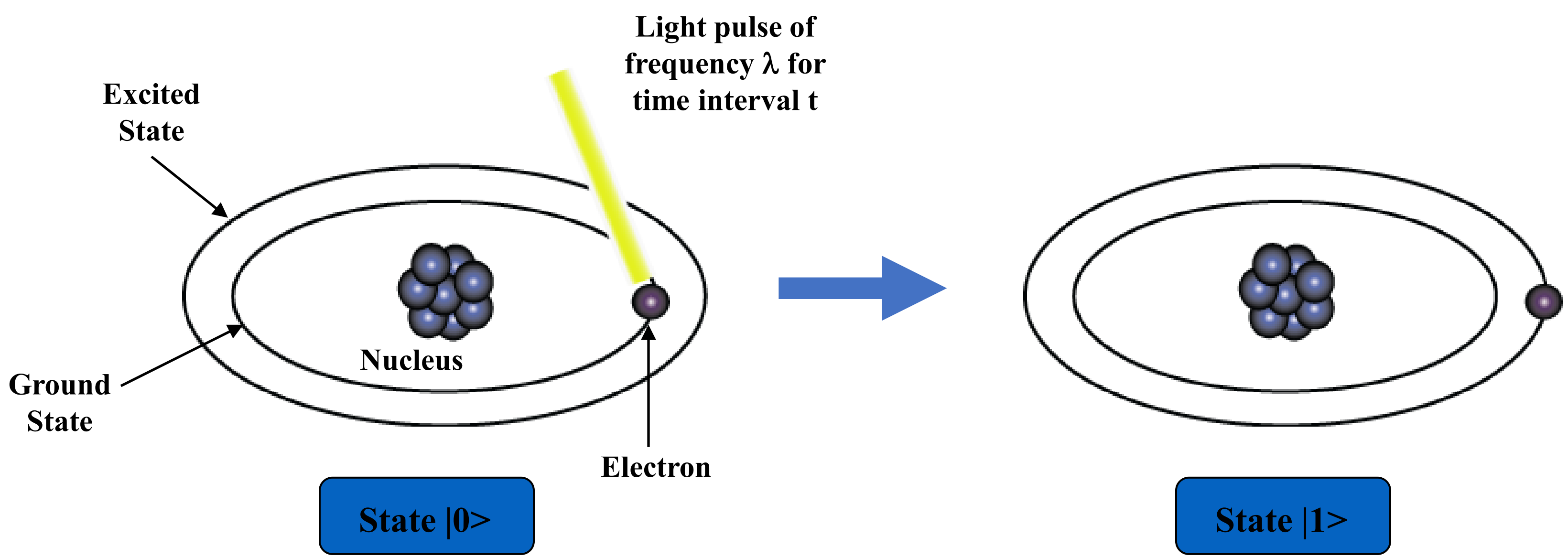
- Quantum computers - based on the strange principles of quantum mechanics, in which the smallest particles of light and matter can be in different places at the same time.
- In a quantum computer, one "qubit" - quantum bit - could be both 0 and 1 at the same time. So with three qubits of data, a quantum computer could store all eight combinations of 0 and 1 simultaneously. That means a three-qubit quantum computer could calculate eight times faster than a three-bit digital computer.
- Typical personal computers today calculate 64 bits of data at a time. A quantum computer with 64 qubits would be 2 to the 64th power faster, or about 18 billion billion times faster. (Note: billion billion is correct.)

A bit of data is represented by a single atom that is in one of two states denoted by |0> and |1>. A single bit of this form is known as a ***qubit***



Representation of Data - Qubits

A physical implementation of a qubit could use the two energy levels of an atom. An excited state representing |1> and a ground state representing |0>.



Superposition

- Now, we know the electron follows quantum laws and can therefore exist with its spin undefined in a "superposition" state that is a complex combination of the 0 and 1 states. It will only become defined (as 0 or 1) if it interacts strongly with something in its environment, an interaction that quantum physicists often refer to as a measurement.
- This doesn't mean it is 0 and 1 at the same time. You could say it will maybe turn out to be 0 or 1
- That process is called "interference." When you assemble multiple qubits together, it's possible to apply a certain set of starting conditions to each of those qubits — creating what quantum physicists call "interference effects" — that skew the undefined spins and set their interactions off on a particular course.

- Qubits can represent numerous possible combinations of 1 and 0 at the same time. This ability to simultaneously be in multiple states is called superposition. To put qubits into superposition, researchers manipulate them using precision lasers or microwave beams.

Representation of Data - **Superposition**

A single qubit can be forced into a ***superposition*** of the two states denoted by the addition of the state vectors:

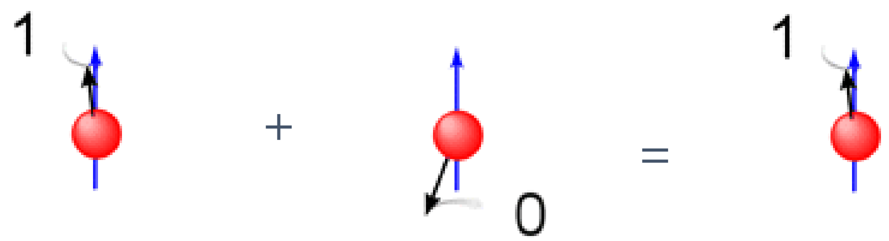
$$|\psi> = \alpha_1 |0> + \alpha_2 |1>$$

Where $\boldsymbol{\alpha^1}$ **and** $\boldsymbol{\alpha^2}$ are complex numbers and $|\alpha_1|^2 + |\alpha_2|^2 = 1$

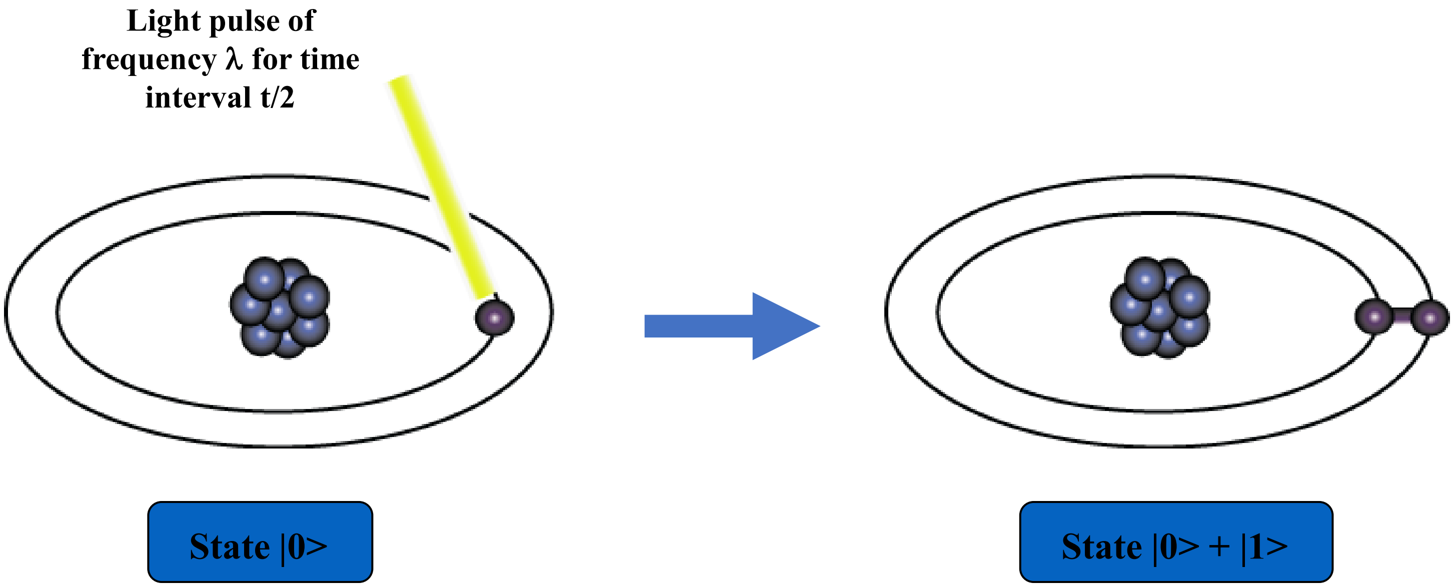
A qubit in superposition is in both of the states |1> and |0 at the same time

Superposition States

$$\left|\Psi\right\rangle = c_1\left|1\right\rangle + c_2\left|0\right\rangle \quad =$$



Representation of Data - Superposition



- Consider a 3 bit qubit register. An equally weighted superposition of all possible states would be denoted by:

$$|\psi\rangle = \frac{1}{\sqrt{8}}|000\rangle + \frac{1}{\sqrt{8}}|001\rangle + \ldots + \frac{1}{\sqrt{8}}|111\rangle$$

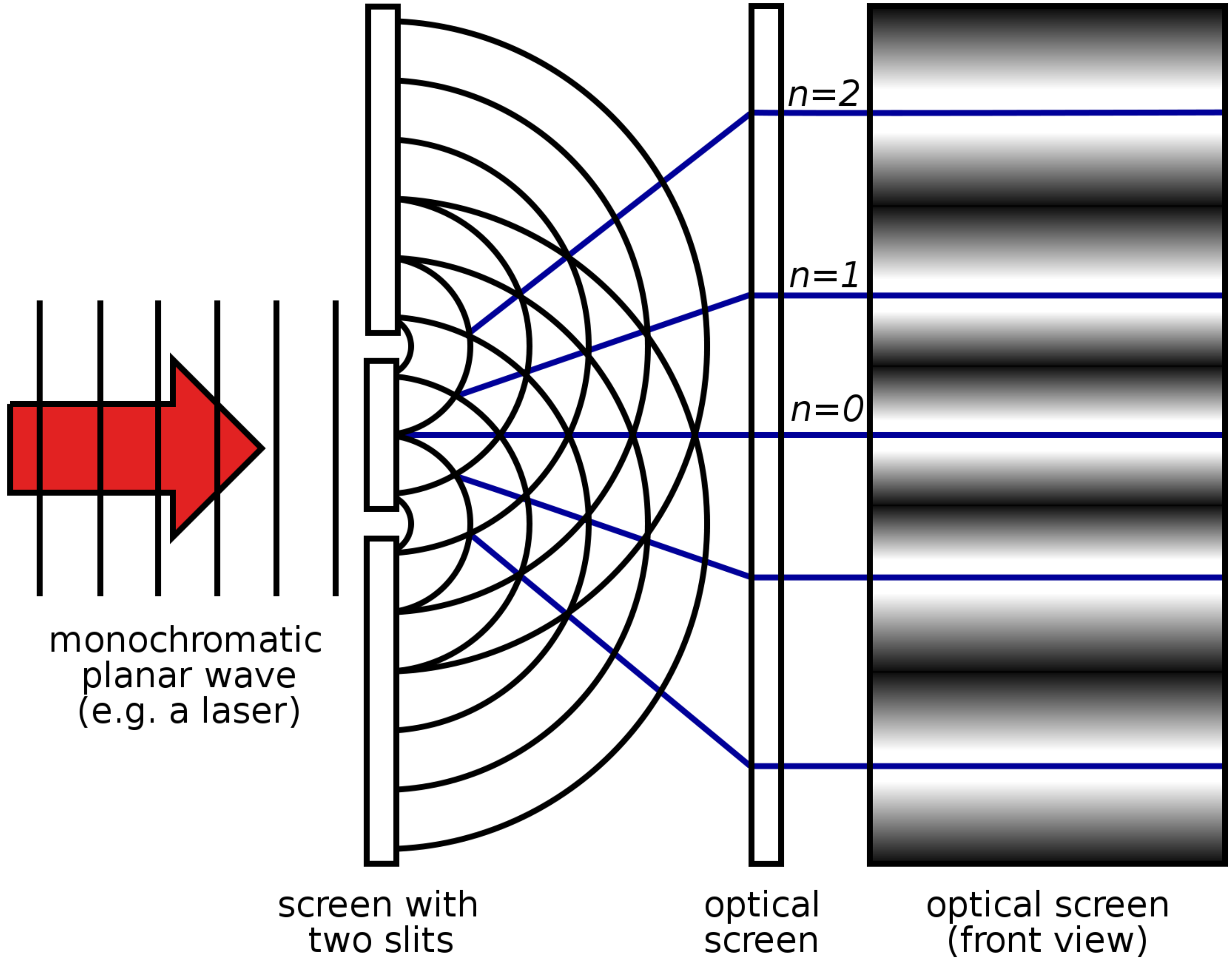
Relationships among data - **Entanglement**

- ***Entanglement*** is the ability of quantum systems to exhibit correlations between states within a superposition.
- Imagine two qubits, each in the state |0> + |1> (a superposition of the 0 and 1.) We can entangle the two qubits such that the measurement of one qubit is always correlated to the measurement of the other qubit.

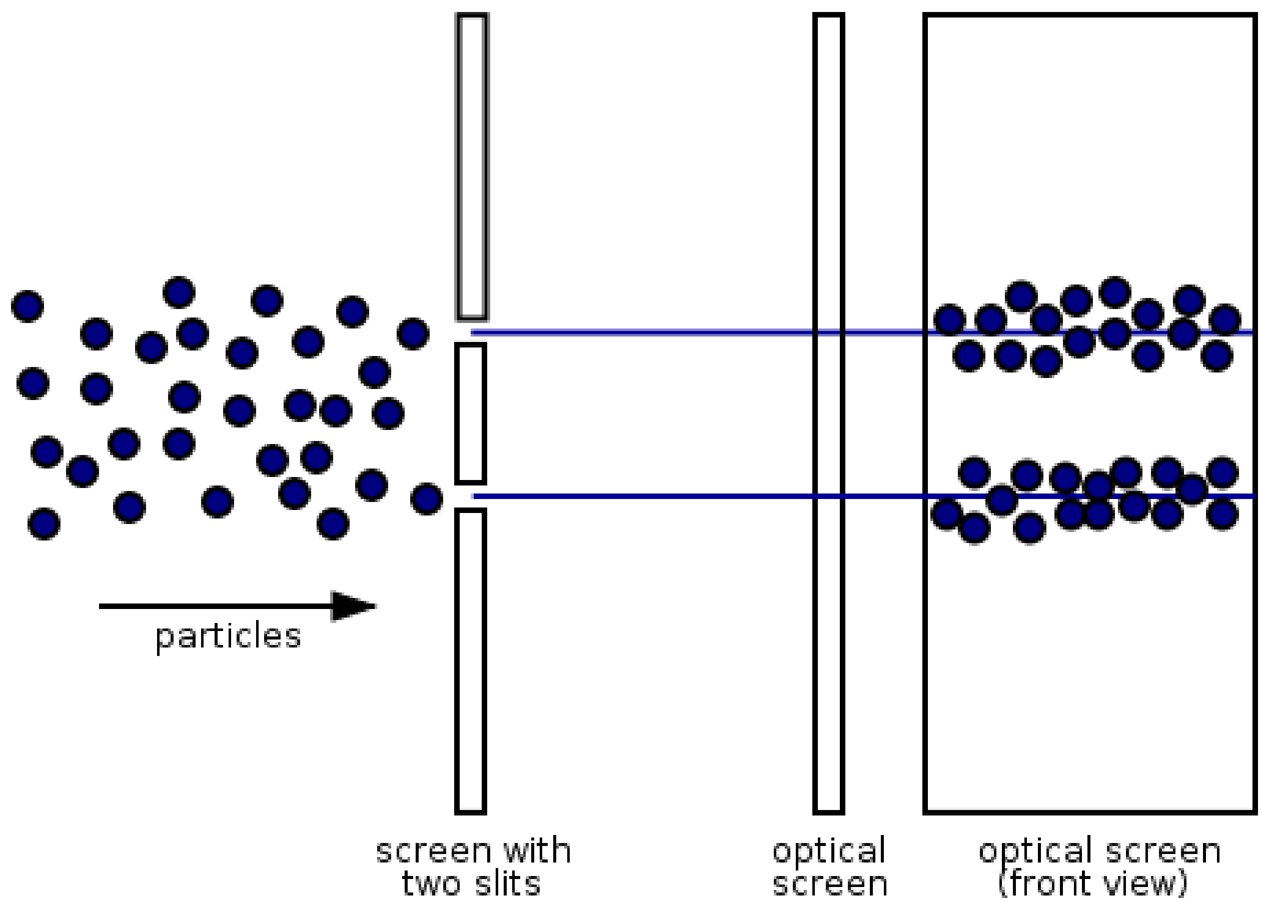
What is entanglement?

- Superposition and interference alone are not quite enough to allow a quantum computer to beat a classical one. The secret sauce that makes quantum computers perform certain computations faster than classical computers also requires a vital third phenomenon, known as **quantum entanglement**.
- Entanglement, which has no parallel in the classical world, arises between quantum particles that interact in particular ways, causing all their properties to become shared between the particles. The result is that measurements on one particle can affect the outcome of subsequent measurements on any particles entangled with it — even when they are not physically connected. That's why Albert Einstein described the phenomenon as "spooky action at a distance.“
- Because entanglement is woven into the mathematics of superposition and interference, it plays a subtle role in the way quantum algorithms work — a role that is extremely difficult to replicate on classical computers. Quantum computers without entanglement would be easy to simulate classically and thus unable to achieve any computational speedup.

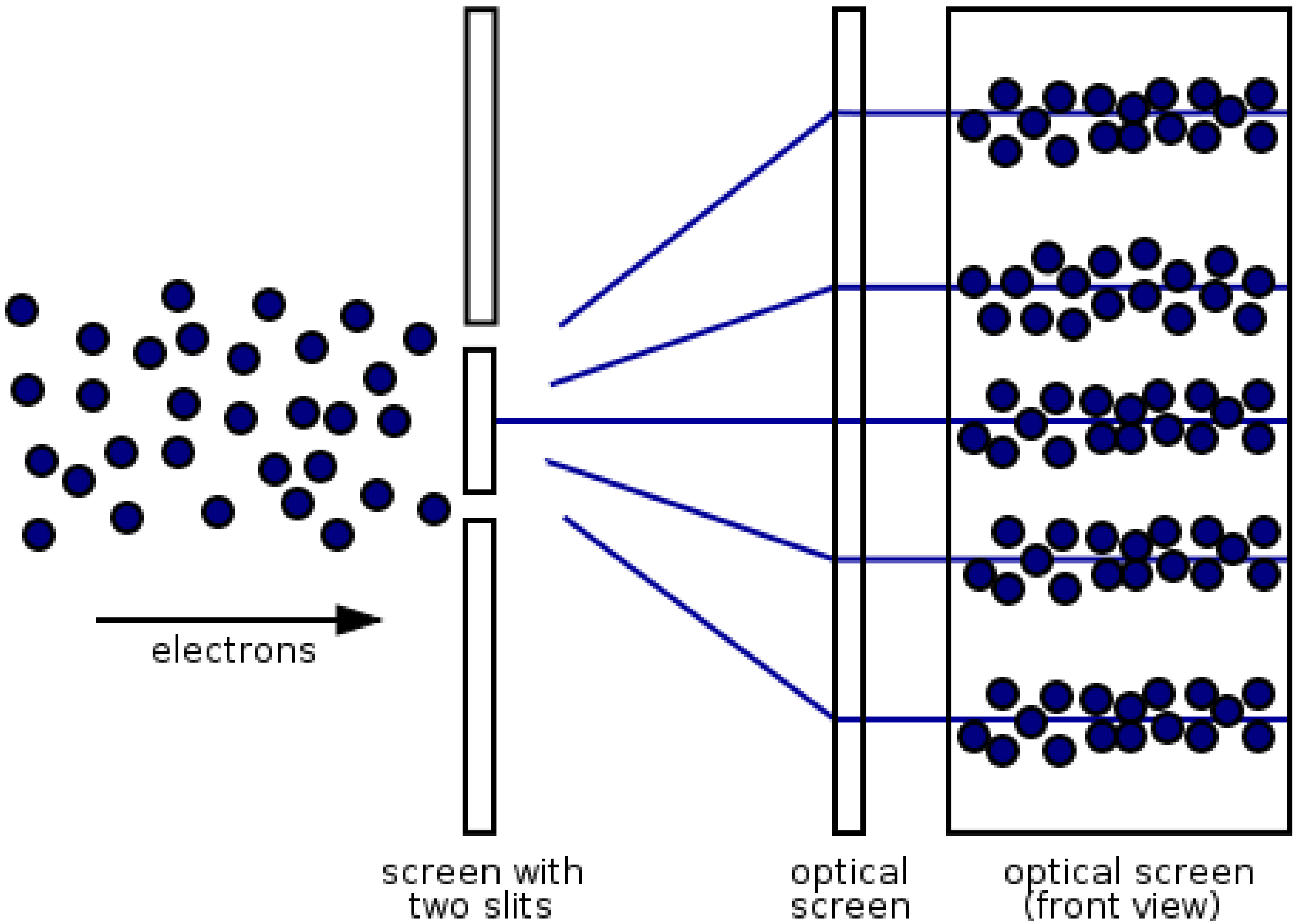
Young’s double slit experiment



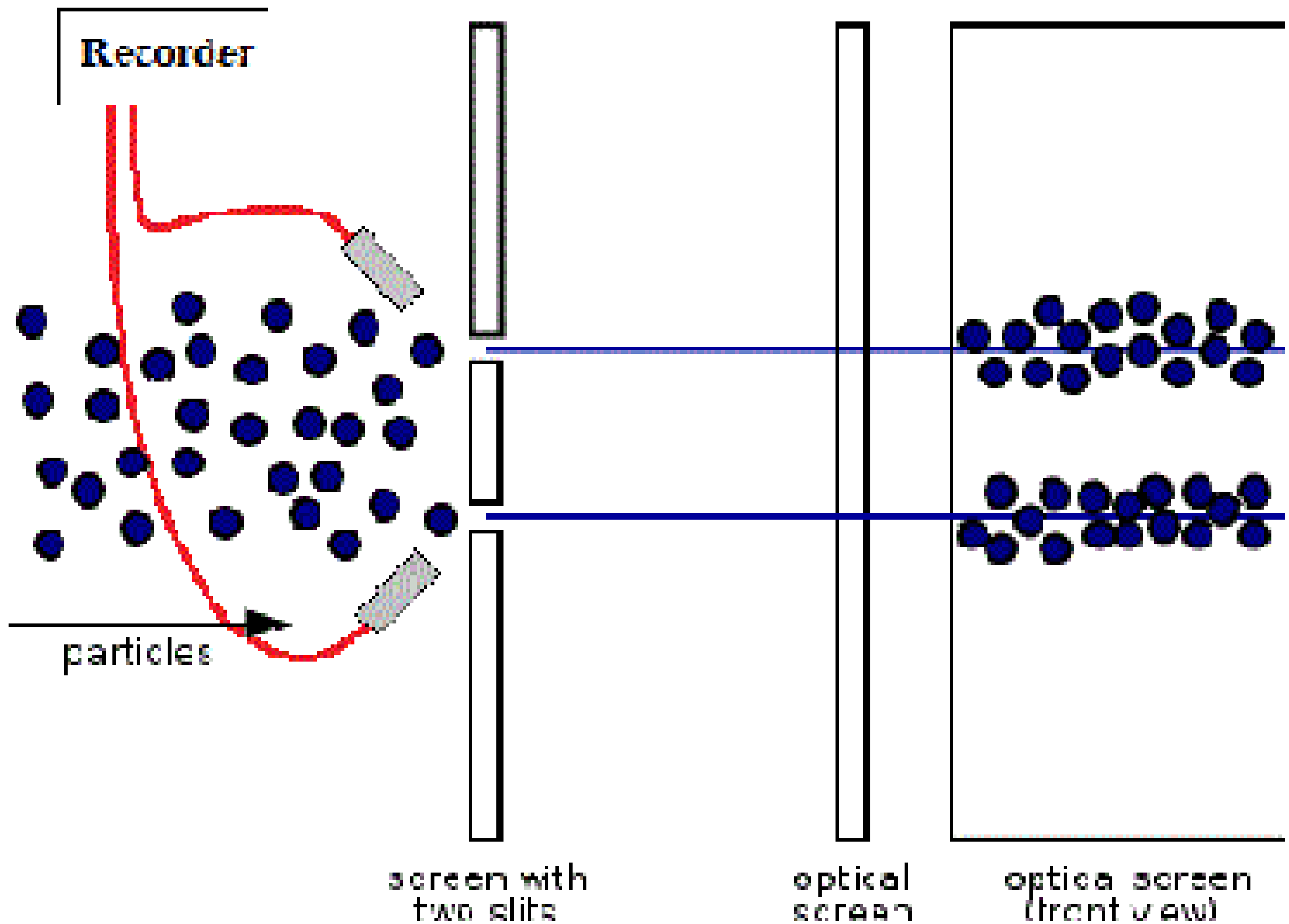
Particles behave differently than waves in double slit experiment



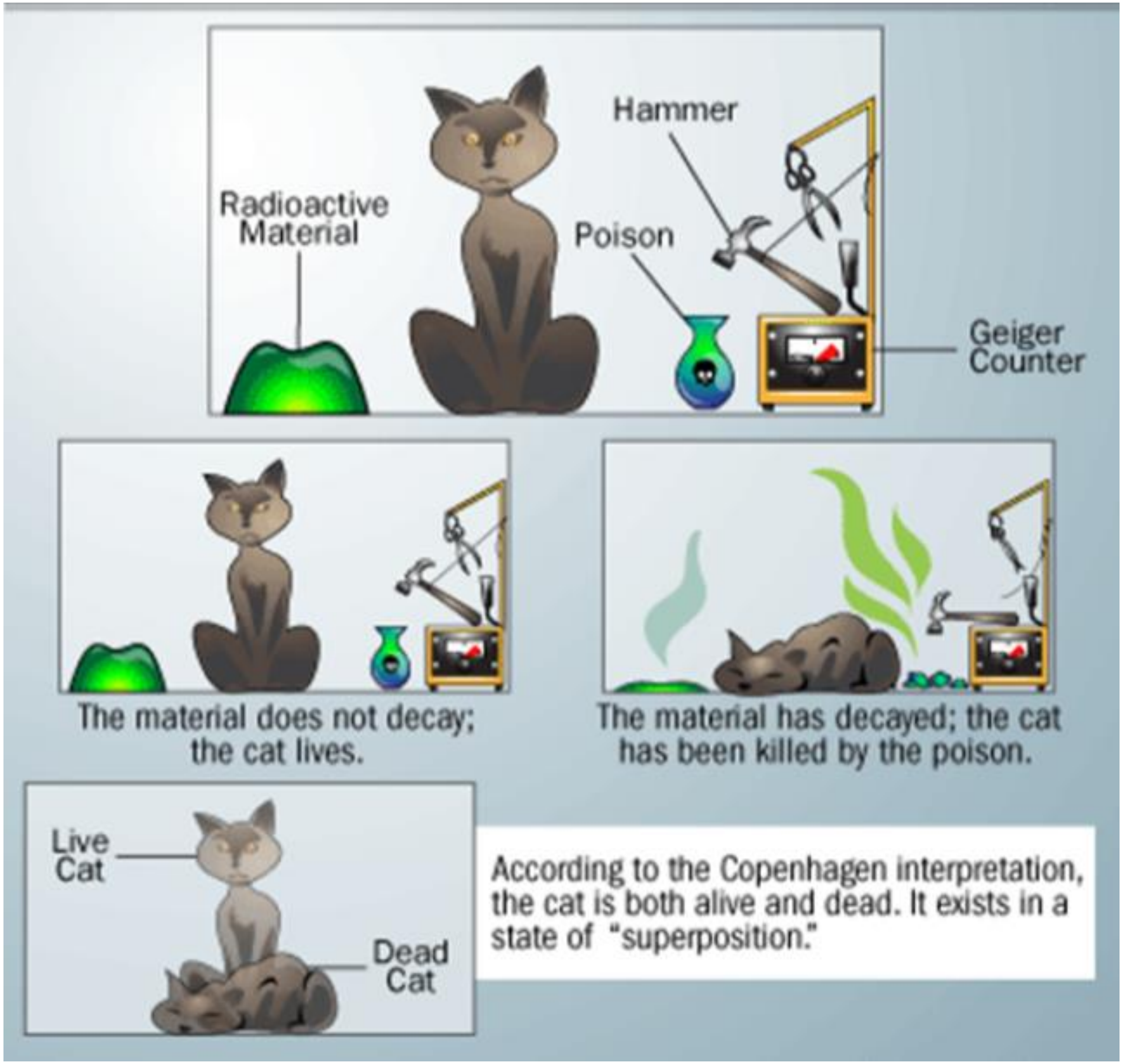
Electrons behave as waves



Electrons behave like particles when detectors are placed

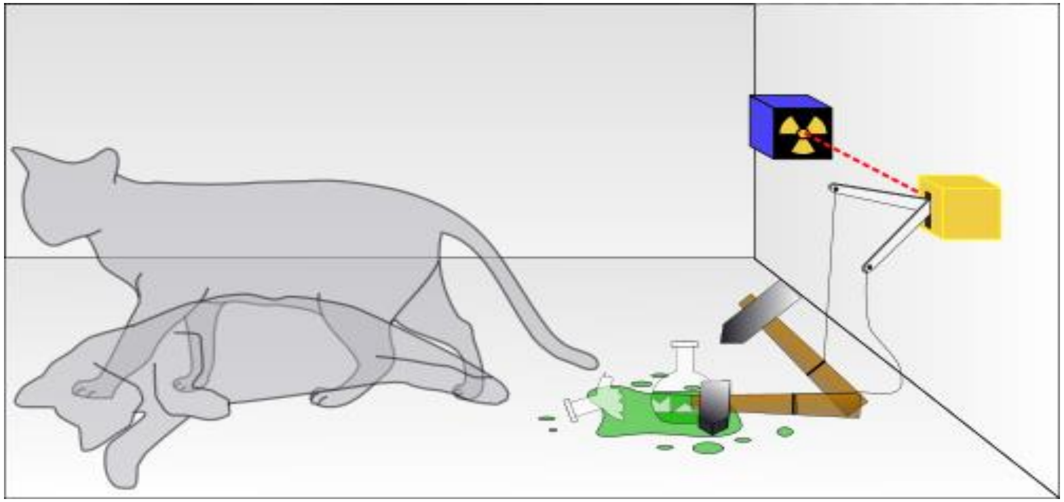


Schrödinger's Cat



Quantum Mechanics: Schrodinger's Cat: Description

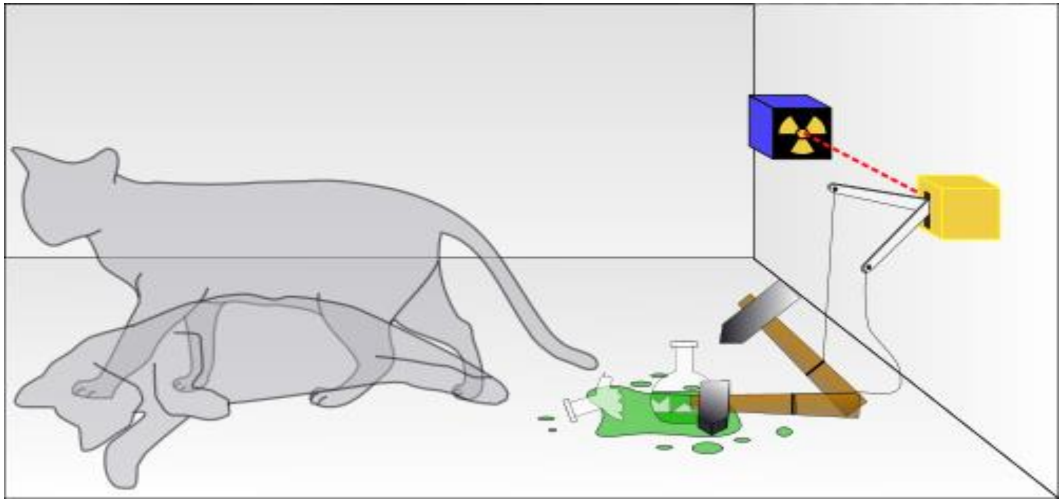
- Cat in a closed box
- A quantum decision is made in the box that may kill the cat
- Time passes



Quantum Mechanics:
Schrodinger's Cat: Description

Just before the box is opened: is the cat dead?

1. Either yes or no, but you won't know until the box is opened.
2. Both yes and no until the box is opened, then either yes or no.



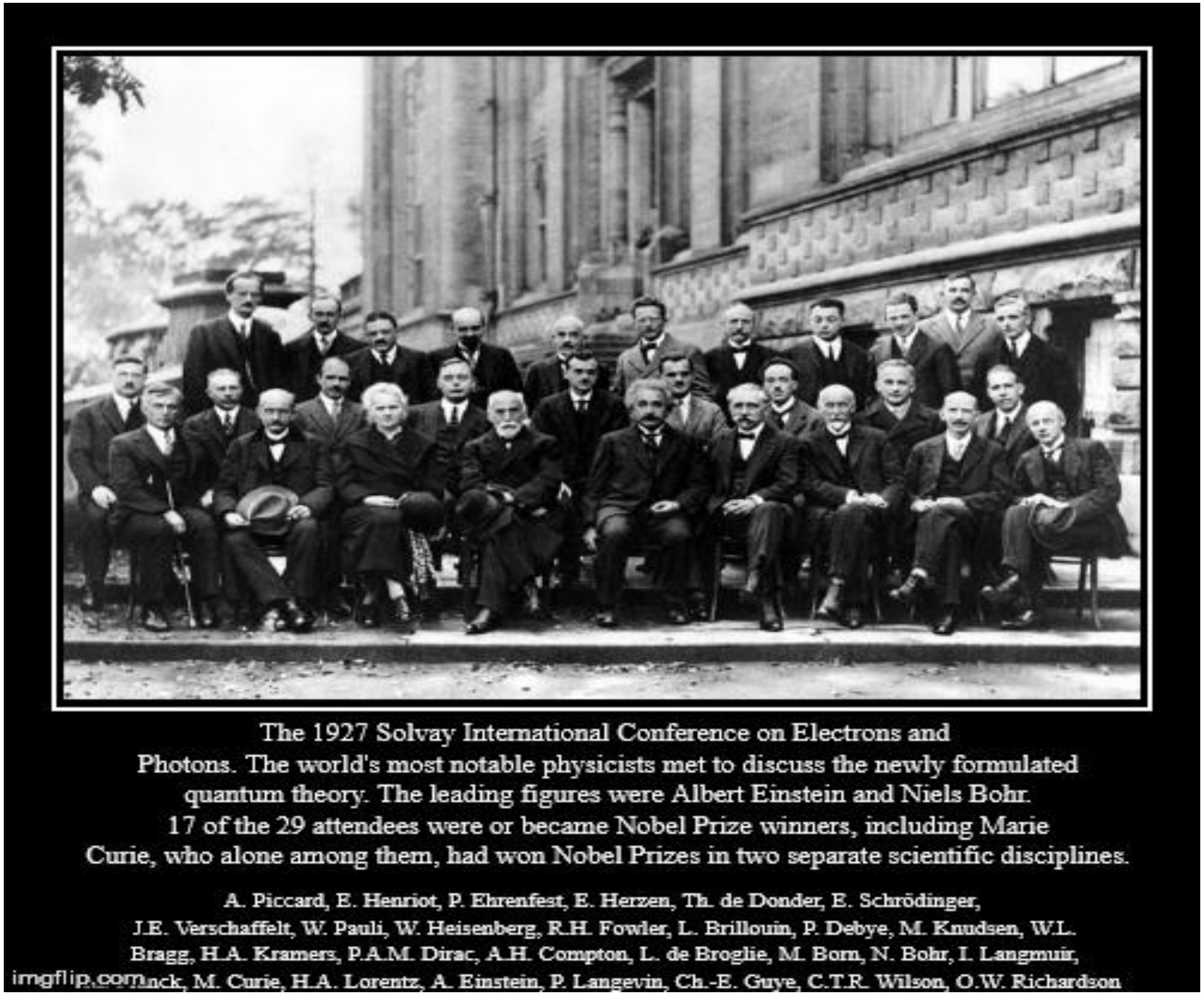
TRIUMPH OF THE COPENHAGEN INTERPRETATION (1925-1927)

"We regard quantum mechanics as a complete theory for which the fundamental physical and mathematical hypotheses are no longer susceptible of modification."

—Heisenberg and Max Born, paper delivered to Solvay Congress of 1927

Heisenberg formulated the uncertainty principle in February 1927 while employed as a lecturer in Bohr's Institute for Theoretical Physics at the University of Copenhagen. Bohr, who had been on a skiing vacation, returned to the institute to find Heisenberg's paper already in draft. Forwarding the paper to Einstein at Heisenberg's request, Bohr complained to Einstein that Heisenberg's approach was too narrow and his gamma-ray microscope was flawed, although the result was correct. For Bohr, the uncertainty relations arose not merely from the quantum equations and the use of particles and discontinuity. Waves and particles had to be taken equally into account, and the scattering of light waves by the electron was also crucial. When Heisenberg corrected his thought experiment, it only confirmed the results

Copenhagen Interpretation



- It states that an object in a physical system can simultaneously exist in all possible configurations, but observing the system forces the system to collapse and forces the object into just one of those possible states.

Copenhagen Interpretation

The Copenhagen interpretation was the first general attempt to understand the world of atoms as this is represented by quantum mechanics.

The founding father was mainly the Niels Bohr, but also Werner Heisenberg, Max Born and other physicists made important contributions to the overall understanding of the atomic world.

Schrodinger's Cat:
Copenhagen Interpretation

2. Both yes and no until the box is opened, then either yes or no.

- The cat is BOTH alive and dead until the box is opened!
- Cat's "wave function state" collapses only when the box is opened
- "Opening the box" can really mean
    - actually opening the box
    - looking into the box
    - doing any determinative experiment to the closed box

Schrodinger's Cat
Contrasting Interpretations

1. Either yes or no, but you won't know until the box is opened.

- Many Worlds Interpretation
  - separate universes house dead and alive cats
  - these universes are decoherent -- do not interact

- Ensemble Interpretation
  - individual cats are either alive or dead, not both, but you can't know which until the box is opened
  - statistics are only built up when many single-cat systems are observed

Schrodinger's Cat: Interpretations

Mathematically, it doesn't matter.

Copenhagen, Many Worlds, and Ensemble Interpretations of quantum mechanics all derive from the same mathematics.

They all predict the same percentage chance that the cat is alive of dead when the box is opened.

Is Schrodinger's cat really a philosophical issue?

Other experiments might be definitive.

Schrodinger's Cat: Thoughts

Thoughts:

- Let say a Crime Scene Investigation (CSI) team examined the dead cat.
  - How warm was the dead cat when the box was opened?
  - Could this tell how long the cat has been dead?
  - Even if they could, it would not negate the Copenhagen Interpretation of quantum mechanics.

Schrodinger's Cat: Thoughts

Thoughts:

- What happens if only incomplete information about the cat is obtained before opening the box?
  - What if one side of the box is slightly warmer than the other?

Quantum Mechanics:
Wigner's Friend

Wigner's friend preforms the Schrodinger Cat experiment while Wigner is away. When Wigner returns, his friend tells him the result of the experiment. For Wigner, when did the cat stop being in state of both alive and dead?

1. When Wigner's friend opened the cat box.
2. When Wigner's friend told Wigner the result of his experiment.

How important is consciousness in wave function collapse? What determines wave function collapse at all?

Quantum Mechanics:
Quantum Suicide Machine

In a closed box, every so often, a 50/50 quantum mechanical (QM) event determines whether an experimenter is killed.

After many of these QM events, will the experimenter survive?

1. No, eventually the experimenter's luck will run out.
2. Yes, the experimenter cannot be killed by such a device.

Quantum Mechanics: Quantum Suicide Machine

- Copenhagen Interpretation: No. The chance of death eventually becomes so great that, practically, no experimenter will survive.

- Many Worlds Interpretation: Yes, if the results of the experiment are only given by the experimenter. Only worlds where the experimenter survives are self-reported, so the experimenter will never seem to die.
  - Does this require a conscience experimenter?

How Quantum Computers Work

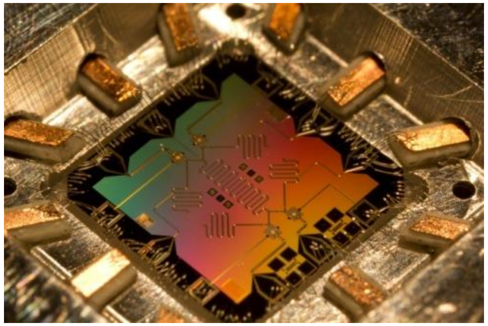
Today's Computers

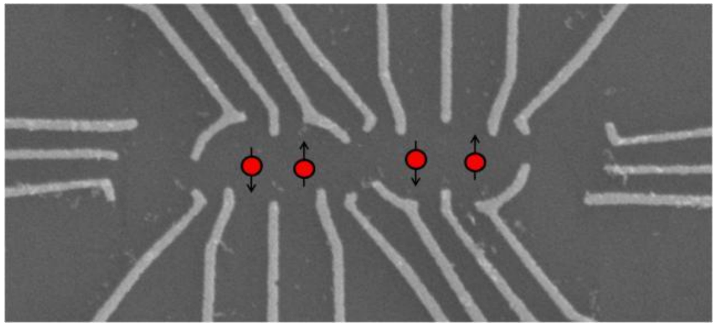
- **Turing Machine-** theoretical device that consists of tape of unlimited length that is divided into little squares. Each square can either hold a symbol (1 or 0) or be left blank.
- Today's computers work by manipulating bits that exist in one of two states: a 0 or a 1.
- 1 and 0's are carried and turned on by states of electrical current

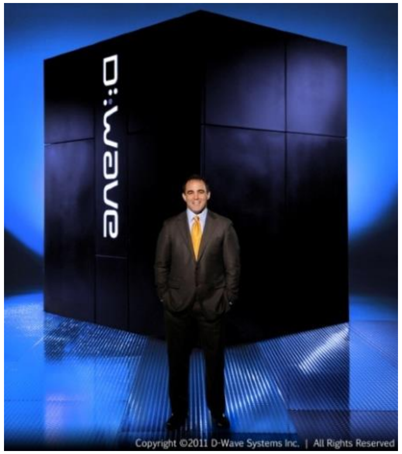
Quantum Computers

- Quantum computers aren't limited to two states like today's computers. They encode information as quantum bits, or **qubits**, which can exist in **superposition**.
- **Superposition-** quantum computers can represent both 0 and 1 as well as everything in between at the same time.
- **Qubits** can be carried as atoms, ions, photons or electrons and their respective control devices that are working together to act as computer memory and a processor.
- **Basically, a quantum computer can work on a million computations at once, while your desktop PC works on one.**

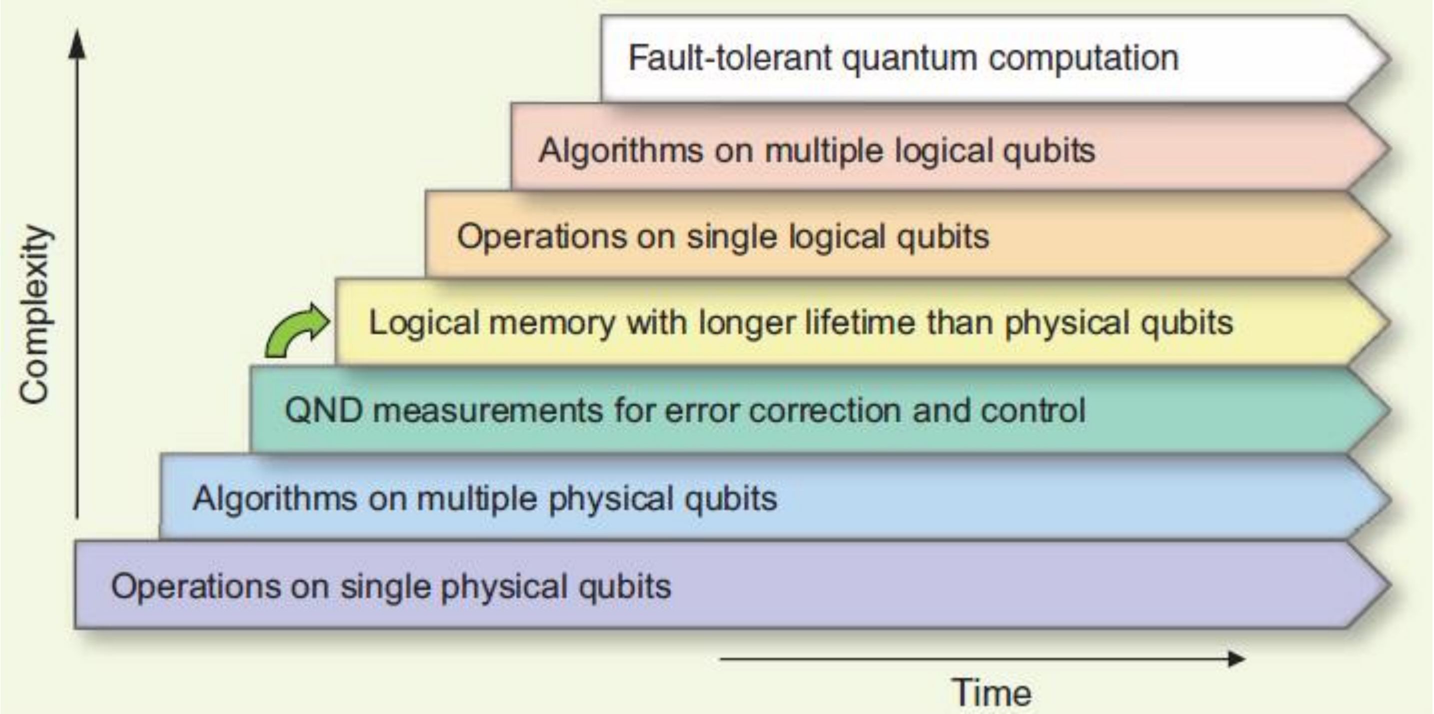
- How to realize a quantum computer







Steps to Build a Quantum Computer



M. H. Devoret and R. J. Schoelkopf, *Science*, **339**, 1169 (2013).

QC Schemes

- Strong control over qubits
  - Trapped ions/atoms
  - Superconducting circuits
  - Spins in various materials

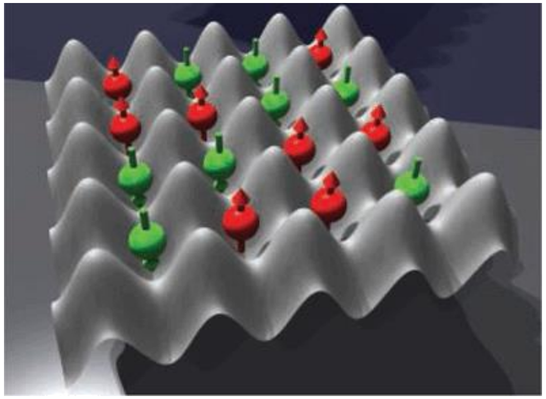
- Isolation from decoherence
  - Topologically protected states

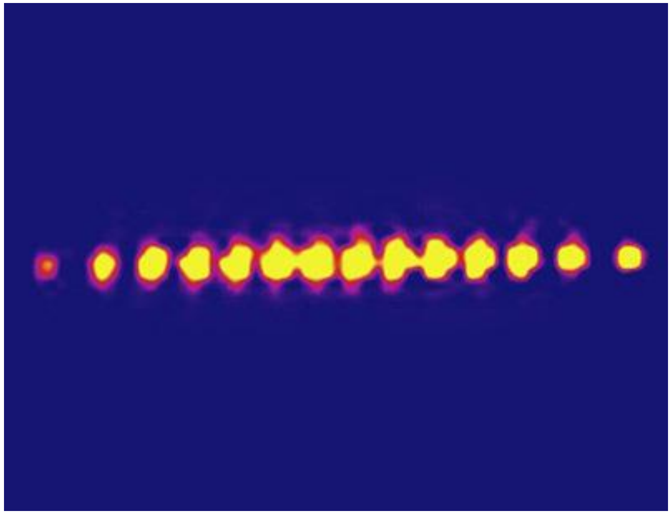
- Quantum annealing (its own separate topic)

Ion Traps

- Electrostatic traps hold ions in place (in vacuum)
  - Motion of ions serves to couple qubits

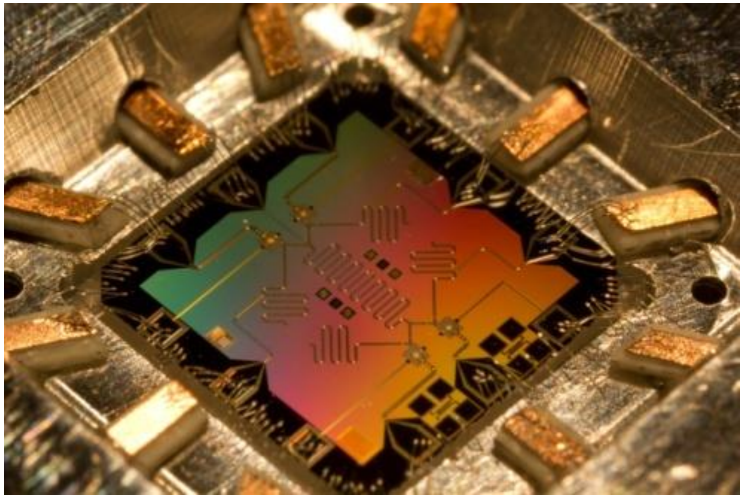
- Technology developed first, and still "furthest along": 14 qubits (2011)





T. Monz *et al*., *Phys. Rev. Lett*. **106**, 130506 (2011).; L. Fallani, M. Inguscio, *Science*, **322**, 1480 (2008).

Superconducting and Spin Qubits



http://web.physics.ucsb.edu/~martinisgroup/

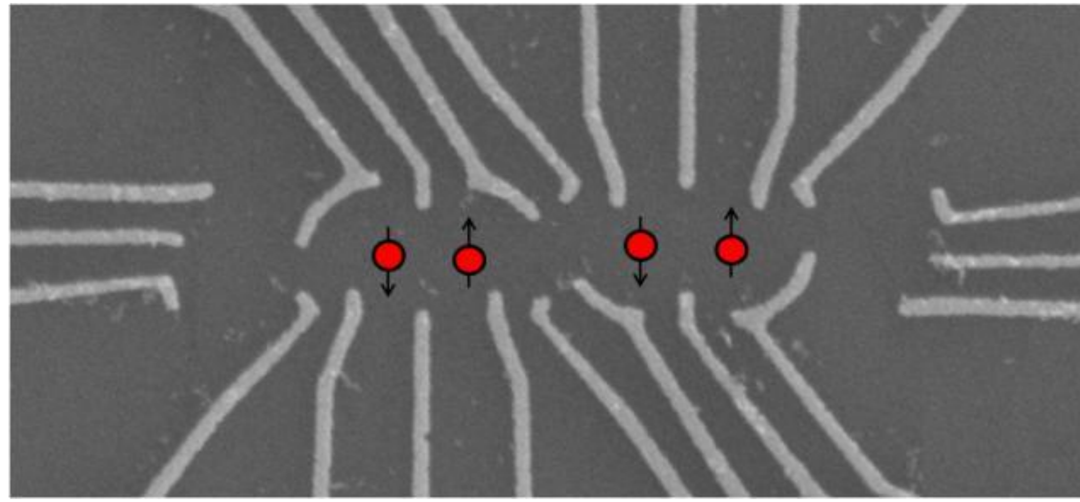


Image courtesy of M.D. Shulman

- Superconducting qubits: aluminum circuits
  - Amount of charge, Direction of superconducting current, Phase of current across a junction
- Spins
  - Defect centers in diamond, silicon
  - Artificial atoms

Summary of Qubit Approaches

Qubit type	Advantages	Weaknesses
Ion/atom Trap	-Extremely good quantum state control -Little interaction with environment -All ions are identical	-Difficult to scale up the number of qubits
Superconducting	-Compatible with current lithography procedures -Electrical control	-Each qubit is slightly different due to fabrication imperfections
Spins	**Depending on the system:** -Potentially long coherence times -Optical and/or electrical control possible -Room temperature operation	-Each qubit may be slightly different -Difficult to isolate from the environment
Topological	-Insensitivity to noise in the environment	-Forming topologically protected states is difficult -No demonstrated qubits yet

Quantum Computers can shine

For example-

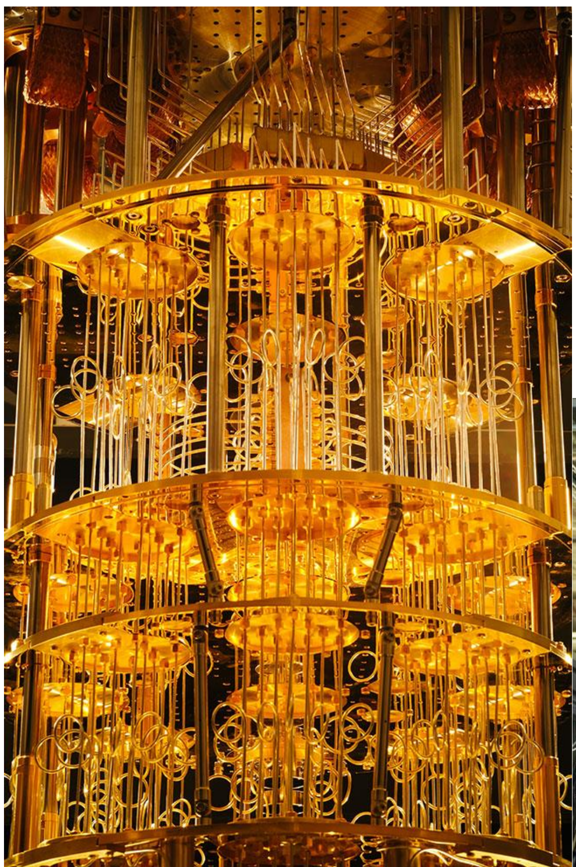
- **They’re great at factoring large numbers,**
- **A vital tool in cryptography and Digital security**
- **Could simulate complex molecular systems, which could aid drug discovery.**

In principle, quantum computers could turbocharge many areas of research and industry

IBM Delivers Its Highest Quantum Volume to Date, Expanding the Computational Power of its IBM Cloud-Accessible Quantum Computers

Company achieves a quantum volume of 64 through full-stack improvements

YORKTOWN HEIGHTS, N.Y., Aug. 20, 2020 /PRNewswire/ -- Today, IBM has unveiled a new milestone on its quantum computing road map, achieving the company's highest Quantum Volume to date. Combining a series of new software and hardware techniques to improve overall performance, IBM has upgraded one of its newest 27-qubit client-deployed systems to achieve a Quantum Volume 64. The company has made a total of 28 quantum computers available over the last four years through IBM Quantum Experience.



Quantum computer developed by IBM Research in Zurich, Switzerland