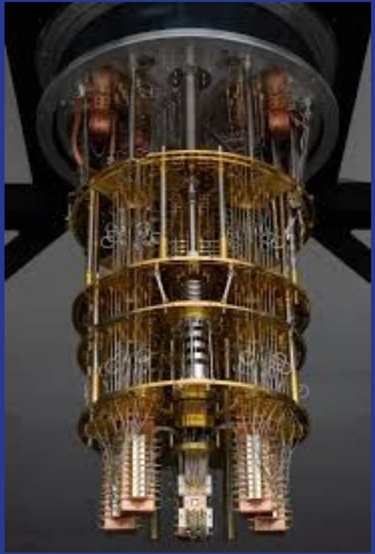
YSIQ: History

Jeffrey Wei



About Me

Acton, Massachusetts

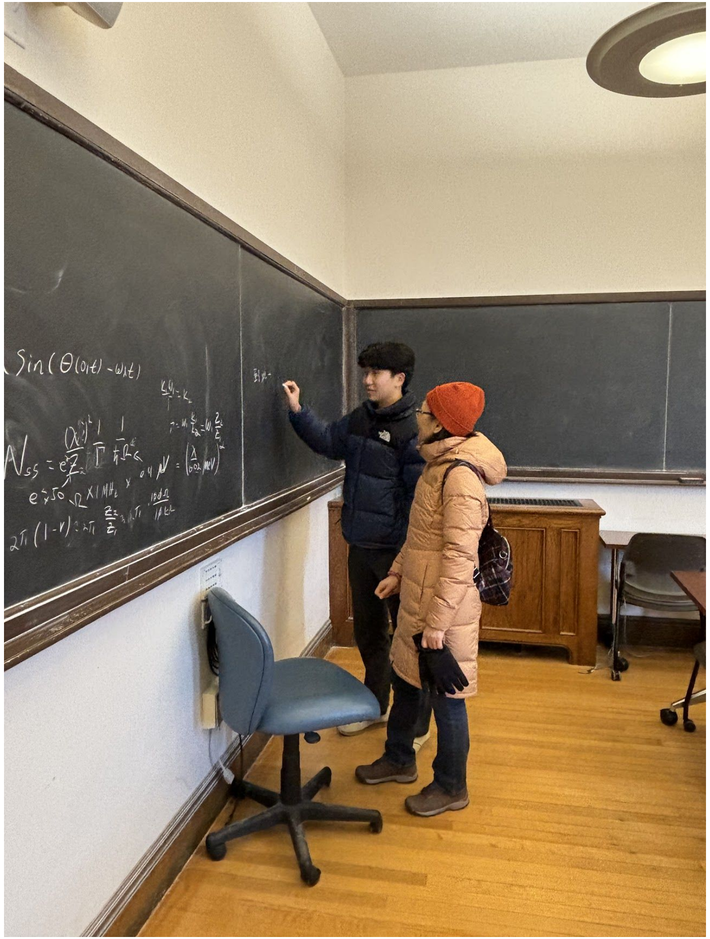
Science Olympiad, Astronomy

Physics & Computer Science ‘27

Interested in Embodied AI, quantum algorithms, AI4Science.

Hope to pursue a PhD in computer science.

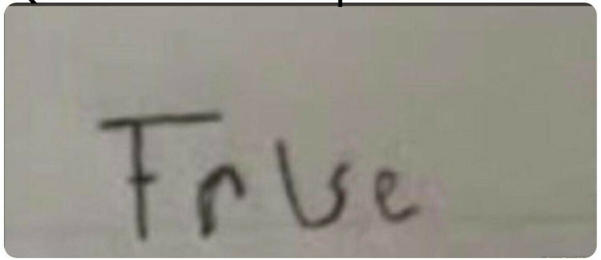
Hobbies: Learning Languages, Films, Sci-Fi, Memoirs / Autobiographies.



Memes of the Day (MOTD)

boolean: exists

Quantum computer:



1. History of Classical Computing
2. Classical to Quantum Mechanics
3. Early Quantum Algorithms
4. Early Quantum Hardware
5. Quantum Computing: Present and Future

1. History of Classical Computing

1. *Some Quick Background*
2. Babbage, Lovelace, Turing
3. The Transistor, and its Limitations
4. Richard Feynman et. al.
5. Why Quantum Computing

Key Concepts

1. Computer

2. Program

3. Bit

4. Algorithm vs Hardware

Key Concepts

1. Computer: a device that follows rules (algorithms) to transform symbols (data).

2. Program

3. Bit

4. Algorithm vs Hardware

Key Concepts

1. Computer: a device that follows rules (algorithms) to transform symbols (data).

2. Program: a precise list of steps a machine can follow.

3. Bit

4. Algorithm vs Hardware

Key Concepts

1. Computer: a device that follows rules (algorithms) to transform symbols (data).

2. Program: a precise list of steps a machine can follow.

3. Bit: a basic yes/no unit (0 or 1)

4. Algorithm vs Hardware

Key Concepts

1. Computer: a device that follows rules (algorithms) to transform symbols (data).

2. Program: a precise list of steps a machine can follow.

3. Bit: a basic yes/no unit (0 or 1)

4. Algorithm vs Hardware: the recipe versus the kitchen.

1. Some Quick Background
2. *Babbage, Lovelace, Turing*
3. The Transistor, and its Limitations
4. Richard Feynman et. al.
5. Why Quantum Computing

Setting the Scene of Pre-1820s

“Computer” meant a human calculator.

Algorithms were methods in books i.e. Newton’s method, long division

Quill and paper, logarithm tables

Slow and error prone — mistakes sank ships and costed money

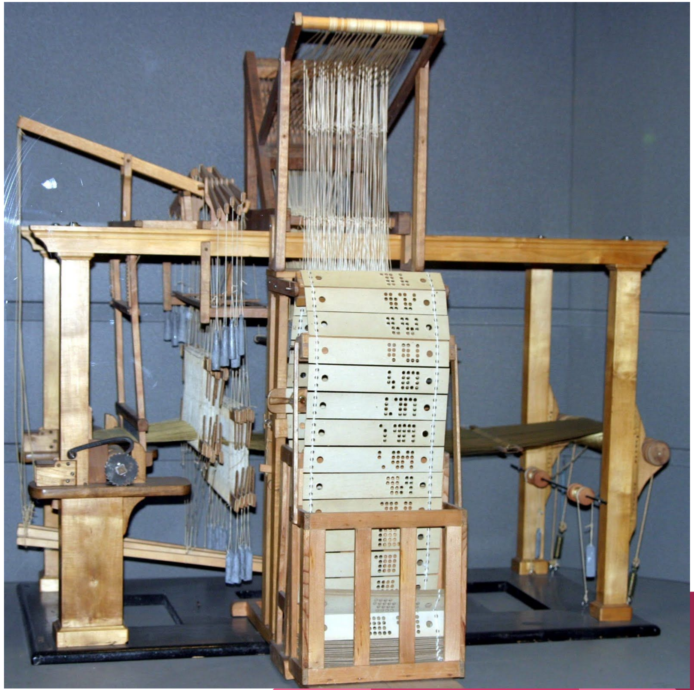
1801 - The Jacquard Loom

Closest thing to computers

Punch cards to control weaving patterns

“Programmers” were predominantly women

Key Idea: store instructions (algorithm) externally



Charles Babbage (1791–1871)

English

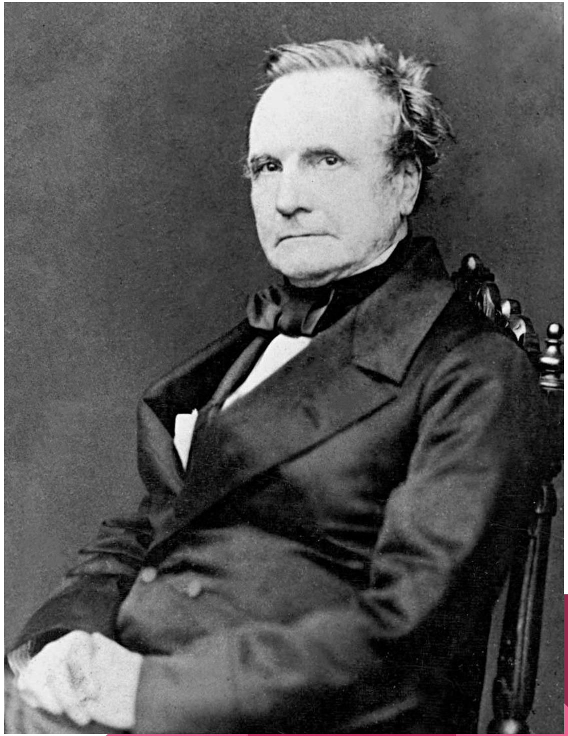
Trinity College, Cambridge

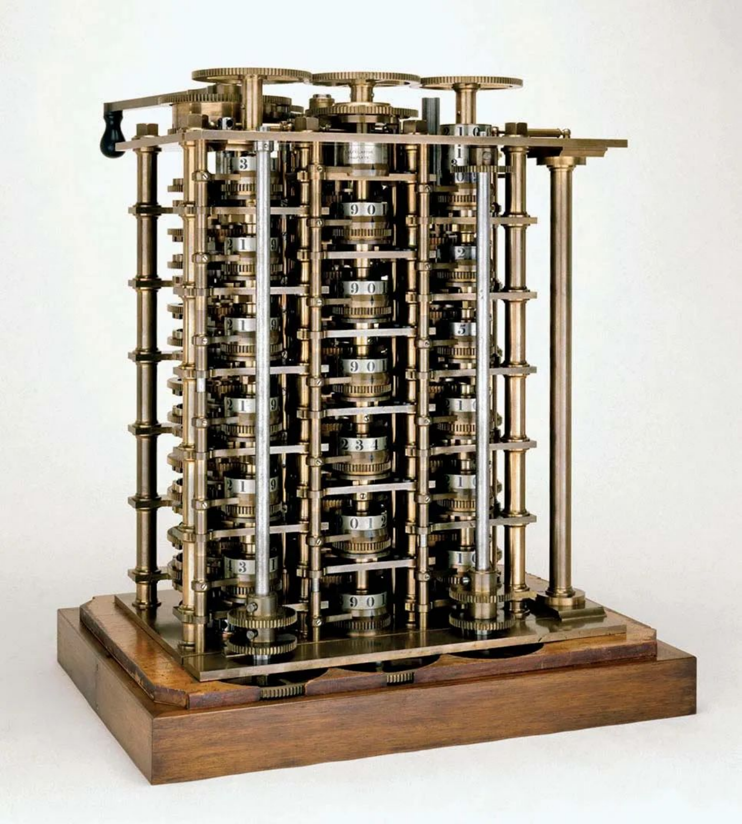
1820 - Difference Engine

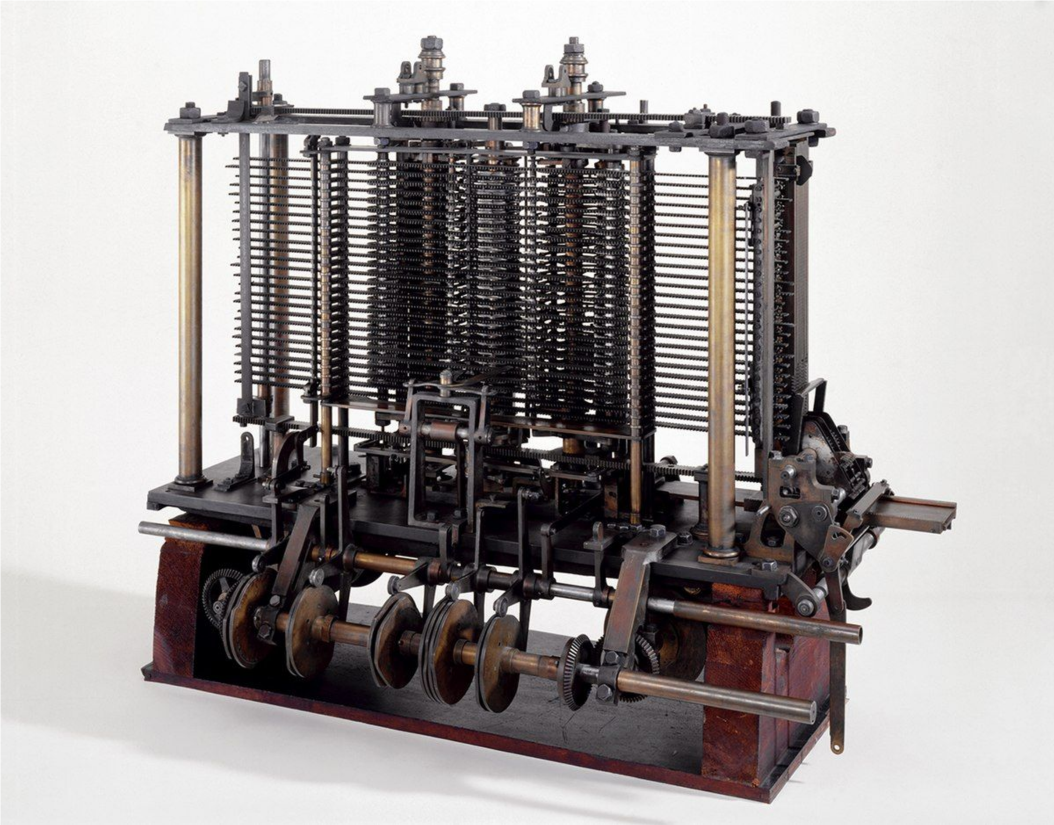
1830s - Analytical Engine

Visionary for Computer Architecture

Never built







Left: Difference Engine | Right: Analytical Engine

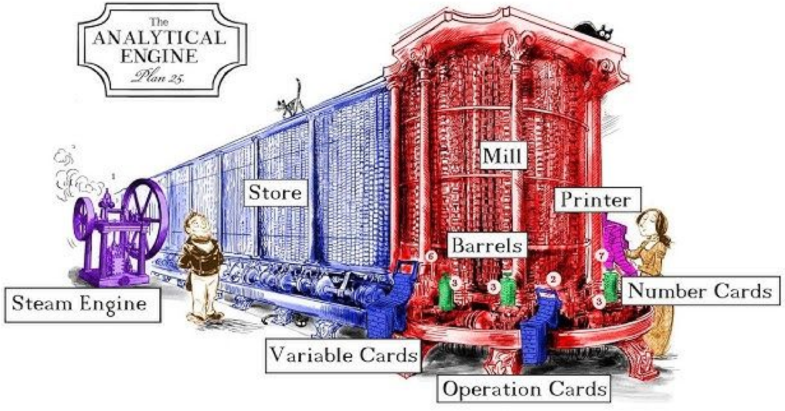
Analytical Engine - Deep Dive

Store and Mill vs memory and CPU

Punched Cards i.e. in/out + control

Conditional branching and loops

Separate Hardware vs Program



Ada Lovelace (1815–1852)

Daughter of Lord Byron

“Poetical Science”

Publishes the Notes A-G on Analytical Engine

First Published Programmer

Visionary of computing uses

1843 – Note G

Publishes Notes G after working on Analytical Engine

Explicit procedure for computing Bernoulli Numbers

Symbols vs Numbers → Music, Graphics, Text

Abstraction: same hardware, different programs

Theorizes Limits: “no spontaneous originality”

$$
\begin{aligned}
B_n &= -\sum_{k=0}^{n-1} \frac{n!}{(n+1-k)! \cdot k!} B_k \\
&= -\sum_{k=0}^{n-1} \binom{n}{k} \frac{B_k}{n+1-k}
\end{aligned}
$$

Diagram for the computation by the Engine of the Numbers of Bernoulli. See Note G. (page 722 *et seq.*)

Number of Operation.	Nature of Operation.	Variables acted upon.	Variables receiving results.	Indication of change in the value on any Variable.	Statement of Results.	Data.			Working Variables.										Result Variables.			
						$^1V_1$ ○ 0 0 0 1 $\boxed{1}$	$^1V_2$ ○ 0 0 0 2 $\boxed{2}$	$^1V_3$ ○ 0 0 0 4 $\boxed{n}$	$^0V_4$ ○ 0 0 0 0	$^0V_5$ ○ 0 0 0 0	$^0V_6$ ○ 0 0 0 0	$^0V_7$ ○ 0 0 0 0	$^0V_8$ ○ 0 0 0 0	$^0V_9$ ○ 0 0 0 0	$^0V_{10}$ ○ 0 0 0 0	$^0V_{11}$ ○ 0 0 0 0	$^0V_{12}$ ○ 0 0 0 0	$^0V_{13}$ ○ 0 0 0 0 …………	$^1V_{21}$ ○ B_1 in a decimal fraction. $\boxed{B_1}$	$^1V_{22}$ ○ B_3 in a decimal fraction. $\boxed{B_3}$	$^1V_{23}$ ○ B_5 in a decimal fraction. $\boxed{B_5}$	$^0V_{24}$ … ○ 0 0 0 0 $\boxed{B_7}$
1	$\times$	$^1V_2 \times {}^1V_3$	$^1V_4, {}^1V_5, {}^1V_6$	$\left\{\begin{matrix}{}^1V_2={}^1V_2\\{}^1V_3={}^1V_3\end{matrix}\right\}$	$=2n$	...	2	n	$2n$	$2n$	$2n$											
2	$-$	$^1V_4 - {}^1V_1$	$^2V_4$	$\left\{\begin{matrix}{}^1V_4={}^2V_4\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=2n-1$	1	...	...	$2n-1$													
3	$+$	$^1V_5 + {}^1V_1$	$^2V_5$	$\left\{\begin{matrix}{}^1V_5={}^2V_5\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=2n+1$	1	...	...	...	$2n+1$												
4	$\div$	$^2V_5 \div {}^2V_4$	$^1V_{11}$	$\left\{\begin{matrix}{}^2V_5={}^0V_5\\{}^2V_4={}^0V_4\end{matrix}\right\}$	$=\frac{2n-1}{2n+1}$	...	...	...	0	0	...	...	...	...	...	$\frac{2n-1}{2n+1}$						
5	$\div$	$^1V_{11} \div {}^1V_2$	$^2V_{11}$	$\left\{\begin{matrix}{}^1V_{11}={}^2V_{11}\\{}^1V_2={}^1V_2\end{matrix}\right\}$	$=\frac{1}{2}\cdot\frac{2n-1}{2n+1}$	...	2	...	...	...	...	...	...	...	...	$\frac{1}{2}\cdot\frac{2n-1}{2n+1}$						
6	$-$	$^0V_{13} - {}^2V_{11}$	$^1V_{13}$	$\left\{\begin{matrix}{}^2V_{11}={}^0V_{11}\\{}^0V_{13}={}^1V_{13}\end{matrix}\right\}$	$=-\frac{1}{2}\cdot\frac{2n-1}{2n+1}=A_0$	...	...	...	...	...	...	...	...	...	...	0	………	$-\frac{1}{2}\cdot\frac{2n-1}{2n+1}=A_0$				
7	$-$	$^1V_3 - {}^1V_1$	$^1V_{10}$	$\left\{\begin{matrix}{}^1V_3={}^1V_3\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=n-1\ (=3)$	1	...	n	...	...	...	...	...	...	$n-1$							
8	$+$	$^1V_2 + {}^0V_7$	$^1V_7$	$\left\{\begin{matrix}{}^1V_2={}^1V_2\\{}^0V_7={}^1V_7\end{matrix}\right\}$	$=2+0=2$	...	2	...	...	...	...	2										
9	$\div$	$^1V_6 \div {}^1V_7$	$^3V_{11}$	$\left\{\begin{matrix}{}^1V_6={}^1V_6\\{}^0V_{11}={}^3V_{11}\end{matrix}\right\}$	$=\frac{2n}{2}=A_1$	...	...	...	...	...	$2n$	2	...	...	...	$\frac{2n}{2}=A_1$						
10	$\times$	$^1V_{21} \times {}^3V_{11}$	$^1V_{12}$	$\left\{\begin{matrix}{}^1V_{21}={}^1V_{21}\\{}^3V_{11}={}^3V_{11}\end{matrix}\right\}$	$=B_1\cdot\frac{2n}{2}=B_1A_1$	...	...	...	...	...	...	...	...	...	...	$\frac{2n}{2}=A_1$	$B_1\cdot\frac{2n}{2}=B_1A_1$	………	B_1			
11	$+$	$^1V_{12} + {}^1V_{13}$	$^2V_{13}$	$\left\{\begin{matrix}{}^1V_{12}={}^0V_{12}\\{}^1V_{13}={}^2V_{13}\end{matrix}\right\}$	$=-\frac{1}{2}\cdot\frac{2n-1}{2n+1}+B_1\cdot\frac{2n}{2}$	...	...	...	...	...	...	...	...	...	...	………	0	$\left\{-\frac{1}{2}\cdot\frac{2n-1}{2n+1}+B_1\cdot\frac{2n}{2}\right\}$				
12	$-$	$^1V_{10} - {}^1V_1$	$^2V_{10}$	$\left\{\begin{matrix}{}^1V_{10}={}^2V_{10}\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=n-2\ (=2)$	1	...	...	...	...	...	...	...	...	$n-2$							
13	$-$	$^1V_6 - {}^1V_1$	$^2V_6$	$\left\{\begin{matrix}{}^1V_6={}^2V_6\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=2n-1$	1	...	...	...	...	$2n-1$											
14	$+$	$^1V_1 + {}^1V_7$	$^2V_7$	$\left\{\begin{matrix}{}^1V_1={}^1V_1\\{}^1V_7={}^2V_7\end{matrix}\right\}$	$=2+1=3$	1	...	...	...	...	...	3										
15	$\div$	$^2V_6 \div {}^2V_7$	$^1V_8$	$\left\{\begin{matrix}{}^2V_6={}^2V_6\\{}^2V_7={}^2V_7\end{matrix}\right\}$	$=\frac{2n-1}{3}$	...	...	...	...	...	$2n-1$	3	$\frac{2n-1}{3}$									
16	$\times$	$^1V_8 \times {}^3V_{11}$	$^4V_{11}$	$\left\{\begin{matrix}{}^1V_8={}^0V_8\\{}^3V_{11}={}^4V_{11}\end{matrix}\right\}$	$=\frac{2n}{2}\cdot\frac{2n-1}{3}$	...	...	...	...	...	...	...	0	...	...	$\frac{2n}{2}\cdot\frac{2n-1}{3}$						
17	$-$	$^2V_6 - {}^1V_1$	$^3V_6$	$\left\{\begin{matrix}{}^2V_6={}^3V_6\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=2n-2$	1	...	...	...	...	$2n-2$											
18	$+$	$^1V_1 + {}^2V_7$	$^3V_7$	$\left\{\begin{matrix}{}^2V_7={}^3V_7\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=3+1=4$	1	...	...	...	...	...	4										
19	$\div$	$^3V_6 \div {}^3V_7$	$^1V_9$	$\left\{\begin{matrix}{}^3V_6={}^3V_6\\{}^3V_7={}^3V_7\end{matrix}\right\}$	$=\frac{2n-2}{4}$	...	...	...	...	...	$2n-2$	4	...	$\frac{2n-2}{4}$	...	$\left\{\begin{matrix}\frac{2n}{2}\cdot\frac{2n-1}{3}\cdot\frac{2n-2}{3}\\=A_3\end{matrix}\right\}$						
20	$\times$	$^1V_9 \times {}^4V_{11}$	$^5V_{11}$	$\left\{\begin{matrix}{}^1V_9={}^0V_9\\{}^4V_{11}={}^5V_{11}\end{matrix}\right\}$	$=\frac{2n}{2}\cdot\frac{2n-1}{3}\cdot\frac{2n-2}{4}=A_3$	...	...	...	...	...	...	...	...	0								
21	$\times$	$^1V_{22} \times {}^5V_{11}$	$^0V_{12}$	$\left\{\begin{matrix}{}^1V_{22}={}^1V_{22}\\{}^0V_{12}={}^2V_{12}\end{matrix}\right\}$	$=B_3\cdot\frac{2n}{2}\cdot\frac{2n-1}{3}\cdot\frac{2n-2}{3}=B_3A_3$	...	...	...	...	...	...	...	...	...	...	0	B_3A_3	………	……	B_3		
22	$+$	$^2V_{12} + {}^2V_{13}$	$^3V_{13}$	$\left\{\begin{matrix}{}^2V_{12}={}^0V_{12}\\{}^2V_{13}={}^3V_{13}\end{matrix}\right\}$	$=A_0+B_1A_1+B_3A_3$	...	...	...	...	...	...	...	...	...	...	………	0	$\left\{A_3+B_1A_1+B_3A_3\right\}$				
23	$-$	$^2V_{10} - {}^1V_1$	$^3V_{10}$	$\left\{\begin{matrix}{}^2V_{10}={}^3V_{10}\\{}^1V_1={}^1V_1\end{matrix}\right\}$	$=n-3\ (=1)$	1	...	...	...	...	...	...	...	...	$n-3$							
					Here follows a repetition of Operations thirteen to twenty-three.																	
24	$+$	$^4V_{13} + {}^0V_{24}$	$^1V_{24}$	$\left\{\begin{matrix}{}^4V_{13}={}^0V_{13}\\{}^0V_{24}={}^1V_{24}\end{matrix}\right\}$	$=B_7$	...	...	...	...	...	...	...	...	...	...	………	………	………	……	……	……	B_7
25	$+$	$^1V_1 + {}^1V_3$	$^1V_3$	$\left\{\begin{matrix}{}^1V_1={}^1V_1\\{}^1V_3={}^1V_3\\{}^5V_6={}^0V_6\\{}^5V_7={}^0V_7\end{matrix}\right\}$	$=n+1=4+1=5$; by a Variable-card. by a Variable-card.	1	...	$n+1$	...	...	0	0										

Ada Lovelace Note G: Calculating Bernoulli Numbers

Alan Turing (1932-1954)

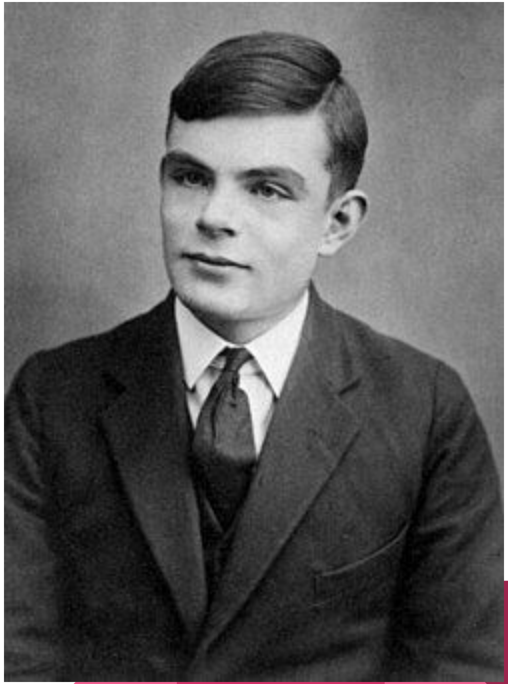
British mathematician and logician

Helped solve the Enigma Problem

Turing Test for Artificial Intelligence

“On Computable Numbers”

Universal Turing Machines



1936 – “On Computable Numbers”

Resolves Hilbert’s Entscheidungsproblem

Invents theory of computation and computability

Conceives Universal Computing Machine (Turing Machine)

Lays foundation for all programmable machines

ON COMPUTABLE NUMBERS, WITH AN APPLICATION TO THE ENTSCHEIDUNGSPROBLEM

By A. M. TURING.

[Received 28 May, 1936.—Read 12 November, 1936.]

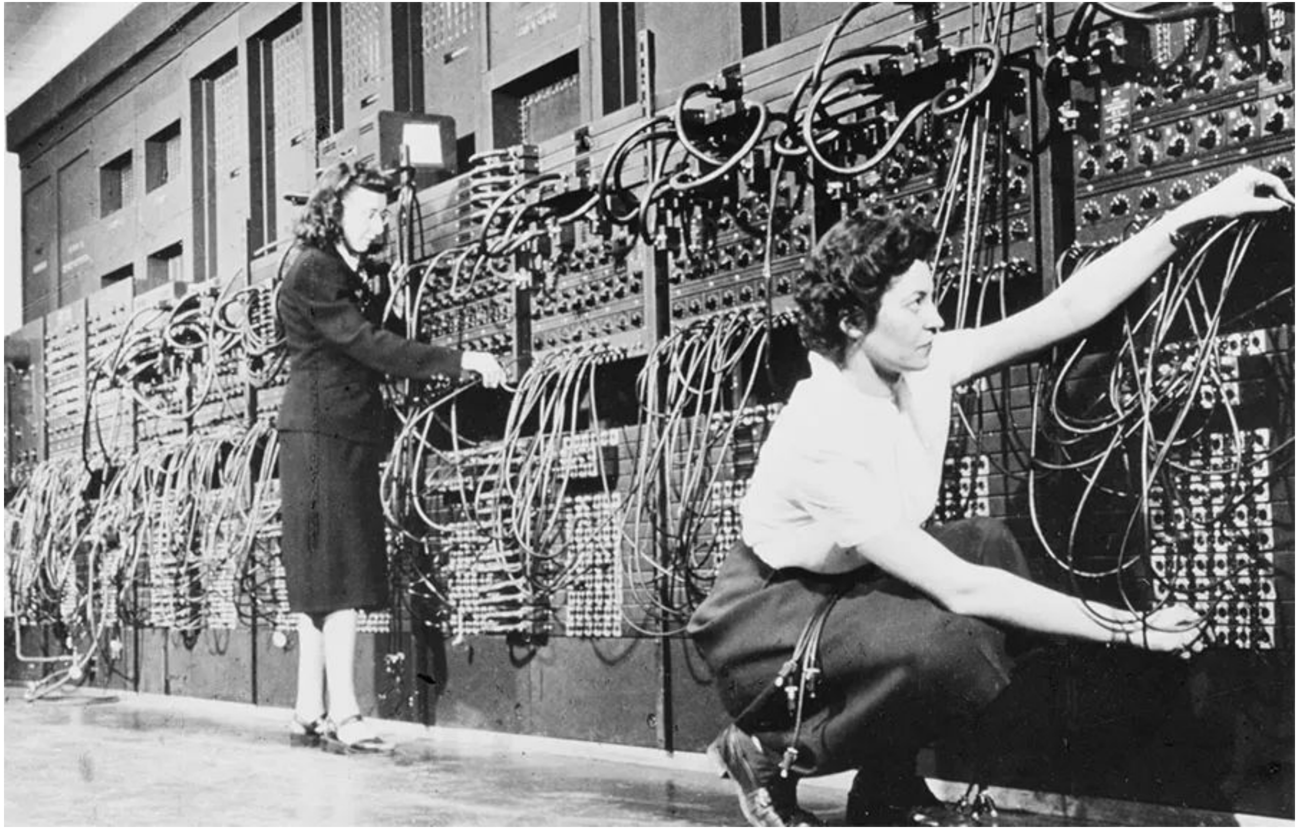
The “computable” numbers may be described briefly as the real numbers whose expressions as a decimal are calculable by finite means. Although the subject of this paper is ostensibly the computable *numbers*, it is almost equally easy to define and investigate computable functions of an integral variable or a real or computable variable, computable predicates, and so forth. The fundamental problems involved are, however, the same in each case, and I have chosen the computable numbers for explicit treatment as involving the least cumbrous technique. I hope shortly to give an account of the relations of the computable numbers, functions, and so forth to one another. This will include a development of the theory of functions of a real variable expressed in terms of computable numbers. According to my definition, a number is computable if its decimal can be written down by a machine.

In §§ 9, 10 I give some arguments with the intention of showing that the computable numbers include all numbers which could naturally be regarded as computable. In particular, I show that certain large classes of numbers are computable. They include, for instance, the real parts of all algebraic numbers, the real parts of the zeros of the Bessel functions, the numbers π, e, etc. The computable numbers do not, however, include all definable numbers, and an example is given of a definable number which is not computable.

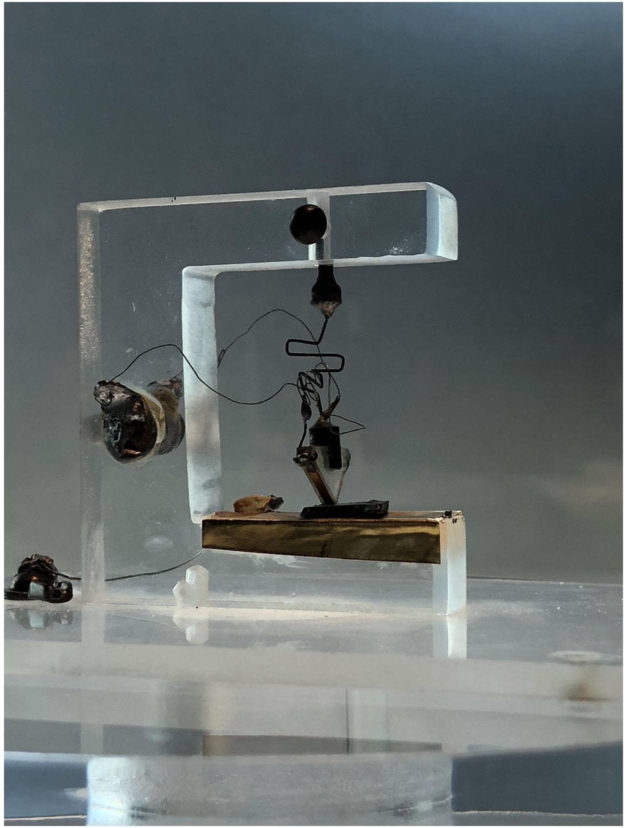
Although the class of computable numbers is so great, and in many ways similar to the class of real numbers, it is nevertheless enumerable. In § 8 I examine certain arguments which would seem to prove the contrary. By the correct application of one of these arguments, conclusions are reached which are superficially similar to those of Gödel†. These results

† Gödel, “Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme, I”, *Monatshefte Math. Phys.*, 38 (1931), 173–198.

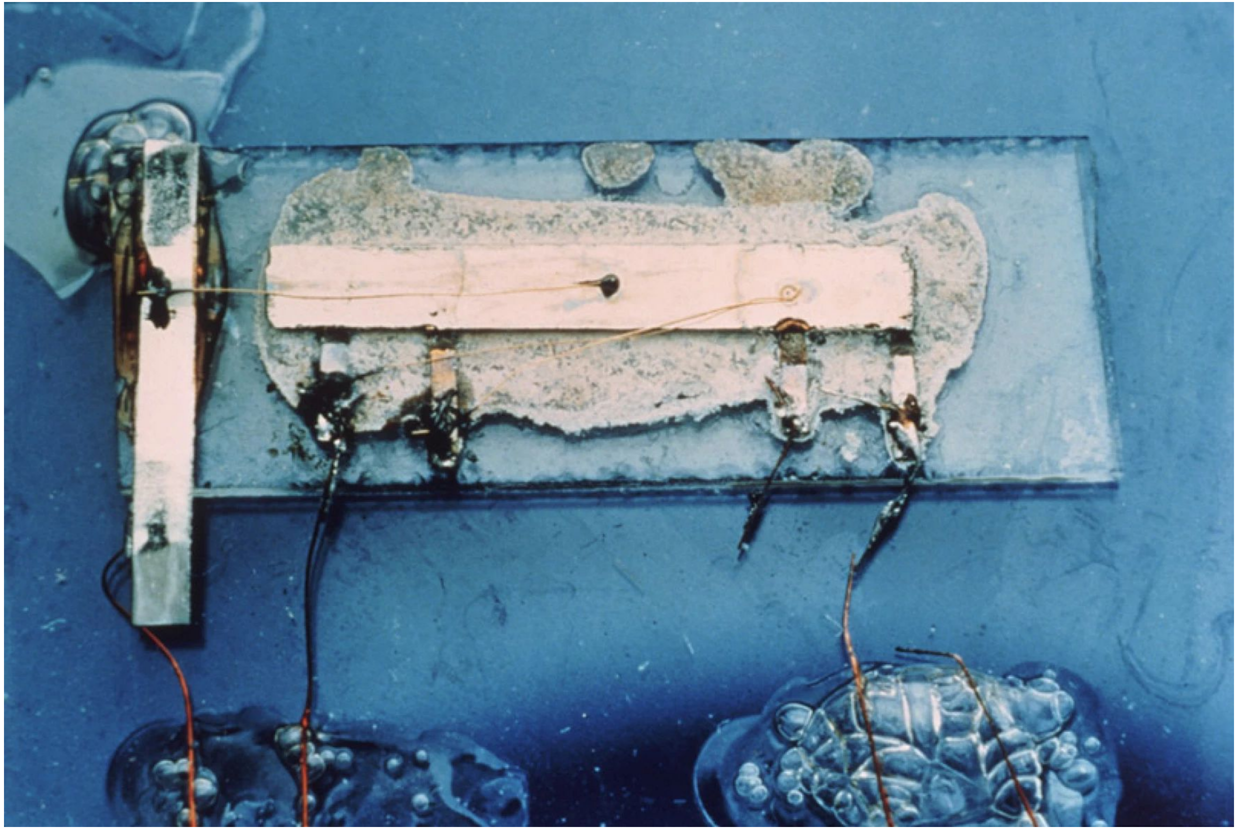
1. Some Quick Background
2. Babbage, Lovelace, Turing
3. *The Transistor, and its Limitations*
4. Richard Feynman et. al.
5. Why Quantum Computing



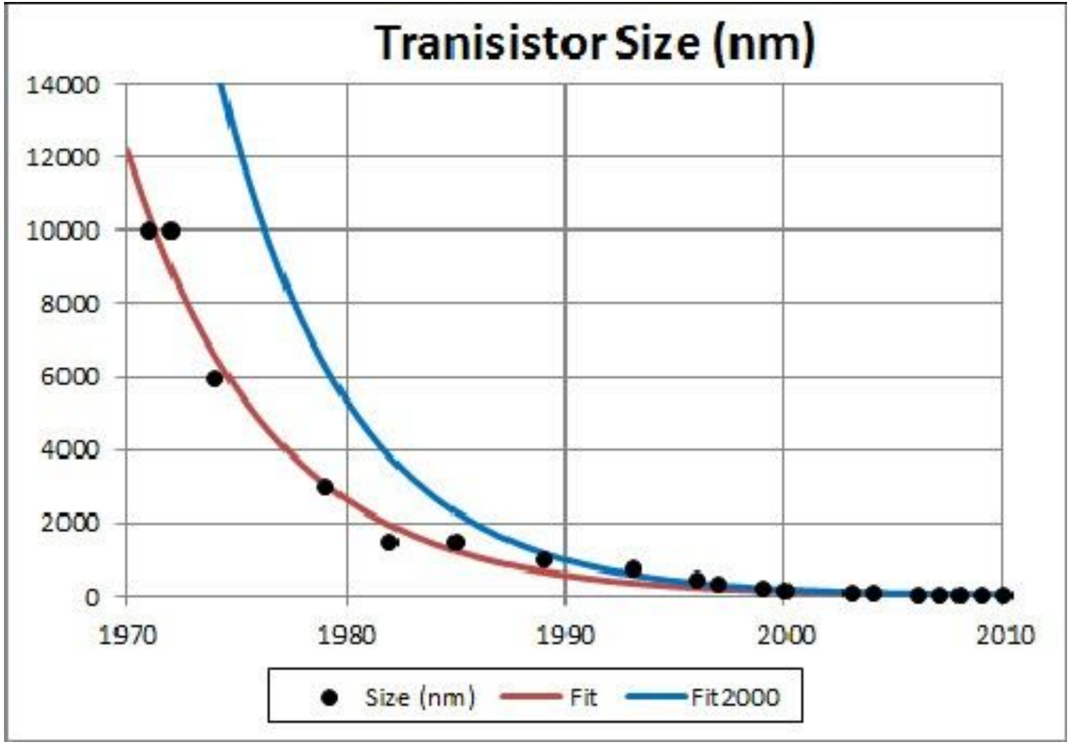
1945 - ENIAC: First Electronic Computer



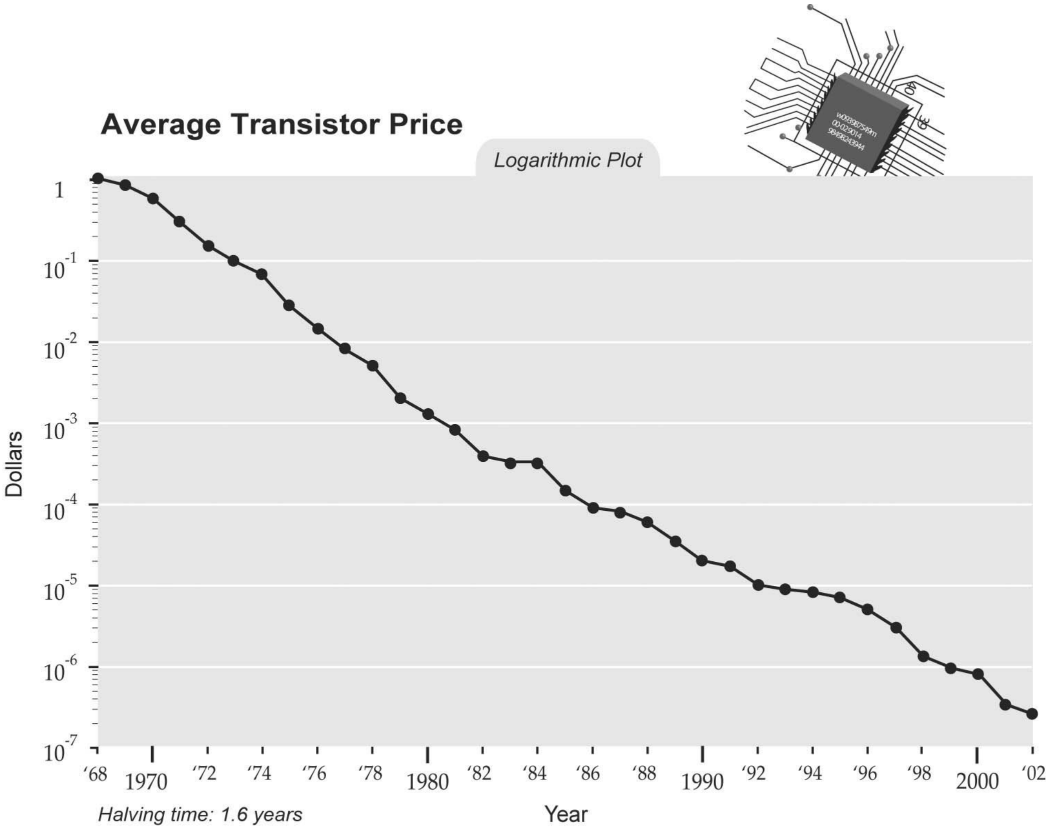
1947 - First Transistor, Shockley, Brattain, Bardeen @ Bell Labs



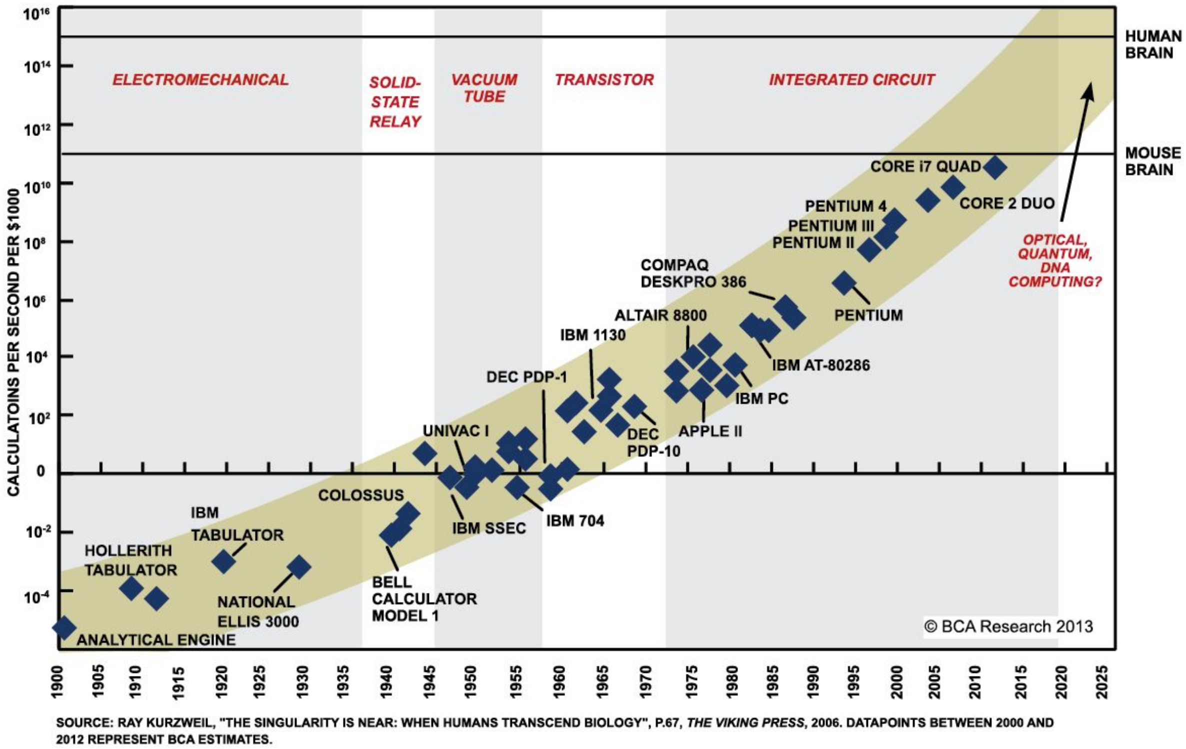
1958 - Integrated Circuit, Jack Kilby @ TI



Transistor Size over Time



Average Transistor Price



1965 - Moore's Law, Cofounder of Intel

Modern Day Chip - Made up of 50 Billion Transistors

Can we keep going smaller?

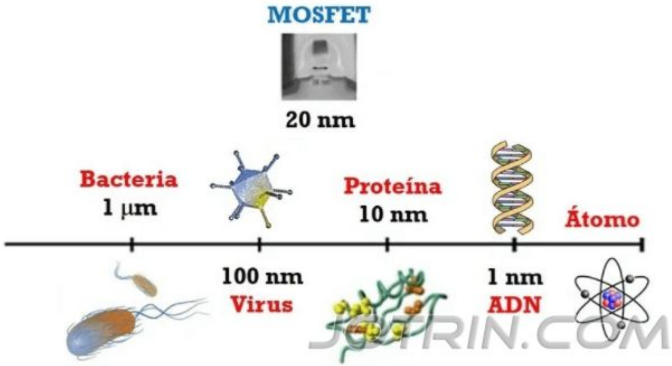
2010s - Transistors and Moore's Law Limitations

Circuits can't be smaller than atoms

Engineering challenges

Quantum Electron Tunneling

Overheating and noise



Setting the scene 2010s

Billions of transistors switch bits at GHz speeds

Stack: languages, compilers, operating systems, cloud

Massive automation: supercomputers/GPUs;

error-correcting codes keep bits reliable.

Hitting physics headwinds: nanometers → heat, leakage,

energy limits; easy Moore-style gains are slowing.

Key Idea: new paradigm of computing

1. Some Quick Background
2. Babbage, Lovelace, Turing
3. The Transistor, and its Limitations
4. *Richard Feynman et. al.*
5. Why Quantum Computing

The Quantum Dynamics Simulation Problem

Goal: Predict how a quantum system changes over time—e.g., a chemical reaction pathway, electrons in a new material, or a molecule binding to a protein.

Classical Solution: A general n-qubit state needs 2^n complex numbers to describe it. Memory blows up fast: 30 qubits ≈ 16 GB, 40 ≈ 16 TB, 50 ≈ 16 PB.

Simulating time evolution means repeatedly applying enormous matrices; entanglement spreads information across many amplitudes, so shortcuts often fail.

How can we solve this problem?

Richard Feynman

I could talk about Feynman for hours...

Renowned Caltech Physics Professor

QED, Nobel Prize, Path Integral, Feynman Diagrams

Recruited to Manhattan Project at 24

Pioneered Quantum Computing and Nanotech

Physics of Computation Conference Endicott House MIT May 6-8, 1981

1 Freeman Dyson
2 Gregory Chaitin
3 James Crutchfield
4 Norman Packard
5 Panos Ligomenides
6 Jerome Rothstein
7 Carl Hewitt
8 Norman Hardy
9 Edward Fredkin
10 Tom Toffoli
11 Rolf Landauer
12 John Wheeler

13 Frederick Kantor
14 David Leinweber
15 Konrad Zuse
16 Bernard Zeigler
17 Carl Adam Petri
18 Anatol Holt
19 Roland Vollmar
20 Hans Bremerman
21 Donald Greenspan
22 Markus Buettiker
23 Otto Floberth
24 Robert Lewis

25 Robert Suaya
26 Stan Kugell
27 Bill Gosper
28 Lutz Priese
39 Madhu Gupta
30 Paul Benioff
31 Hans Moravec
32 Ian Richards
33 Marian Pour-El
34 Danny Hillis
35 Arthur Burks
36 John Cocke

37 George Michaels
38 Richard Feynman
39 Laurie Lingham
40 Thiagarajan
41 ?
42 Gerard Vichniac
43 Leonid Levin
44 Lev Levitin
45 Peter Gacs
46 Dan Greenberger

1981 Physics of Computation Conference

Now I explicitly go to the question of how we can simulate with a computer ...the quantum mechanical effects ...But the full description of quantum mechanics for a large system with R particles is given by a function which we call the amplitude to find the particles at x1,x2,...xR, and therefore because it has too many variables, it cannot be simulated with a normal computer...

Can you do it with a new kind of computer — a quantum computer? Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind...

Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy...

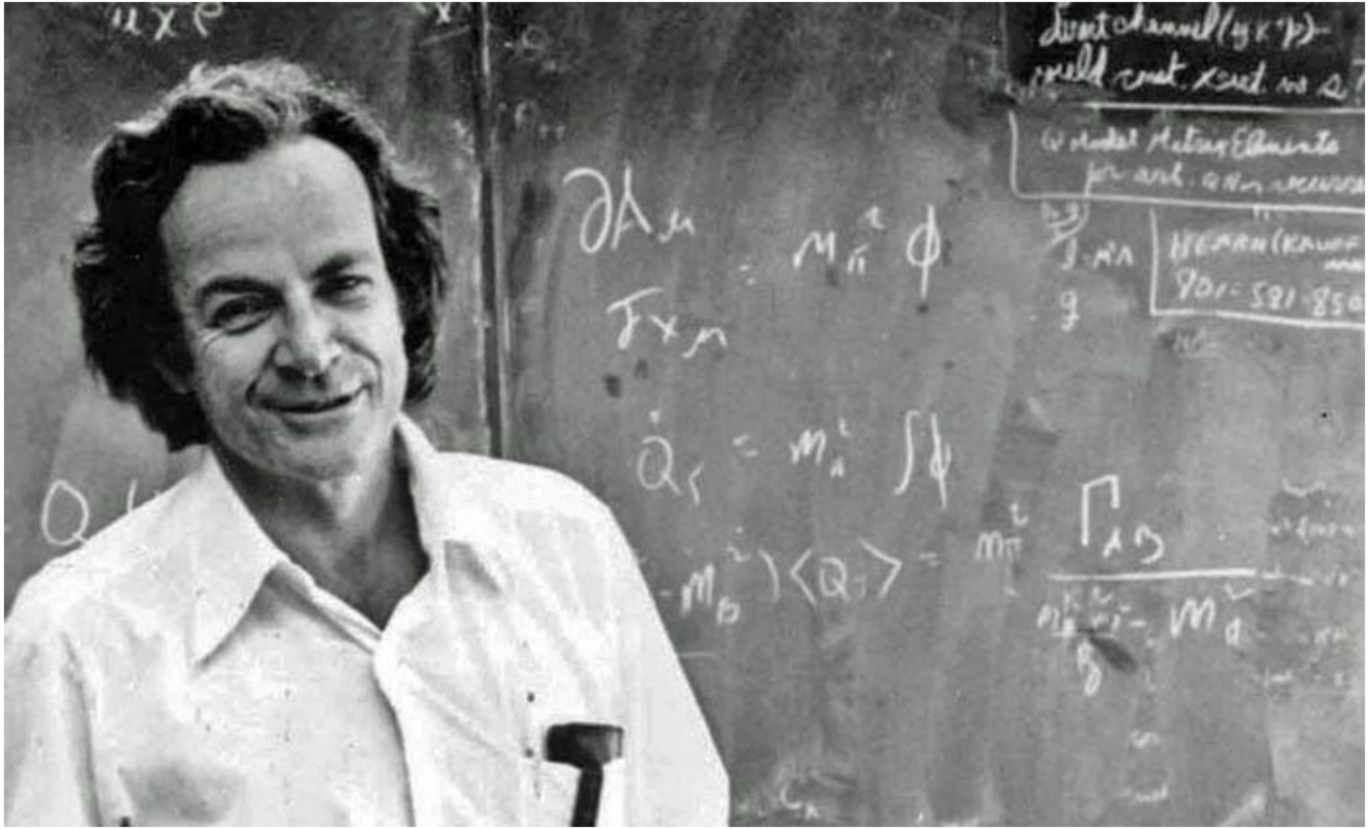
Ideas of a Quantum Computer

1980 - Russian Mathematician Yuri Manin and physicist Paul Benioff independently come up with the idea of a quantum mechanical Turing machine - essentially a computer that obeys quantum rules.

1981 - Feynman proposes idea of quantum computer at Physics of Computation conference. Computer that stores information in quantum states.

Turn quantum theory from limitation to a resource, by computing with quantum bits i.e. qubits.

A machine that can naturally mimic any quantum process, bypass exponentiality of classical simulations.



Richard Feynman, a fine man

Summary: Motivation for Quantum Computing

2010s - Limits of Transistor improvement and Moore's Law

→ find alternative modes of faster and more powerful computation

→ end of easy scaling galvanized interest in quantum computing research and funding

1980s - physics visionaries of better computation and simulation by harnessing quantum mechanics

→ simulate nature with quantum hardware

→ algorithmic improvements

→ radical new set of rules, new set of problems to solve

Problems We Want to Solve

1. Chemistry, Materials, Drug Discovery

Accurate molecular energies, reaction pathways, catalysts, battery & solar materials, superconductors, strongly-correlated solids.

2. Cryptography

RSA/ECC (Shor), quadratic speedups against brute-force search (Grover), stress-testing crypto to drive post-quantum standards.

3. Optimization Problems

Routing, scheduling, supply chains, chip layout, portfolio optimization, risk management.

4. Direct Quantum Simulation

Lattice models (Fermi-Hubbard), quantum field theory, high-energy and nuclear physics toy models.

What are these new set of rules?

Day 1: Recommended Reading

The Imitation Game (2014) - biopic of Alan Turing

The Innovators (Walter Isaacson) – Covers famous Computer Scientists

Hidden Figures (2016) - human computers

ENIAC: The Triumphs and Tragedies of the World’s First Computer

Quantum computing 40 years later (Preskill)

Feynman Lectures on Computation

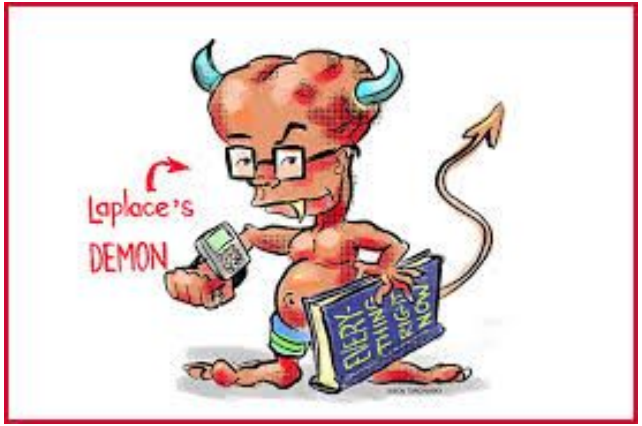
Simulating Physics with Computers (1982 Feynman paper)

2. Classical to Quantum Mechanics

1. *Pre-1900s Physics*
2. Max Planck and Heat Radiation
3. Heisenberg, Schrödinger, and the Cat
4. Einstein vs Bohr: Clash of Titans
5. Bell, Aspect, and Einstein’s Nightmare

Pre-1900 Physics: Framework of Thinking

Laplacian determinism via Newtonian Mechanics



Continuous physical quantities i.e. energy flowed smoothly

Realism vs Instrumentalism; atoms were good models, not necessarily "real"

Pre-1900 Physics: Important Questions

1897 - discovery of Electron

Atomic Hypothesis was not universally accepted

Energy to change temperature of diatomic gas i.e. O_2

Why gas atoms glow in different colors i.e. neon lights.

1. Pre-1900s Physics
2. *Max Planck and Heat Radiation*
3. Heisenberg, Schrödinger, and the Cat
4. Einstein vs Bohr: Clash of Titans
5. Bell, Aspect, and Einstein’s Nightmare

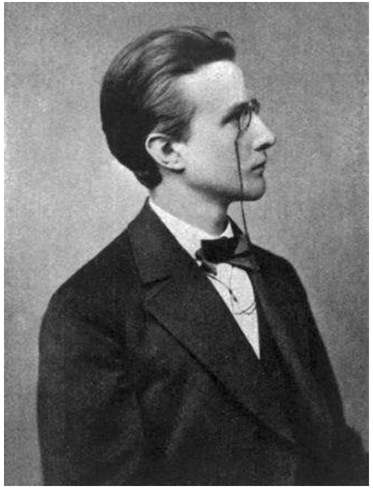
Max Planck (1858-1947)

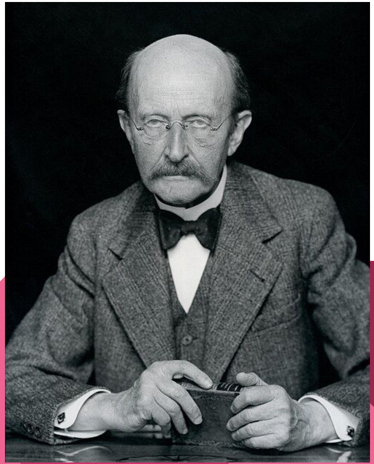
German theoretical physicist

1918 Nobel Prize for energy quanta

Originator of quantum theory, founder of modern physics

“highly developed, nearly fully matured science, that through the crowning achievement of the discovery of the principle of conservation of energy will arguably soon take its final stable form”





14 December 1900 - The Heat Radiation Problem

Objects radiate waves e.g. coals of campfire, coils of electric stove

Assume "atomic jigglers" must take on specific quantized values i.e. energy is quantized

$$u_\nu(\nu, T) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}.$$

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_B T)} - 1}$$

> I can characterize the whole procedure as an act of desperation, since, by nature I am peaceable and opposed to doubtful adventures. However, I had already fought for six years (since 1894) with the problem of equilibrium between radiation and matter without arriving at any successful result. I was aware that this problem was of fundamental importance in physics, and I knew the formula describing the energy distribution . . . hence a theoretical interpretation *had* to be found at any price, however high it might be.

Albert Einstein (1879-1955)

German theoretical physicist; Swiss

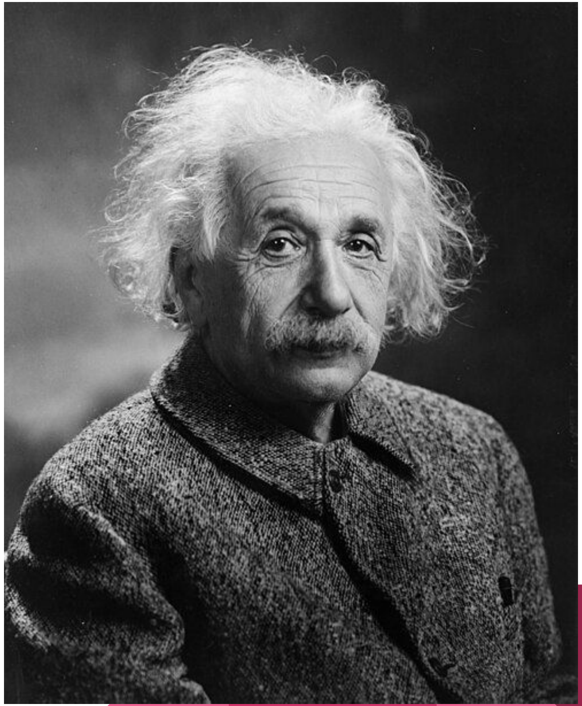
1905 - *Annus Mirabilis*: photoelectric effect, Brownian motion, special relativity, $E=mc^2$

1915 - General Theory of Relativity

1921 Nobel Prize for Photoelectric effect

"Two things are infinite: the universe and human stupidity; and I'm not sure about the universe”

“God does not play dice”, Unified Field Theory



Niels Bohr (1885–1962)

Danish theoretical physicist and philosopher

Nobel Prize in 1922 Hydrogen atom and spectra

Bohr model of the atom

Complementarity: items can be separately analysed in terms of contradicting properties

Held record for causing explosions in lab at University of Copenhagen

Old Quantum Theory

Classical Mechanics still hold, but added assumption of specified physical quantities

1905 - Albert Einstein (26) total energy of a beam of light is quantized ($E = hf$), later extends this for photoelectric effect

1911 - Ernest Rutherford (40), discovered atomic nucleus

1913 - Niels Bohr (28) Quantization for hydrogen atom model while working in Rutherford's lab; excites old quantum theory

1924 - de Broglie wave-particle duality

1. Pre-1900s Physics
2. Max Planck and Heat Radiation
3. *Heisenberg, Schrödinger, and the Cat*
4. Einstein vs Bohr: Clash of Titans
5. Bell, Aspect, and Einstein’s Nightmare

Werner Heisenberg (1901–1976)

German theoretical physicist; Nazi scientist

1925 - matrix formulation of quantum mechanics

1927 - Uncertainty Principle

1932 Nobel Prize, creation of quantum mechanics

Skilled classical pianist

Admired Eastern philosophy, resonated with the Tao of physics

Max Born (1882-1970)

German-British theoretical physicist at University of Göttingen

1954 Nobel Prize for statistical interpretation of the wave function i.e. Born Rule

Friends with Minkowski, Hilbert; Supervised Heisenberg, Oppenheimer; Assistants: Pauli, Teller, Fermi

The Born Rule

(Max Born, 1926)

If an observable $\hat{X}$ is measured, the state vector $|\psi\rangle$ of a quantum system collapses to some $|x\rangle$ (an eigenvalue-x eigenstate of $\hat{X}$) with probability $|\langle x|\psi\rangle|^2$.

1925 - Matrix Formulation of Quantum Mechanics

Became ill, vacation @ Helgoland in June

Extremely mathematical, hard to understand

One evening I reached the point where I was ready to determine the individual terms in the energy table, or, as we put it today, in the energy matrix, by what would now be considered an extremely clumsy series of calculations. When the first terms seemed to accord with the energy principle, I became rather excited, and I began to make countless arithmetical errors. As a result, it was almost three o'clock in the morning before the final result of my computations lay before me. The energy principle had held for all the terms, and I could no longer doubt the mathematical consistency and coherence of the kind of quantum mechanics to which my calculations pointed. At first, I was deeply alarmed. I had the feeling that, through the surface of atomic phenomena, I was looking at a strangely beautiful interior, and felt almost giddy at the thought that I now had to probe this wealth of mathematical structures nature had so generously spread out before me. I was far too excited to sleep, and so, as a new day dawned, I made for the southern tip of the island, where I had been longing to climb a rock jutting out into the sea. I now did so without too much trouble, and waited for the sun to rise.

Erwin Schrödinger (1887-1961)

Austrian-Irish theoretical physicist

Shared Nobel Prize with Paul Dirac for contributions to quantum mechanics

Schrödinger Equation and Cat

Coined term “quantum entanglement”

1926 - Wave Function Formulation of Quantum Mechanics

Two competing versions of Planck's new physics

Schrödinger and Eckart prove they are mathematically equivalent

Time-dependent Schrödinger equation *(general)*

$$i\hbar\frac{d}{dt}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle$$

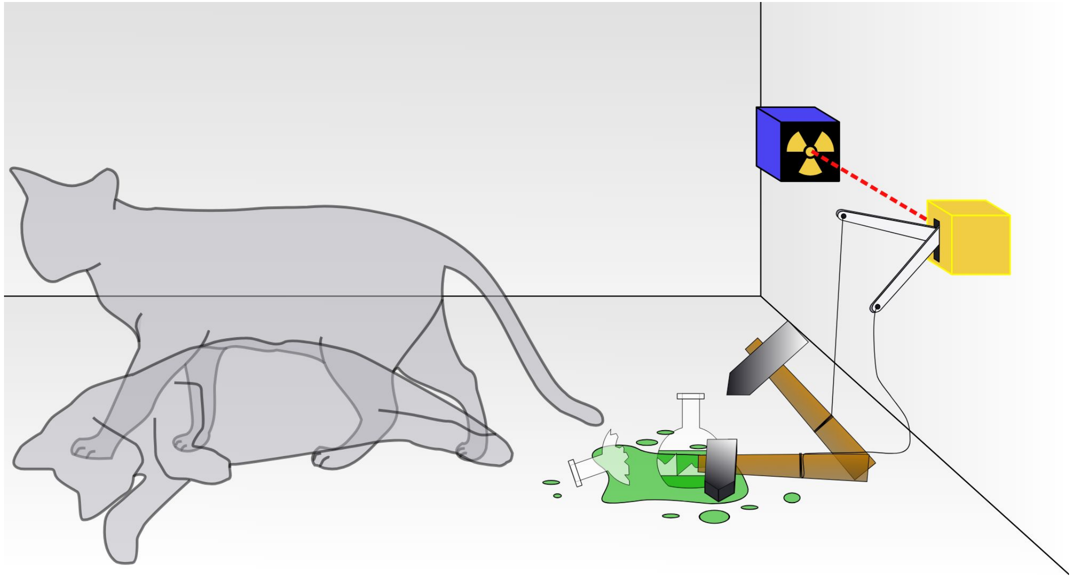
The more I think of the physical part of the Schrödinger theory, the more detestable I find it. What Schrödinger writes about visualization makes scarcely any sense, in other words I think it is shit. The greatest result of his theory is the calculation of matrix elements.

1935 - Schrödinger’s Cat

Superposition, Entanglement

Copenhagen: measurement is a primitive

Many Worlds Interpretation: perceive one branch of parallel universes



1. Pre-1900s Physics
2. Max Planck and Heat Radiation
3. Heisenberg, Schrödinger, and the Cat
4. *Einstein vs Bohr: Clash of Titans*
5. Bell, Aspect, and Einstein’s Nightmare

1926 – Einstein Writes to Max Born

Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing. The theory produces a good deal but hardly brings us closer to the secret of the Old One. I am at all events convinced that *He* does not play dice.

1927 - Fifth Solvay Conference

Einstein to Bohr: "God does not play dice with the universe."

Bohr to Einstein: "Stop telling God how to behave!"

In reality: Bohr replied by pointing out the great caution, already called for by ancient thinkers, in ascribing attributes to Providence in every-day language.

1927 - Fifth Solvay Conference

1935 - Einstein-Podolsky-Rosen Paradox

Example with entanglement particle, measuring one instantly determines the corresponding property of another, regardless of distance separating them: this implied faster than light communication which violates special relativity.

“Spooky action at a distance”

"No reasonable definition of reality could be expected to permit this."

Bohr’s response: complementarity properties of measurement i.e. measuring one excludes possibility of knowing the other with certainty

1941 - Amplitude Formulation

Feynman (23) develops Amplitude Formulation of Quantum Mechanics (or path integral formulation, Lagrangian, method of least action)

Mathematically equivalent to Matrix and Wave formulations, but much more elegant.

Wheeler, his thesis advisor, asks Einstein.

“Doesn't this marvelous discovery make you willing to accept the quantum theory, Professor Einstein?" He replied in a serious voice, "I still cannot believe that God plays dice. But maybe", he smiled, "I have earned the right to make my mistakes."

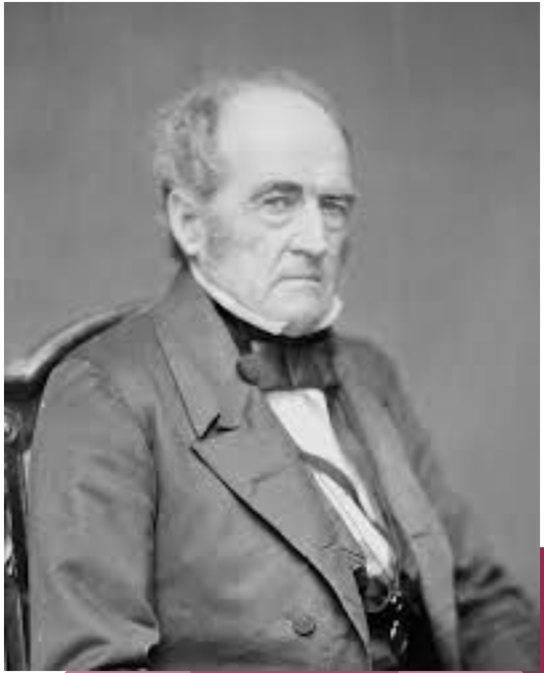
1. Pre-1900s Physics
2. Max Planck and Heat Radiation
3. Heisenberg, Schrödinger, and the Cat
4. Einstein vs Bohr: Clash of Titans
5. *Bell, Aspect, and Einstein's Nightmare*

1961 - John Bell and Bell's Theorem

Locality: an event can only be influenced by immediate surroundings, with no faster than light communication

Realism: objects have definite properties, regardless of whether they are measured.

Bell's Theorem: if local realism is true, must satisfy Bell's inequality. Quantum Mechanics predicts that these inequalities can be violated.

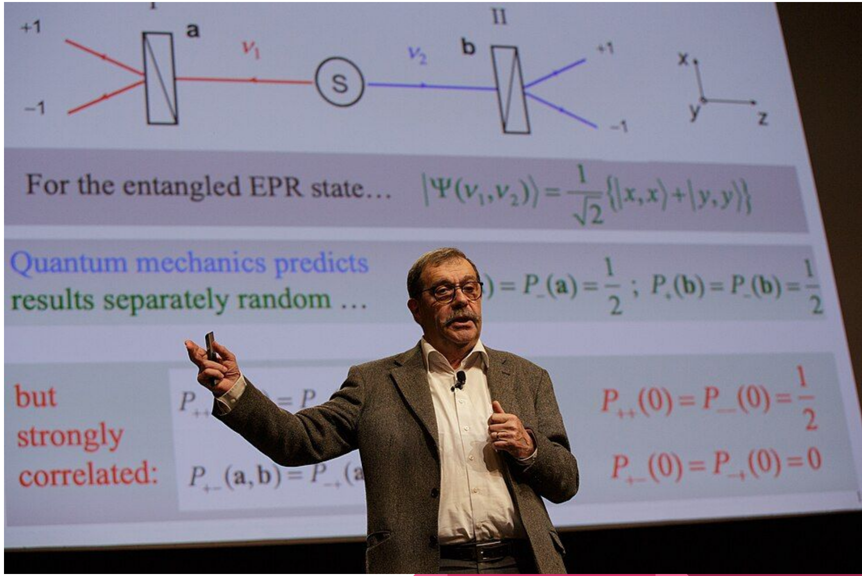


1982 - Alain Aspect et. al

Awarded 2022 Nobel Prize in Physics

First quantum mechanics experiment to demonstrate violation of Bell's inequalities using entangled photons and distant detectors

Further validation of entanglement.



How should we interpret physics?

Copenhagen Interpretation: intrinsic randomness at measurement (Bohr)

- Entanglement: nonlocal correlations
- Superposition: encodes potential outcomes relative to measurement setup

Many-Worlds: full determinism (no collapse) with outcomes realized in different branches.

- Entanglement: nonlocal correlations
- Superposition: superposed components are real and decohere into separate worlds

Day 2: Recommended Reading

A Brief History of Quantum Mechanics (Dan Styer)

Oppenheimer (2023) - mentions famous quantum physicists

Quantum Mechanics: The Theoretical Minimum (Leonard & Susskind)

Introduction to Quantum Mechanics (Griffiths)

The Emperor's New Mind (Roger Penrose)

Speakable And Unspeakable (John Bell)

Bananaworld: Quantum Mechanics for Primates (Jeffrey Bub)

3. Early Quantum Algorithms

1. *Key Ingredients of Quantum Mechanics*
2. Teleportation and Cryptography
3. 1980s, Laying the Groundwork
4. Shor and Breakthrough Algorithms
5. QEC and the Need for Fault Tolerance

Key Ingredient of Quantum Mechanics

Superposition: If a system can be in state A or state B, it can also be in a “mixture” of the two states. If we measure it, we see either A or B, probabilistically

Entanglement: a system cannot be described independently of the state of the others, even when the particles are separated by a large distance.

Collapse: any further measurement will give the same result.

Uncertainty Principle: certainty of one outcome implies uncertainty of the outcome of another measurement.

Non-locality and Entanglement

Imagine we have a pair of entangled qubits.

Measuring one qubit, instantaneously collapses the other. Global state of the two qubits cannot be described solely in terms of each of them.

No Cloning Theorem

Qubit: the Basic Building Block

Qubit: a quantum system that has two distinct states. Qubits often exist in a superposition of both states.

Examples: photon, superconducting circuit, trapped ions, neutral atoms

1. Key Ingredients of Quantum Mechanics
2. *Teleportation and Cryptography*
3. 1980s, Laying the Groundwork
4. Shor and Breakthrough Algorithms
5. QEC and the Need for Fault Tolerance

Charles H. Bennett (1943-)

Physicist and IBM Fellow

Brandeis B.S. and Harvard PhD

1984 - Collaborated with Gilles Brassard to propose BB84 establishing quantum cryptography

1993 - Collaborated with Brassard and others at Caltech to propose quantum teleportation

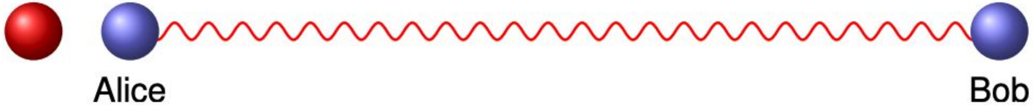
Not to be confused with the boxer

1984 - Quantum Key Distribution, BB84

Developed by Bennett and Brassard, allowed for secure communication.

1. Alice prepares bit using random bases. Bob chooses to measure in random bases
2. Alice and Bob publicly share over classical channel baseis used
3. Eavesdropper (Eve) needs to guess correct basis; if wrong, introduces error in photon's polarization, which Alice and Bob can detect
4. No-Cloning Theorem ensures that Eve cannot create perfect copy

1993 - Quantum Teleportation and Networks



1. Entangle two particles to form a Bell state
2. Alice performs measurement on her particle, which affects Bob’s particle
3. Results of Alice’s measurement are communicated to Bob via classical channel
4. Bob can reconstruct original quantum state

Experimental Validation

1989: Quantum Key distribution demonstrated experimentally

Validated by Bennett and Brassard using a 403-bit string over a distance of 30 cm.

1997-8: Quantum teleportation demonstrated experimentally

Validated by Zeilinger and his team by creating entangled photon pairs and teleporting information over 143 km between Canary Islands and Tenerife using optical fiber links. Located at high altitudes to minimize atmospheric interference.

1. Key Ingredients of Quantum Mechanics
2. Teleportation and Cryptography
3. *1980s, Laying the Groundwork*
4. Shor and Breakthrough Algorithms
5. QEC and the Need for Fault Tolerance

1985 - David Deutsch and the Turing Machine

British physicist

Proposes mathematical concept of quantum Turing machine to model quantum computation

Establishes theoretical foundation of quantum computation.

“The intuitive explanation of these properties places an intolerable strain on all interpretations of quantum theory other than Everett’s.”

1992 - Deutsch-Jozsa Algorithm

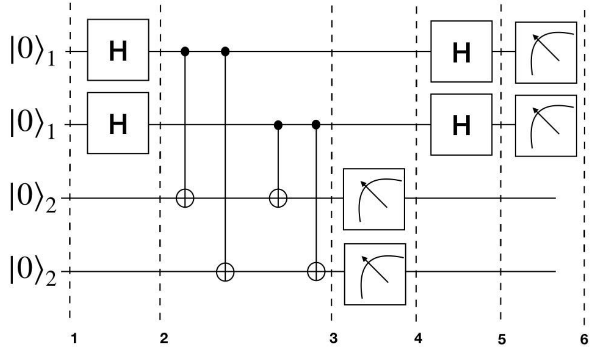
First toy algorithm demonstrating significant quantum advantage. Not significant speedup.

Determining a global property in one iteration using

- Quantum parallelism (superposition)
- Interference
- Phase kickback
- Oracle

1994 - Dan Simons and Simon's Algorithm

Wanted to show that there was no exponential speedup, but ended up finding an exponential speedup for a black box problem.



Implication

- First clear exponential separation between classical and quantum
- Direct ancestor of Shor, which is also a hidden-structure problem

Do these algorithms have practical applications?

1. Key Ingredients of Quantum Mechanics
2. Teleportation and Cryptography
3. 1980s, Laying the Groundwork
4. *Shor and Breakthrough Algorithms*
5. QEC and the Need for Fault Tolerance

Peter Shor (1959-)

Theoretical Computer Scientist; Professor at MIT

Caltech B.S. and MIT PhD

Silver medal at International Mathematics Olympiad

1994 - Developed Shor’s Algorithm for Prime Factorization

1996 - Developed Quantum Error Correcting Codes and Shor’s Code, CSS Code

1994 – Shor's Algorithm

Solved a problem that people actually care about. Algorithm produces an exponential speedup over the best known classical methods.

Given an integer $N = p \times q$ for prime numbers p and q,

Shor's algorithm outputs p and q.

Problems

1. Need millions of physical qubits with long coherent times.
2. Highly precision sensitive
3. Arithmetic overhead dominates due to deep circuits

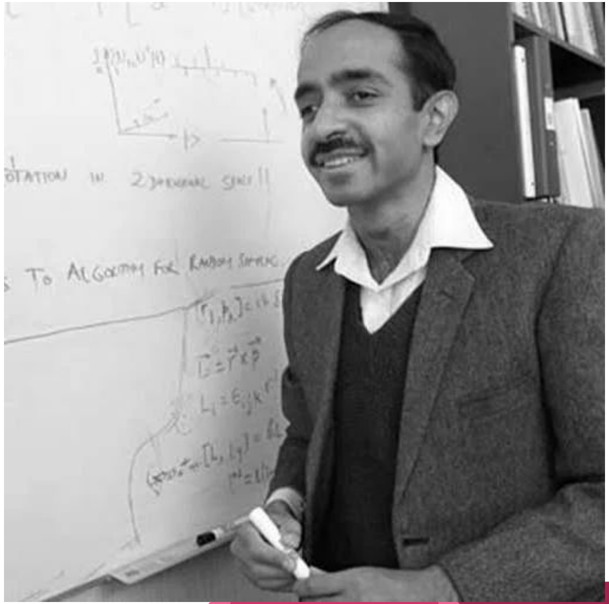
1996 – Lov Grover and Grover's Search

You have an unstructured list of N items and an oracle telling you yes/no if a given item is the correct item. Find the one correct item.

- Classically O(N) vs Grover: O(sqrt(N))
- Amplitude Amplification

In reality, there are many problems

- Assumes QRAM
- Oracle is nontrivial to implement
- Does not turn exponential to polynomial



1996 - Seth Lloyd and Quantum Simulation

Predict how a quantum system evolves in time.

- Simulate time in tiny slices
- At each slice, simulate local pieces one by one (Trotter decomposition) using quantum circuit
- Capable of simulating all quantum systems

In reality

- Works better on local / sparse; hard on denser interactions

Experimental Validation

Shor's Algorithm

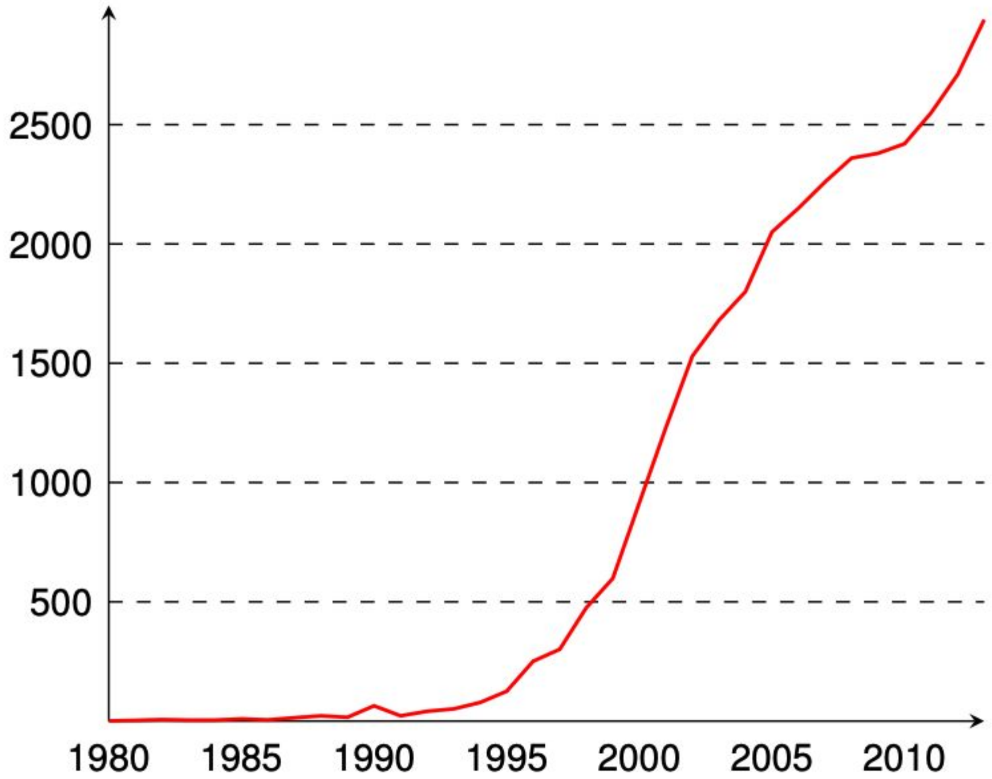
In 2001 IBM and Stanford factored 15 using 7 qubit NMR quantum computer

Grover's Algorithm

February 2025, Silicon Quantum Computing on silicon-based quantum process achieved 93.46% success rate.

Lloyd's Quantum Simulation

In 2002, experiments on quantum simulations realized by Greiner and Leibfried.



Rise of quantum computing papers.

1. Key Ingredients of Quantum Mechanics
2. Teleportation and Cryptography
3. 1980s, Laying the Groundwork
4. Shor and Breakthrough Algorithms
5. *QEC and the Need for Fault Tolerance*

The Quantum Decoherence Problem

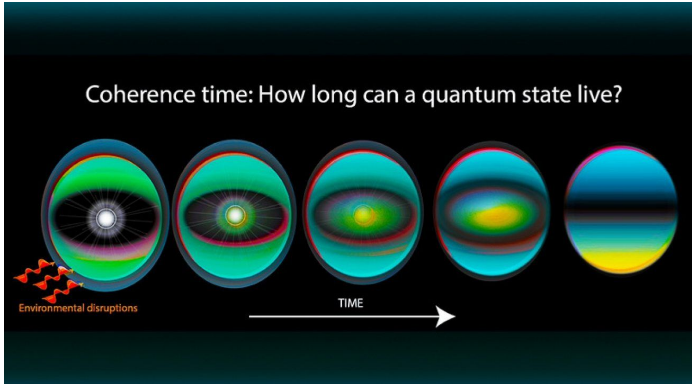
Quantum systems are never perfectly isolated e.g. noise, fluctuating fields

Gates, measurement, crosstalk

Interaction entangled qubit with surroundings; loses coherence

Classical parallel; error correction

No-cloning theorem, measurement problem



1995-6 - Quantum Error Correcting Codes

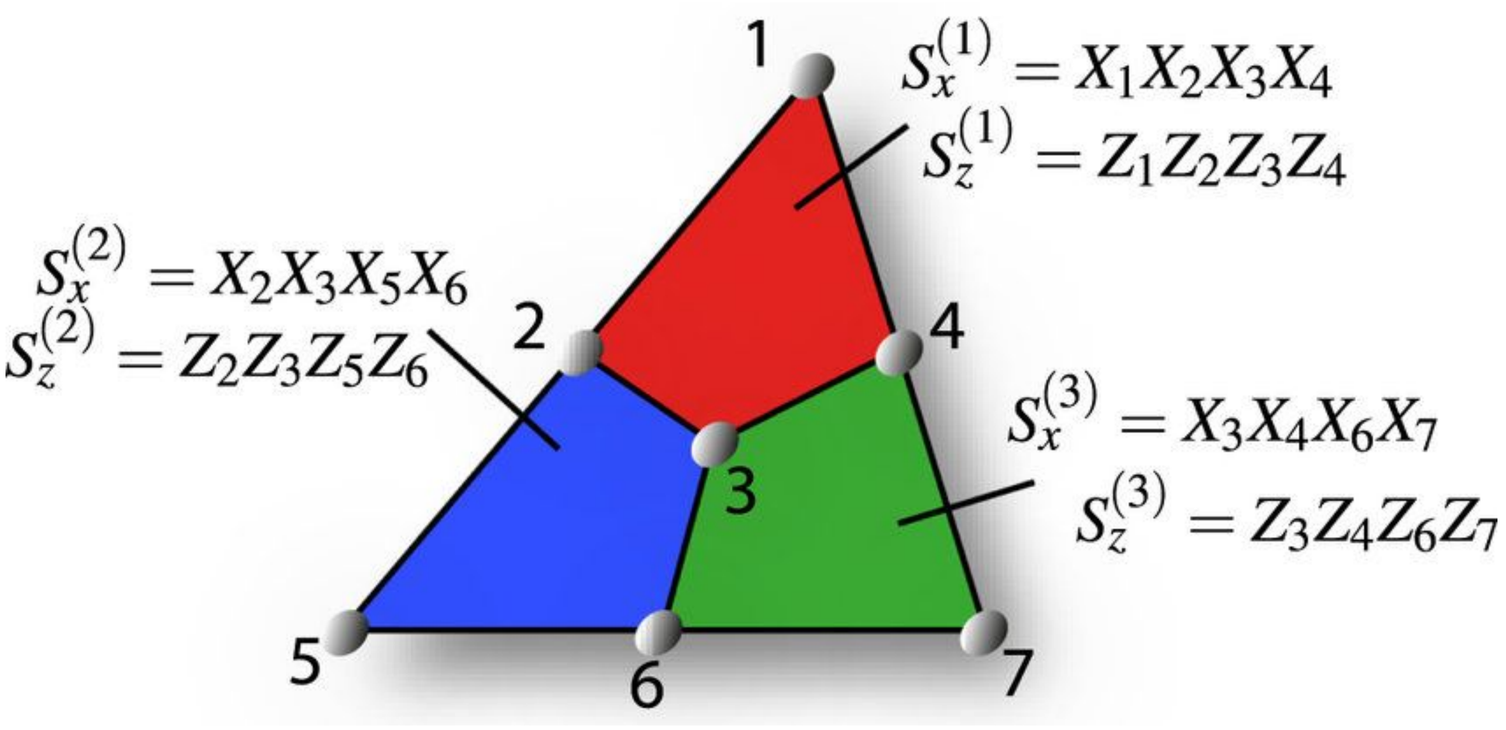
Physicist were doubtful of quantum computing because of decoherence.

Quantum Error Correcting Codes:

- Physical qubits form logical qubits
- Bypass the no-cloning theorem
- Stabilizes the error by repeated checks

Calderbank-Shor-Steane Codes

- Andrew Steane produces a cleaner, more compact code than Shor's
- Calderbank and Shor formalize broad recipe of codes



Steane Code; S’s are the stabilizers

Alexei Kitaev (1963-)

Russian-American Theoretical Physicist, Professor at Caltech

Researcher at Google Quantum AI

Pioneer in Topological Quantum Computation

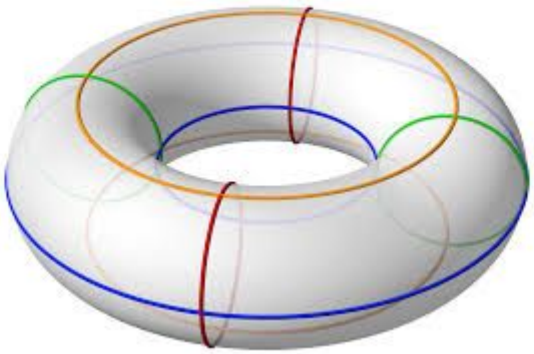
Developed toric and subsequently surface codes.

Refined Shor's Fault Tolerance Theorem

1997 - Torus and Surface Codes

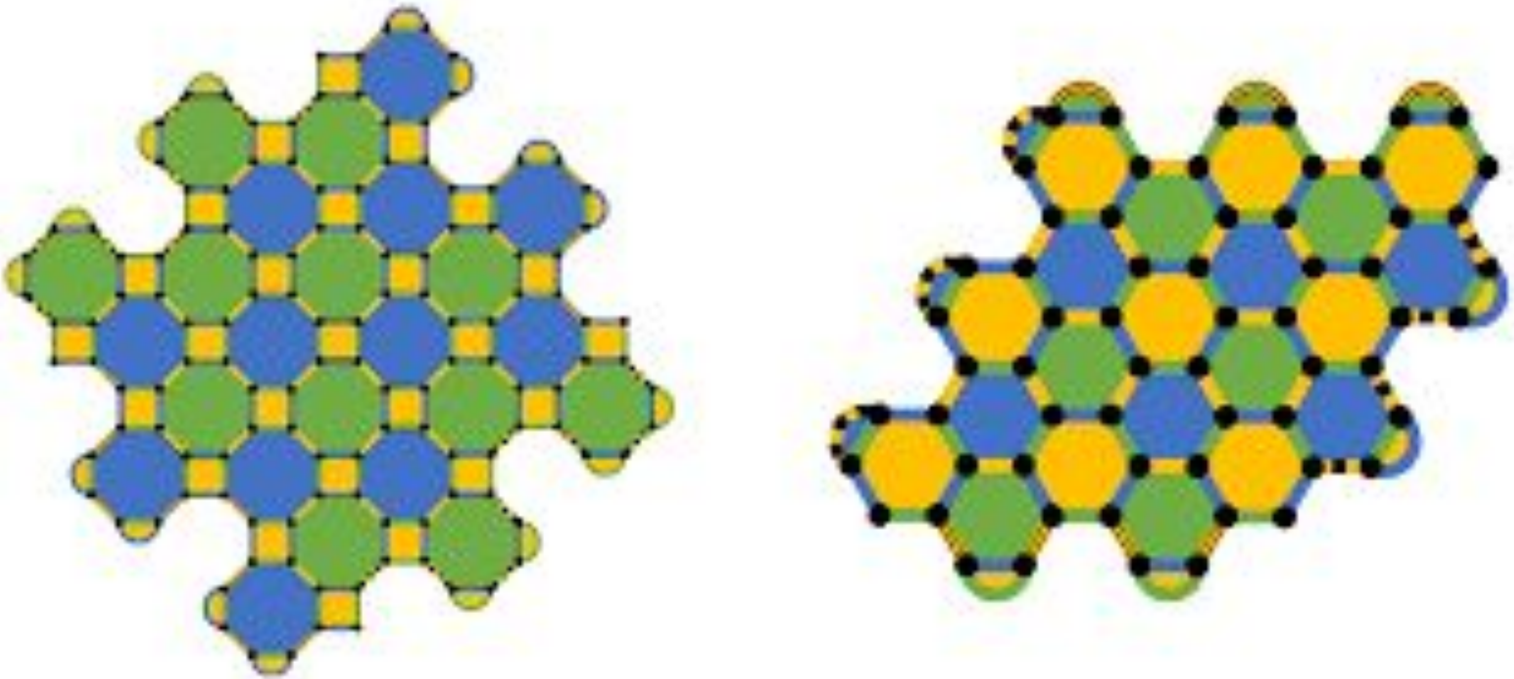
Toric Code

- Topological phases condensed-matter physics
- Local disturbances make tiny ripples
- If errors trace a loop, then flip information



Surface Code

- Labs build flat devices
- Project Torus onto 2D plane
- Errors are from boundary to boundary
- Scaling decreases error



Topological Surface Codes

FTQC and Scalable Quantum Computing

Threshold Theorem: if physical error rates are below threshold of around 1%, suppress logical error arbitrarily by increasing number of qubits.

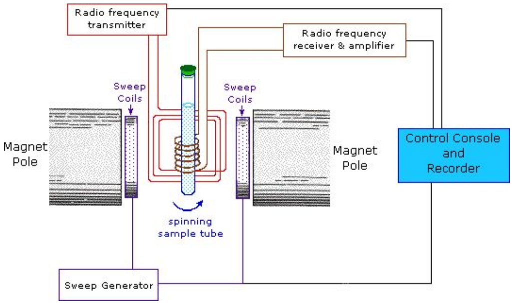
Fault Tolerant Quantum Computing will need 100-1000 physical qubits per logical qubit, and only then can we scale.

How do build a quantum computer?

4. Early Quantum Hardware

1. *Nuclear Magnetic Resonance Computing*
2. Trapped Ions, Precision with Lasers
3. Superconducting Qubits and the Big Three
4. Neutral Atoms & Optical Tweezers

Nuclear Magnetic Resonance (NMR)



Certain atomic nuclei are tiny magnets (^{1}H, ^{13}C, ^{19}F, ^{31}P)

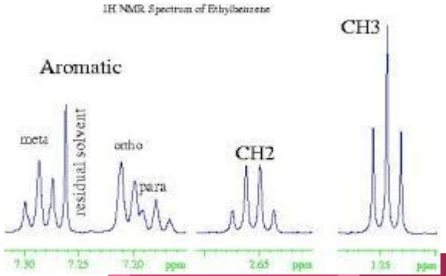
Liquid sample aligns "spin" to strong magnetic field *B*

Use Radio-Frequency (RF) pulses to rotate net magnetization

- Act as natural single qubit gate

Neighboring nuclei experience weak J-coupling

- Act as natural multi-qubit gate



When relaxed, nuclei emits tiny signal detected by a coil

- Acts as natural measurement

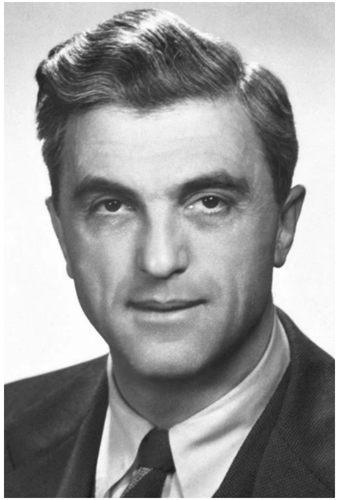
History of NMR

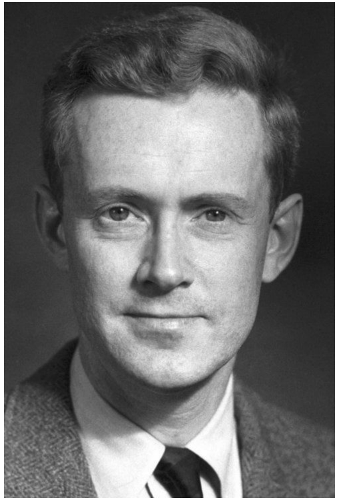
1940s - Felix Bloch and Edward Purcell jointly awarded 1952 Nobel Prize for NMR

1960s–1980s - control theory development i.e. pulse sequences, decoupling

1990s - apply NMR to quantum computing

- MIT / Harvard laid out how to use NMR for computation
- Isaac Chuang and co. demonstrate first quantum algorithms on hardware





NMR: Accomplishments

April 13, 1998 - Grover's Search demonstrated by MIT, Berkeley, and IBM

- Used N=4 qubit system with ^{1}H–^{13}C in chloroform

May 14, 1998 - Deutsch-Jozsa NMR demo led by Stanford/MIT

- Two qubit on cytosine

September 7, 1998 - Quantum Error Correction (bit/phase-flip protection)

- Three qubits to encode one logical qubit

2001 - Shor's algorithm demonstration by team at Stanford

NMR: Pros and Cons

Pros

1. Superb Control
   a. long term NMR research → good control protocol + precise calibrations
2. Long coherence
   a. well isolated nuclear spin (0.1–10 s)
3. Rapid iteration
   a. fast experiments and easy to set up + repeat; no need for complex hardware
4. Formed training ground for the field

Cons

1. Tiny magnetization at room temperature
2. Ensemble readout
   a. Measure averages, not single systems
   b. Complicates ancilla preparation
   c. Complicates projective measurements
3. Entanglement Controversy
   a. hard to prove strong entanglement due to highly mixed states
4. Can't scale
   a. good for 2–10 qubits because of precise control, but cannot go higher

No longer SOTA because of scaling limits; good for tests and demos

1. Nuclear Magnetic Resonance Computing
2. *Trapped Ions, Precision with Lasers*
3. Superconding Qubits and the Big Three
4. Neutral Atoms & Optical Tweezers

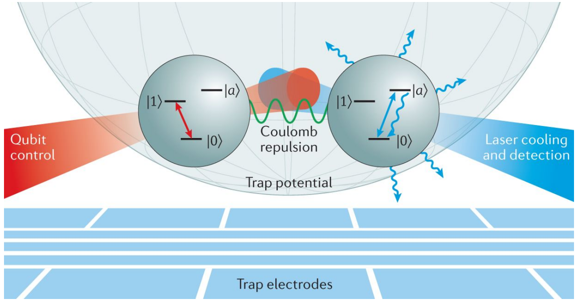
Trapped Ion Qubit

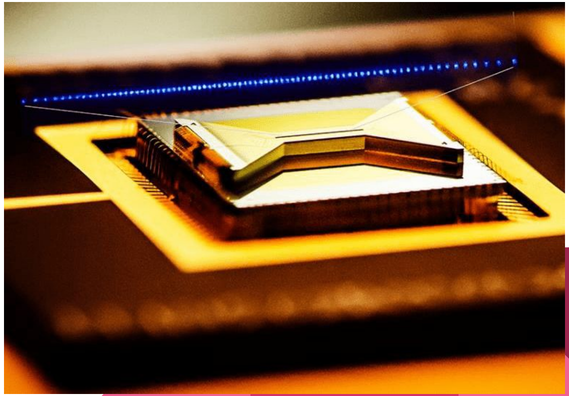
Use electric field to levitate ion in vacuum (Paul trap, 1989 Nobel Prize)

Use lasers as ultra-precise tweezers for quantum state manipulation i.e. gates

Two states: hyperfine ground vs excited state

At measurement, the one-state scatters many photons while zero-state remains dark. Measured by photo-diode as “glow”.





History of Trapped Ion Qubits

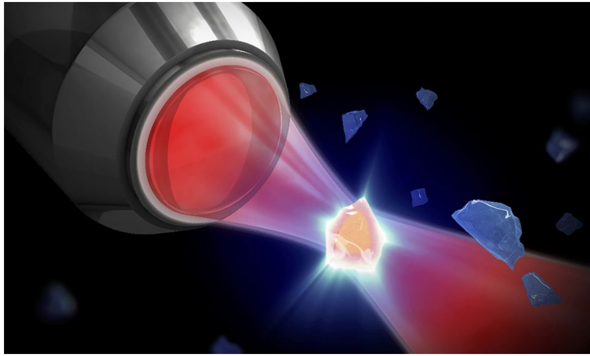
1950s - Paul Traps (1989 Nobel) oscillating fields that confined charged particles using radio-frequency fields.

1980s - Laser cooling (2012 Nobel), allowing near total control of qubit by damping its motion

1995 - First CNOT-type operation demonstrated by NIST

2000 - First multi-ion entanglement (NIST)

2024 - 512 qubit at Tsinghua



Trapped Ions: Pros and Cons

Pros

1. Fidelity & Coherence
   a. Among the best one and two qubit gate fidelities
   b. Single shot readout and coherence from seconds - minutes
   c. Ideal for error corrected experiments
2. Uniformity & Consistency
   a. Ions are identical by nature, do not need much calibration
3. Algorithmic Firsts
   a. Early demonstration of quantum teleportation, entanglement and other algorithms

Cons

1. Speed vs Fidelity
   a. Gates are slower (10-100 μs) to keep balance of ions
2. Crowding & Crosstalk
   a. As ion chains grow, unintentional physical interactions between ions
   b. Hard to isolate one single ions
3. Can't scale indefinitely
   a. Can not fit all ions into one trap

Trapped ions are still SOTA, with many top labs / companies pursuing this research.

1. Nuclear Magnetic Resonance Computing
2. Trapped Ions, Precision with Lasers
3. *Superconding Qubits and the Big Three*
4. Neutral Atoms & Optical Tweezers

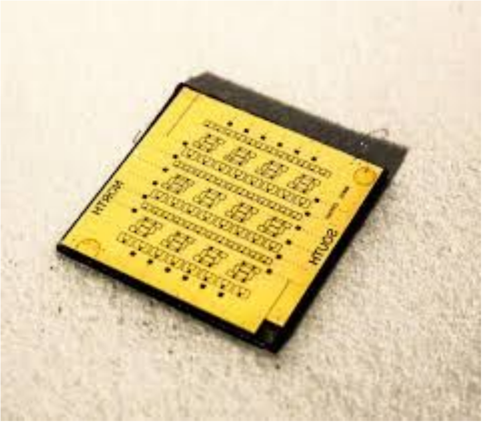
Superconducting Circuits

Tiny superconducting electrical circuits with Josephson Junction

Lowest two energy levels form zero and one state

Cool chip in dilution fridge (2-10 mK) to minimize thermal noise

Measurement using microwave pulses to get signal and act as rotation gates



Quantum Lab at Yale

The Big Three

Schoelkopf, Girvin, Devoret

2004 - Pioneered circuit Quantum Electrodynamics

Designed the transmon qubit

Schoelkopf Law

Main technology used at IBM, Google Quantum AI

IBM's Condor Chip has 1121 qubits

Superconducting Circuits: Pros and Cons

Pros

1. Speed & Integration
   a. gates times ~ 10 ns
   b. Flat, good for 2D lattices
2. High throughput
   a. Chips can run millions of gates / sec
   b. Allows for deep circuits, and complex algorithms
3. Fast, high-contrast measurements
4. Ecosystem
   a. microwaves , digital electronics aer well developed technology

Cons

1. Leakage & Drift
   a. Lossy dielectrics and microscopic defects limit coherence
2. Crosstalk & Crowding
   a. Dense microwave wiring and simultaneous drives bleed into neighbors
   b. Large lattices
3. Ultra cold

Transmon Qubit is SOTA used at IBM, Google Quantum AI

1. Nuclear Magnetic Resonance Computing
2. Trapped Ions, Precision with Lasers
3. Superconding Qubits and the Big Three
4. *Neutral Atoms & Optical Tweezers*

Neutral Atom Computing

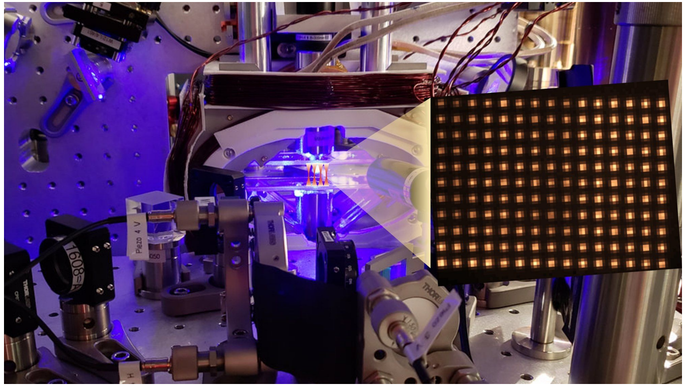
Cool individual neutral atoms (Rb, Cs, Sr, Yb)

Hold in place using focused laser spot in ultra-high vacuum i.e. tweezers

Single-qubit rotations with laser or microwave pulses

To perform entanglement: excite neutral atom to fragile Rydberg states

Measurement using fluorescent light



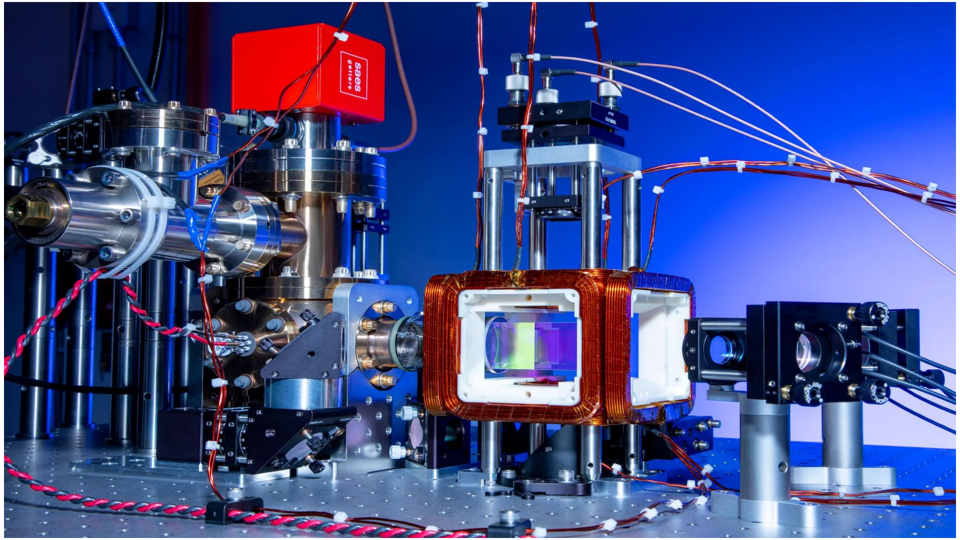
Neutral Atoms: Pros and Cons

Pros

1. Scalability in 2D / 3D
   a. Can make large regular atom arrays
2. Fast, parallel readout
   a. Cameras see all qubits at once

Cons

1. Crosstalk error



SOTA at QuEra Computing, founded by Harvard Prof.

5. Quantum Computing: Present and Future

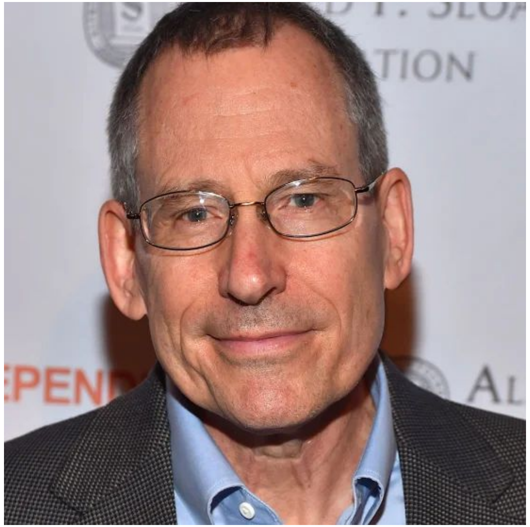
1. *Noisy Intermediate-Scale Quantum (NISQ)*
2. Major Players and Global Landscape
3. State of the Art
4. Challenges and the Road Ahead
5. Recap

John Preskill and NISQ

NISQ = Noisy Intermediate-Scale Quantum

Definition:

1. Noisy devices (gate, measurements, limited coherence)
2. Intermediate qubit counts (50-1000)
3. No full error correction
4. Can do interesting physics and task specific advantages
5. Cannot do industry problems



Road to FTQC

FTQC = Fault Tolerant Quantum Computing

Definition: Run arbitrarily long programs despite imperfect physical qubits and gates

Steps:

1. Improve hardware to pass error threshold
   a. ~1% for surface code like schemes
2. Demonstrate scaling property of surface codes i.e. better error correction

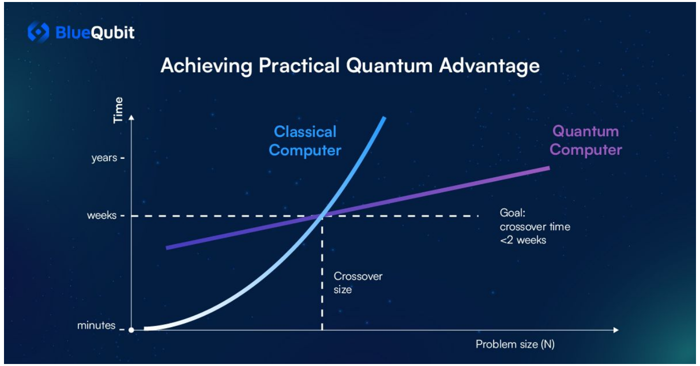
Quantum Supremacy vs Quantum Advantage

Quantum Supremacy

1. Goal: demonstrate a QC performing computation beyond capabilities of CC
    a. Does not have practical application
2. Example: 2019 Google Sycamore chip performing random circuit sampling
    a. 10,000 years → 200 seconds

Quantum Advantage

1. Goal: using QC to solve real-world problem faster than CC
    a. Useful problem and a quantum solution with significant speedup
2. Has not been achieved yet. Will need fault tolerance and better algorithms



1. Noisy Intermediate-Scale Quantum (NISQ)
2. *Major Players and Global Landscape*
3. State of the Art
4. Challenges and the Road Ahead
5. Recap

Major Industry Contributions

10/23/19 - Google release Sycamore quantum processor (53 qubits)

- first demonstration of quantum supremacy via RCS
- 200s vs 10,000 years classically

2/22/23 - Google show first surface code logical qubit that improves with distance

6/14/23 - IBM + UC Berkeley use 127-qubit Eagle quantum processor

- Demonstrate quantum utility on 2D Ising dynamics

12/4/23 - IBM releases Condor Chip (1,121 qubits)

4/3/24 - Microsoft + Quantinuum use trapped ions to show logical qubits with 800x lower error rate than physical.

12/9/24 - Google releases Willow Chip with 105 qubits and below threshold surface code.

2/19/25 - Microsoft Majorana topological qubits.

3/18/25 - NVIDIA announces Accelerated Quantum Research Center

1. Noisy Intermediate-Scale Quantum (NISQ)
2. Major Players and Global Landscape
3. *State of the Art*
4. Challenges and the Road Ahead
5. Recap

What is the State of the Art?

Hardware

- Superconducting Circuits (IBM, Google, Quantinuum): ~ 400-1000 high quality physical qubits
  - Coherence Time: 100-300 μs
- Trapped ions (IonQ): Best gate fidelities (>99.9%), ~35-40 algorithmic qubits
  - Coherence Time: s to min
- Neutral atoms (QuEra): >1000 atoms
  - Coherence Time: ms to s
- Photonic Qubits (Xanadu, PsiQuantum)

Main focus: crosstalk + scaling

Error Correction

- Google (2023 - 2025): scaling surface code
  - Shows exponential suppression with more qubits
- Leading Codes
  - Surface codes (2D architecture)
  - Bosonic Codes (Yale, AWS)
  - LDPC (Long distance parity check)

Medium to late NISQ era.

1. Noisy Intermediate-Scale Quantum (NISQ)
2. Major Players and Global Landscape
3. State of the Art
4. *Challenges and the Road Ahead*
5. Recap

What we need to work on

Main two technical paths

1. Scale up qubit count
2. Improve qubit quality (Error rates)

Applications

1. Quantum simulations
2. Post quantum cryptography
3. Chemistry, Biology, Natural Sciences
4. Optimization, Machine Learning

Hype vs. Reality, VC vs Academia Interests, Optimism vs Pessimism

Like classical computing, new technological revolution, but a slow one

How long until we reach FTQC?

1. **Noisy Intermediate-Scale Quantum (NISQ)**
2. **Major Players and Global Landscape**
3. **State of the Art**
4. **Challenges and the Road Ahead**
5. ***Recap***

1. History of Classical Computing

Can we keep going smaller?

How can we solve this problem?

What are these new set of rules?

2. Classical to Quantum Mechanics

3. Early Quantum Algorithms

Do these algorithms have practical applications?

How do build a quantum computer?

4. Early Quantum Hardware

5. Quantum Computing: Present and Future

How long until we reach FTQC?

Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy...