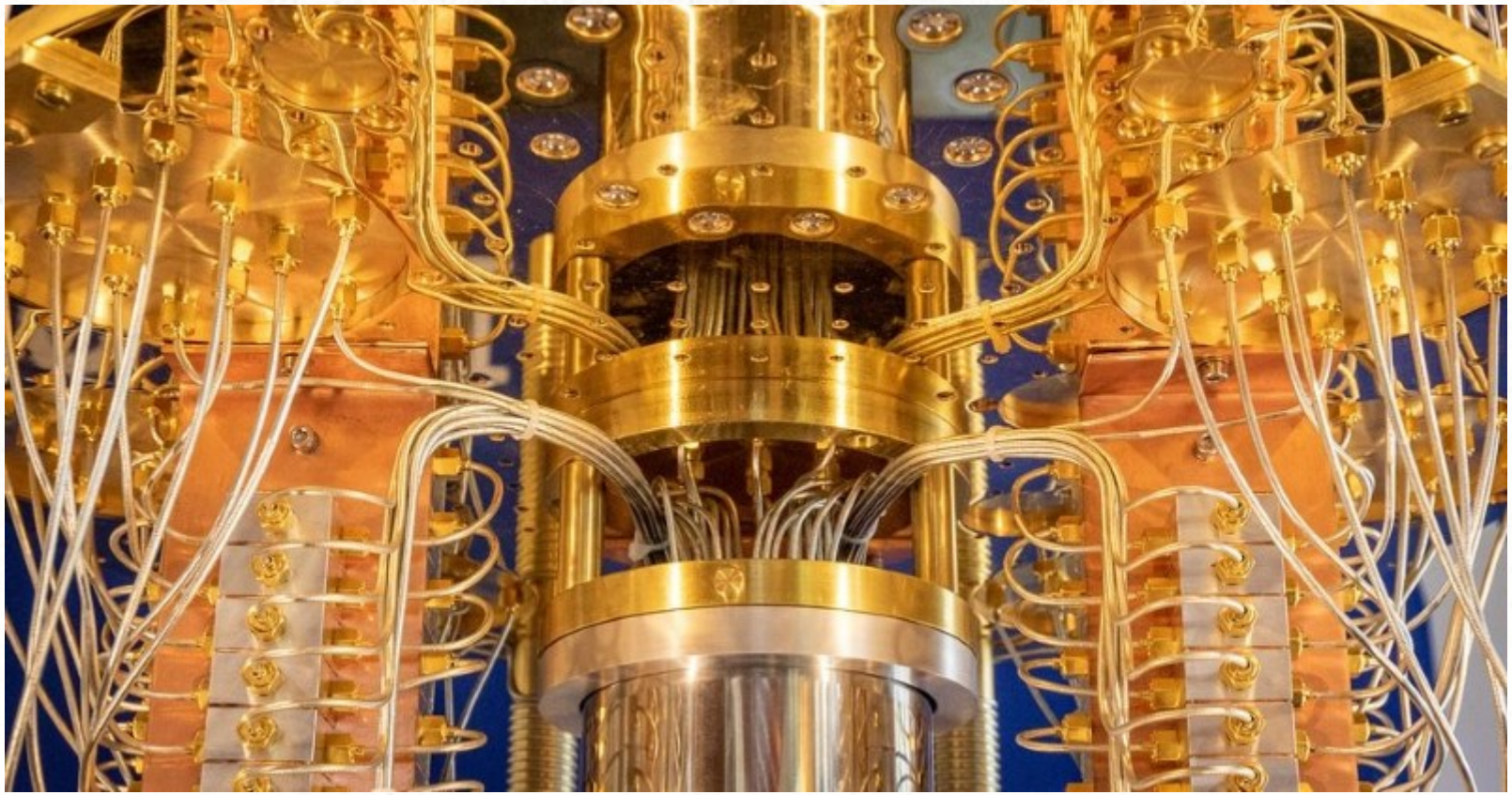
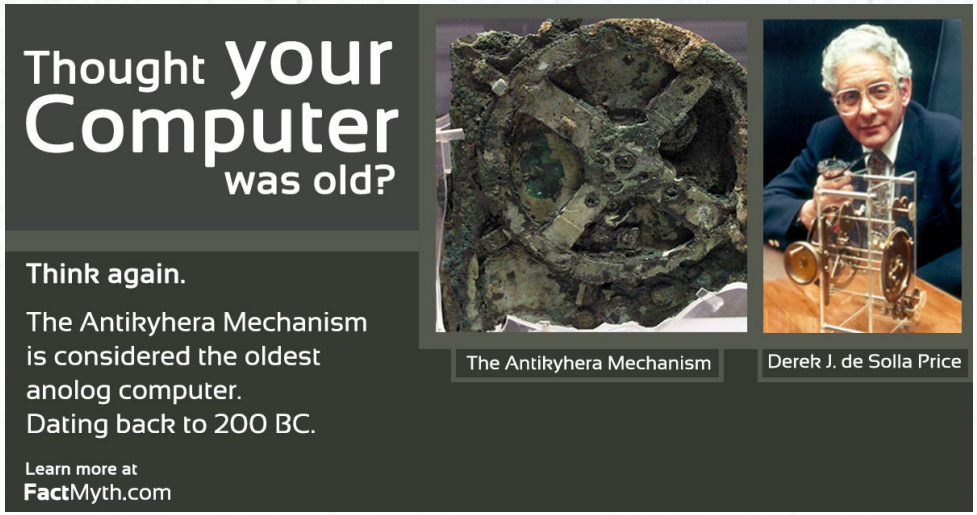
How Many Atoms Does It Take to Show 15 = 3(5)?

Dr. R. L. Herman, UNCW



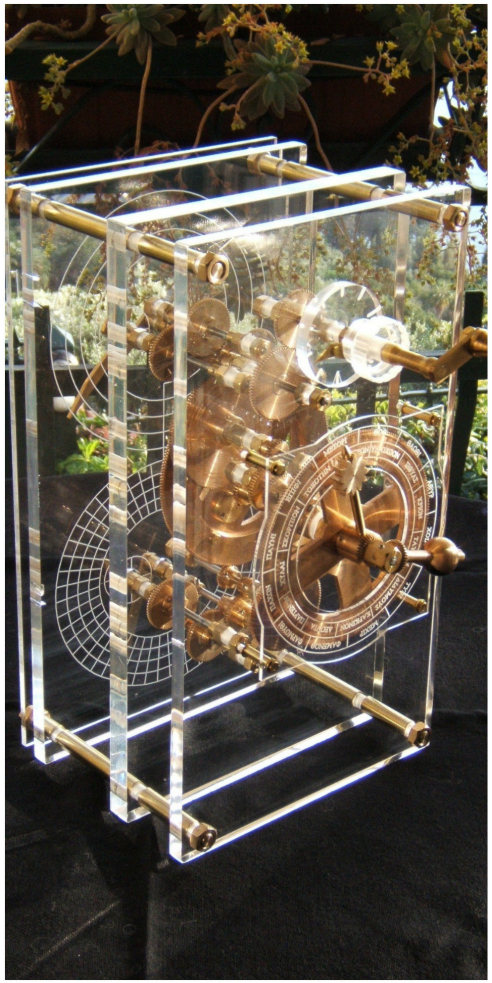
Outline

- Classical Computers
- Quantum Theory
- Quantum Algorithms
- Quantum Computers



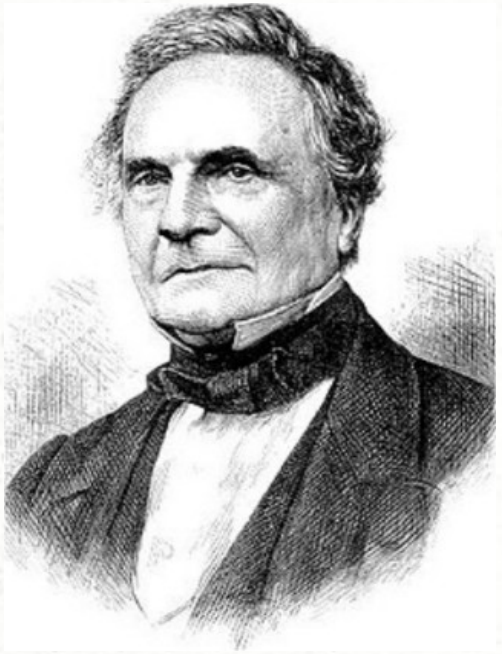
First Computers

- Antikythera Mechanism
- Found 1901
- Circa 70 BC

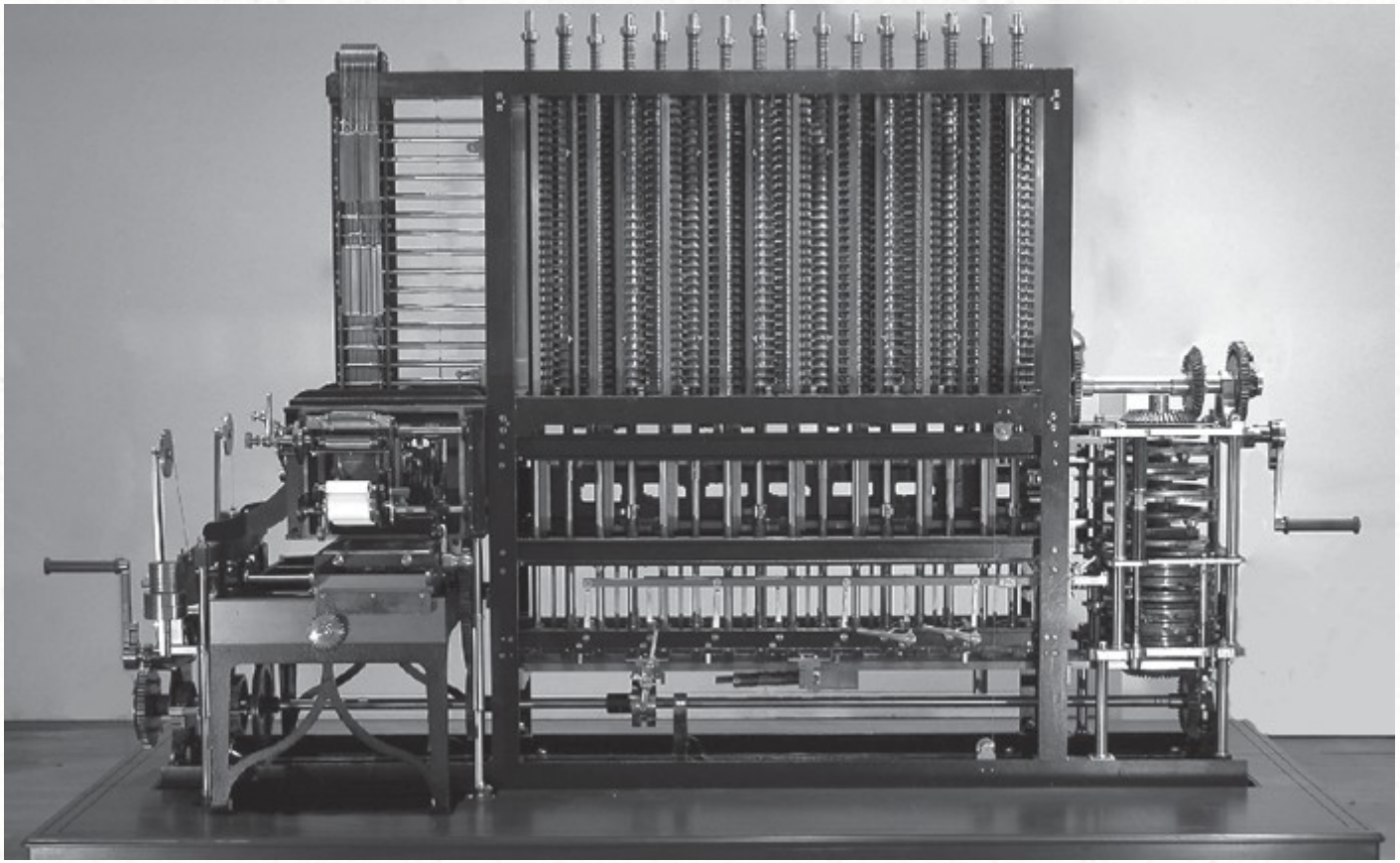


Charles Babbage

- 1822 Difference Engine
  - Evaluate numbers,
  - First automatic computing machine
  - Ada Lovelace, first programmer
- 1837 Analytical Engine
  - Arithmetic Logic Unit, flow control, punch cards, and integrated memory

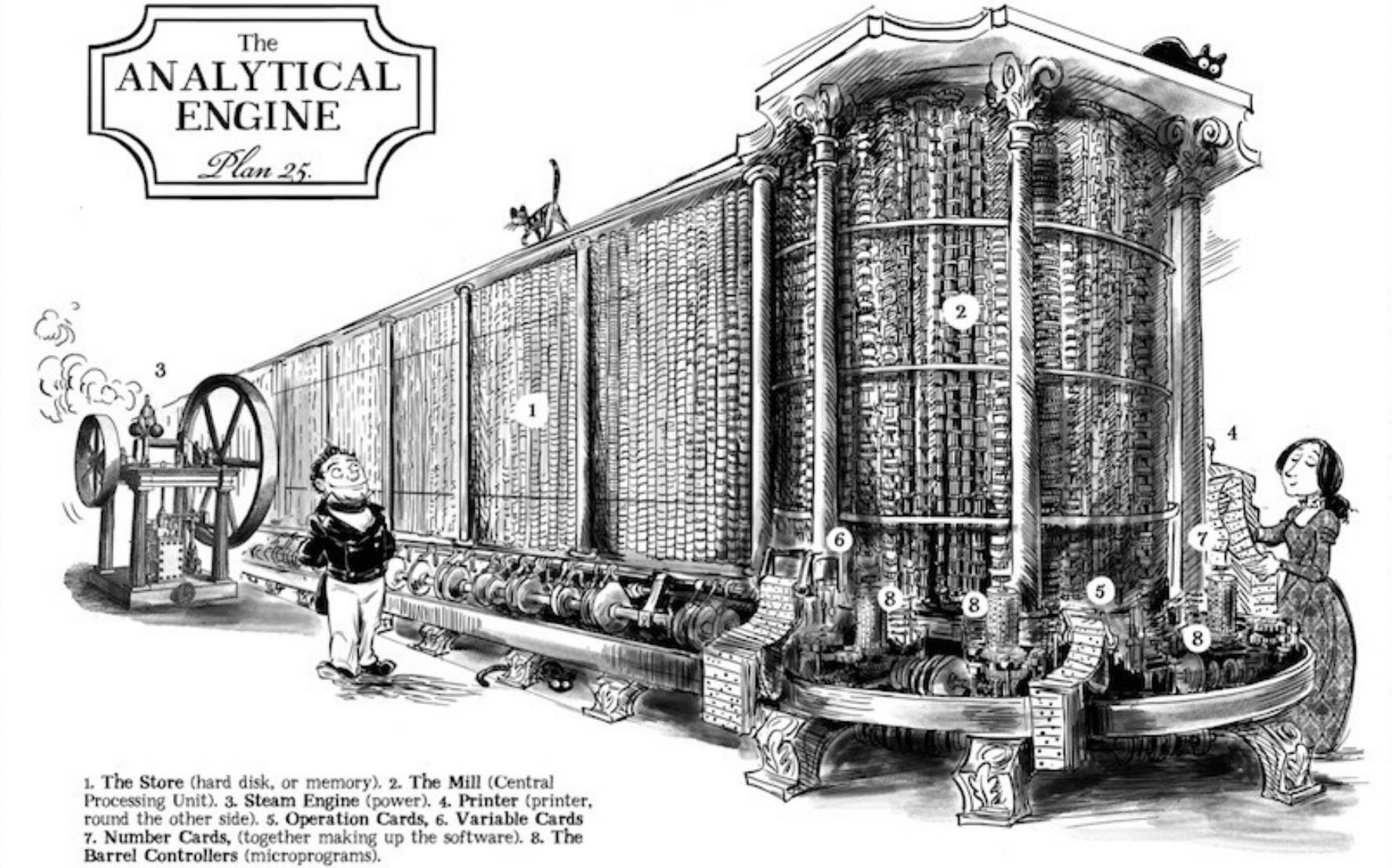


Babbage's Difference Engine



https://www.hackerearth.com/blog/developers/charles-babbage-computer-history-computer-programming-part-1/

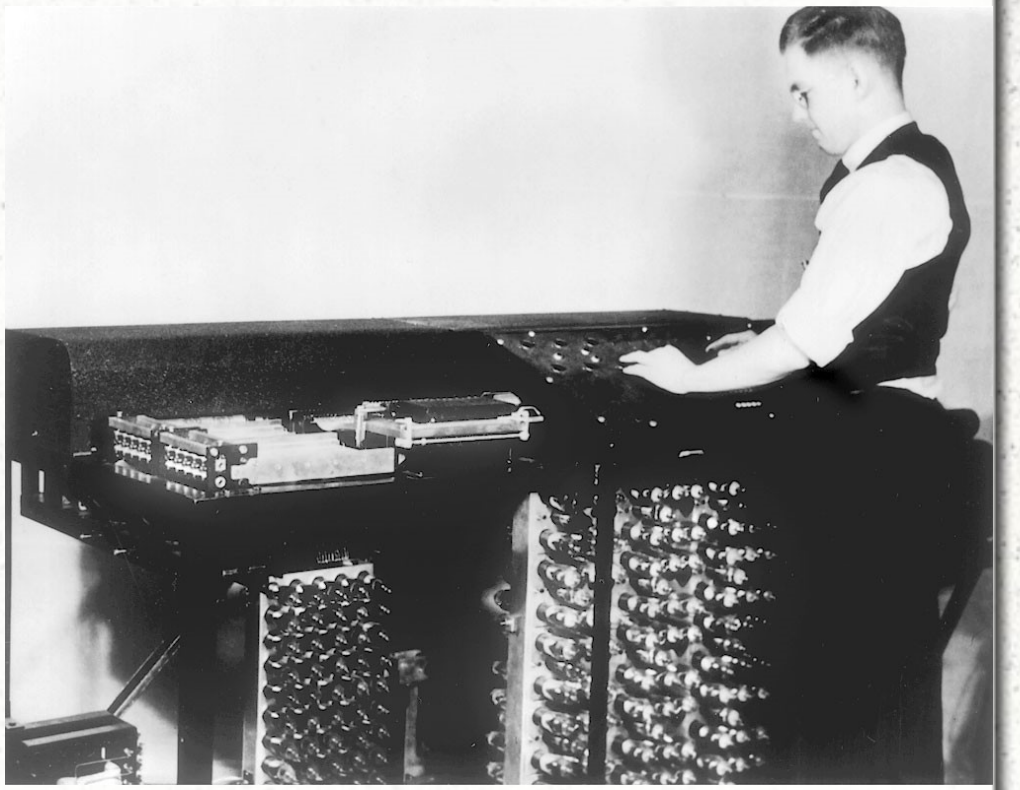
Charles Babbage's Analytical Engine



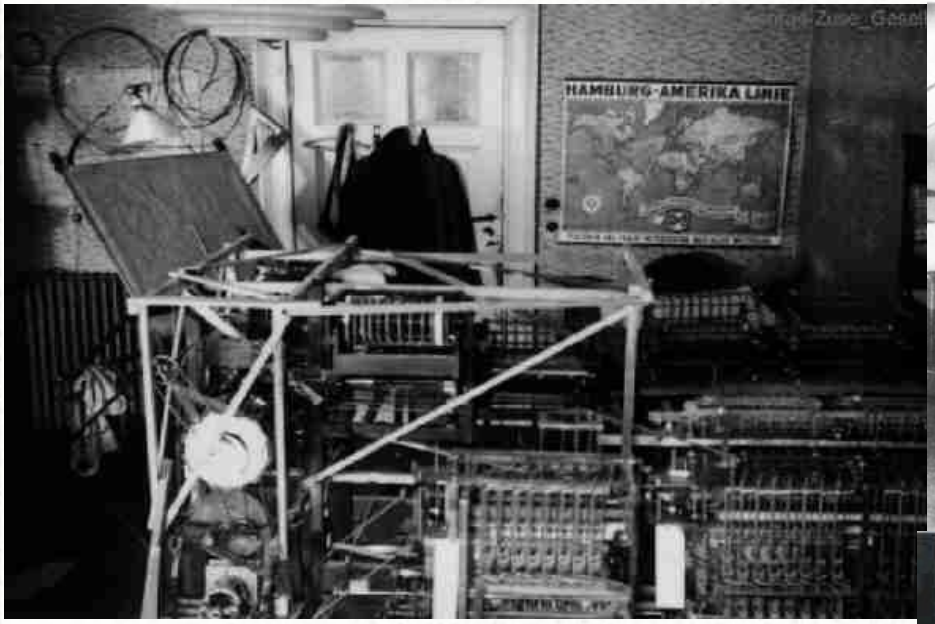
1. **The Store** (hard disk, or memory). 2. **The Mill** (Central Processing Unit). 3. **Steam Engine** (power). 4. **Printer** (printer, round the other side). 5. **Operation Cards**, 6. **Variable Cards** 7. **Number Cards**, (together making up the software). 8. **The Barrel Controllers** (microprograms).

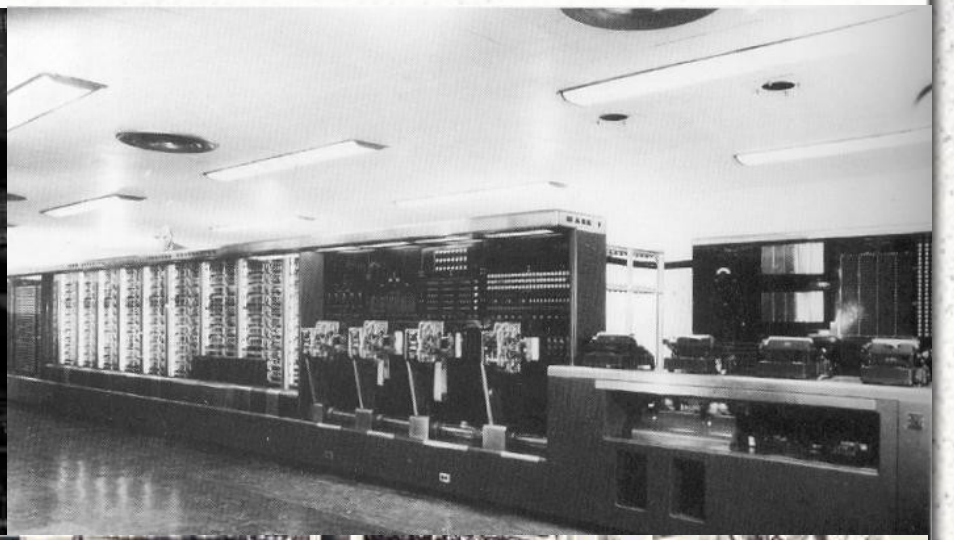
Atanasoff–Berry Computer - 1942

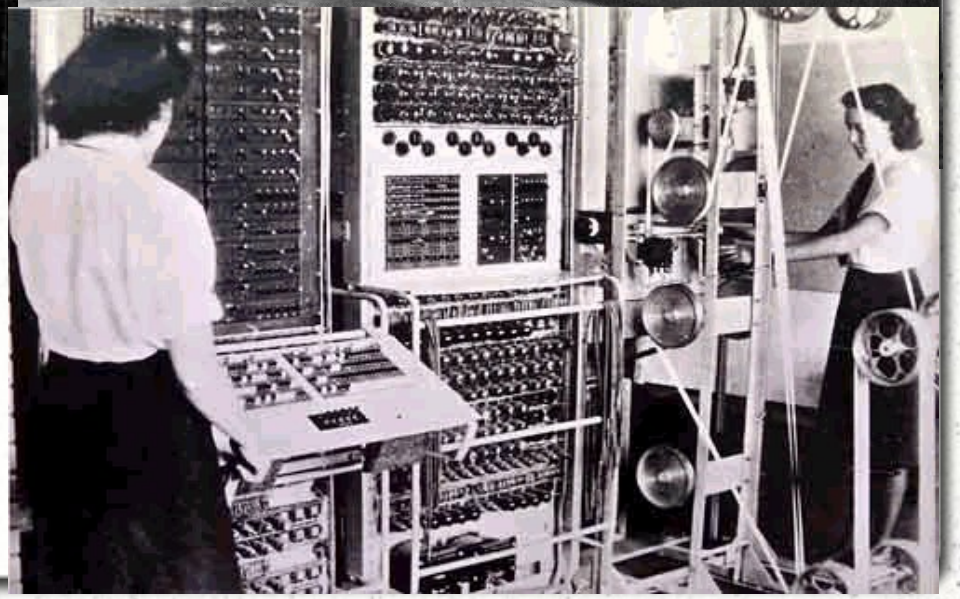
- Iowa State College
  - John Vincent Atanasoff, student Clifford Berry
- 300 vacuum tubes
  - Control and arithmetic calculations,
  - used of binary numbers, logic operations,
- Memory capacitors, and punched cards



Harvard Mark 1, the German Zuse Z3 and Great Britain's Colossus



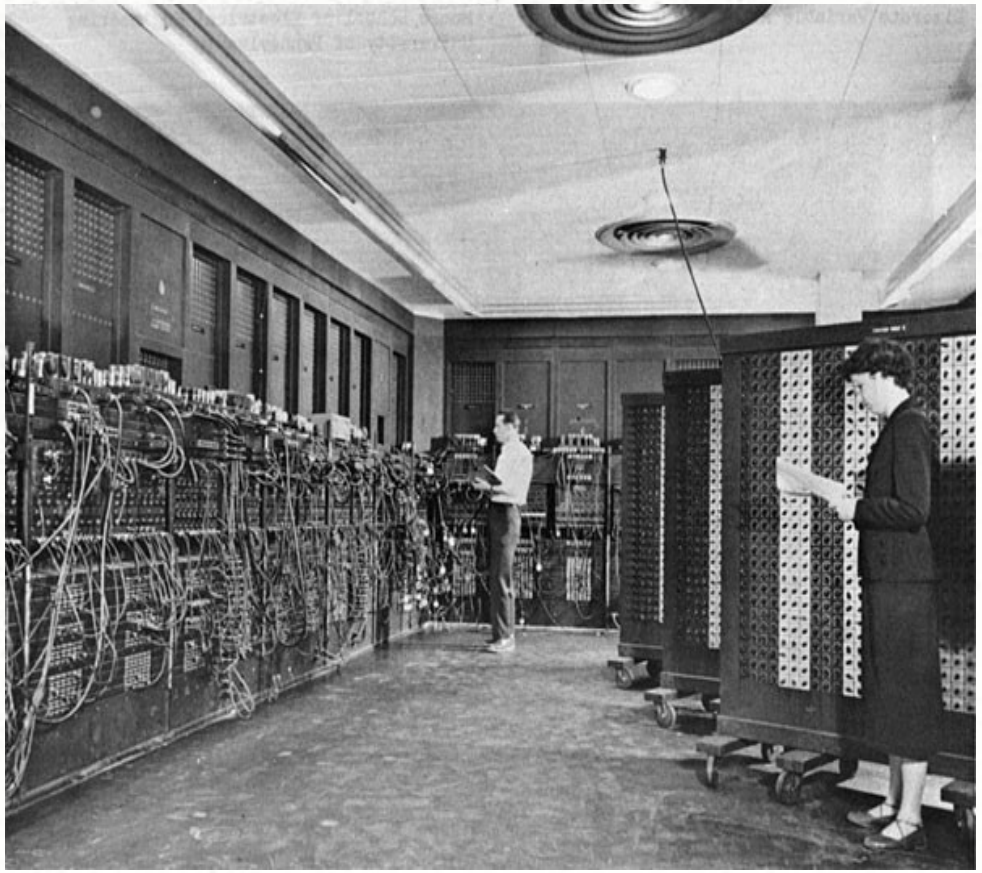




- Mark I 1944
- Zuse 1936-8
- Colossus 1943-5

ENIAC

- Electronic Numerical Integrator and Calculator
- 1943-1946
- U. of Pennsylvania
- Calculate artillery firing tables for US.



Vannevar Bush

- Electrical engineering faculty of MIT.
- Constructed the Differential Analyzer,
  - a mechanized analog computer that solved differential equations.
- Digital circuit design theory was developed by graduate student **Claude Shannon**.
- 1922 Bush co-founded defense contractor Raytheon Corporation.
- 1932 VP and Dean of Engineering.

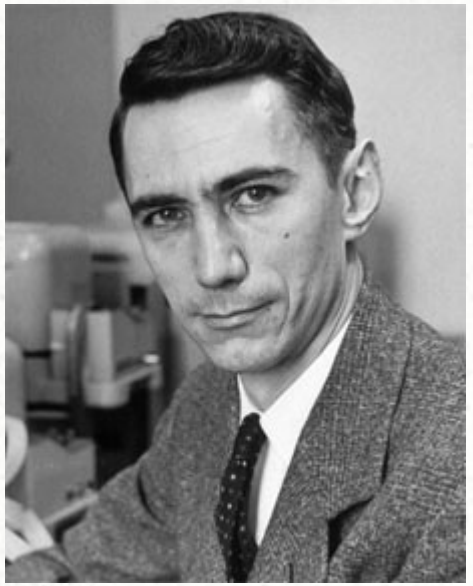
Differential Analyzer

Vannevar Bush (cont'd)

- President - Carnegie Institution of Washington
- Chairman - National Advisory Committee for Aeronautics in 1939.
- Chair of the National Defense Research
- 1941 Created the Office of Scientific Research and Development.
- 1942 The Manhattan Project
- 1950 Recommendations led to NSF.
- 1945 "As We May Think." "Memex," precursor to the modern personal computer.

Claude E. Shannon (1916-2001)

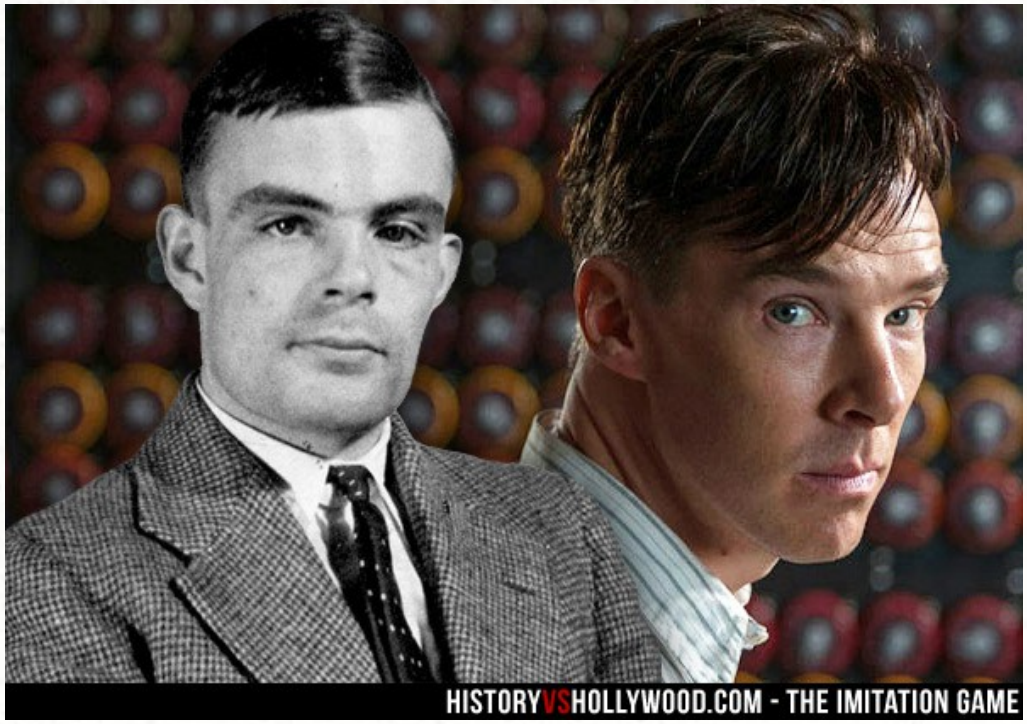
- U. Michigan
  - Engineering/ Mathematics
- MIT
  - Electrical Engineering
  - Ph.D. Mathematics
- Differential Analyzer
  - Work led to switches (on-off, 0/1 bits = binary digits)
  - Father of Information Theory
  - How much information can we transmit?



Alan Turing (1912-1954)

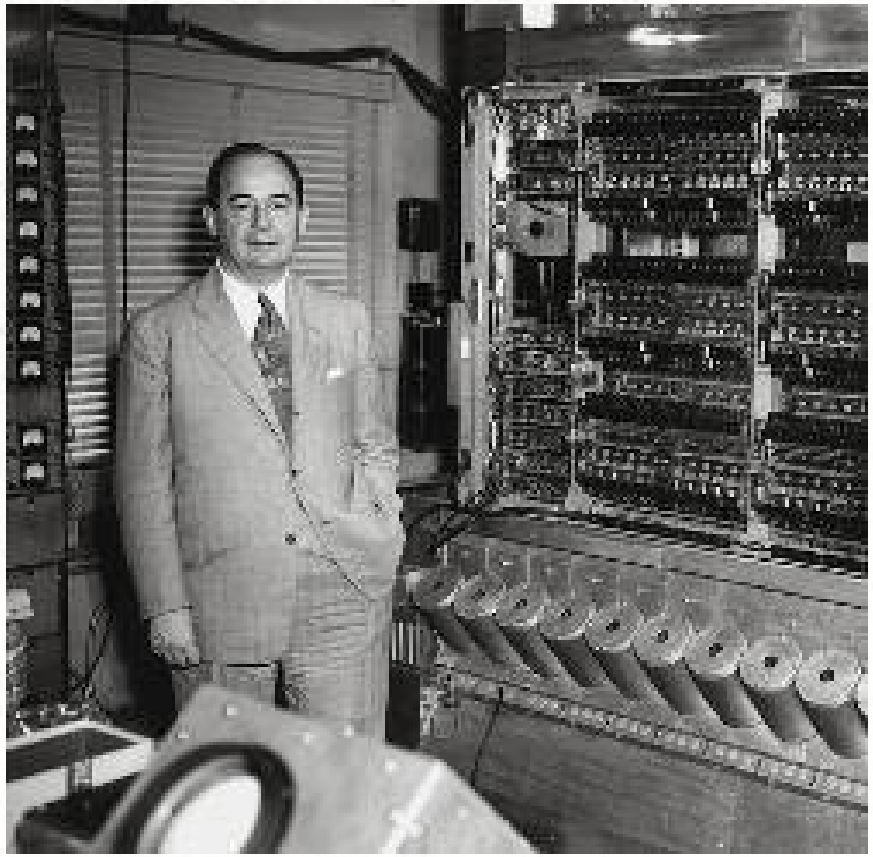
Developed theoretical computer science.

- Mathematician,
- Logician, Biologist
- Cryptanalyst
- Bletchley Park
  - Codebreaking
  - Enigma
  - Benedict Cumberbatch
- Turing Machine



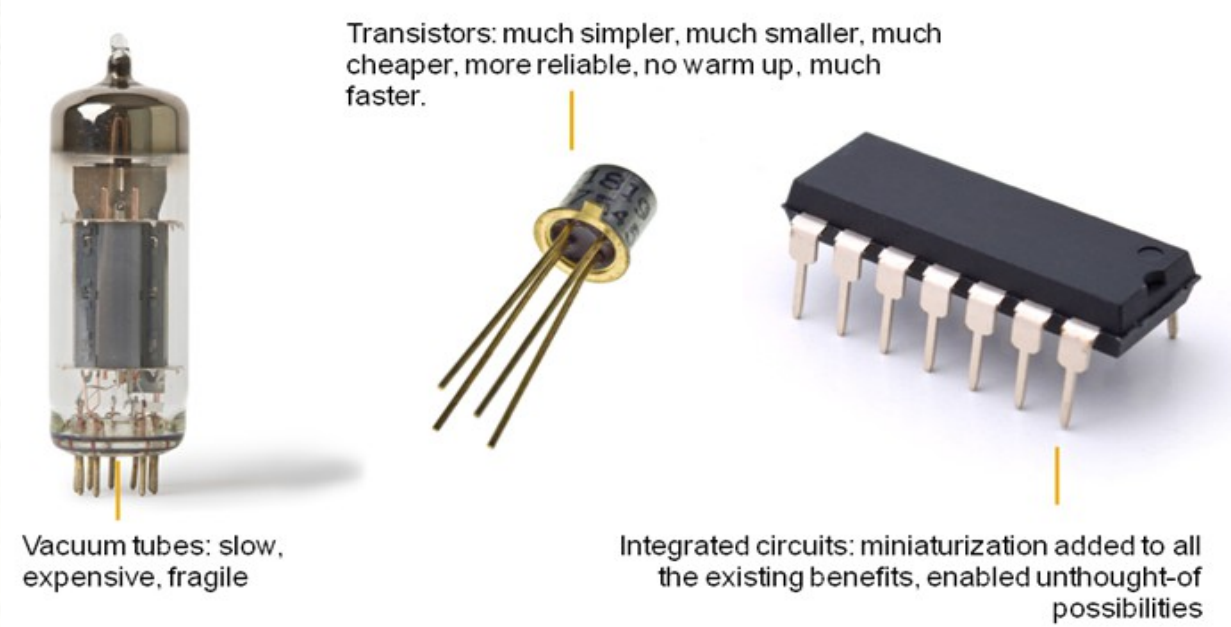
John von Neumann (1903-1957)

- The use of memory in digital computers to store both sequences of instructions and data
- EDVAC
  - Electronic Discrete Variable Automatic Computer
  - Binary
  - 12,000 vacuum tubes
  - 17,300 lb, 490 sq. ft.



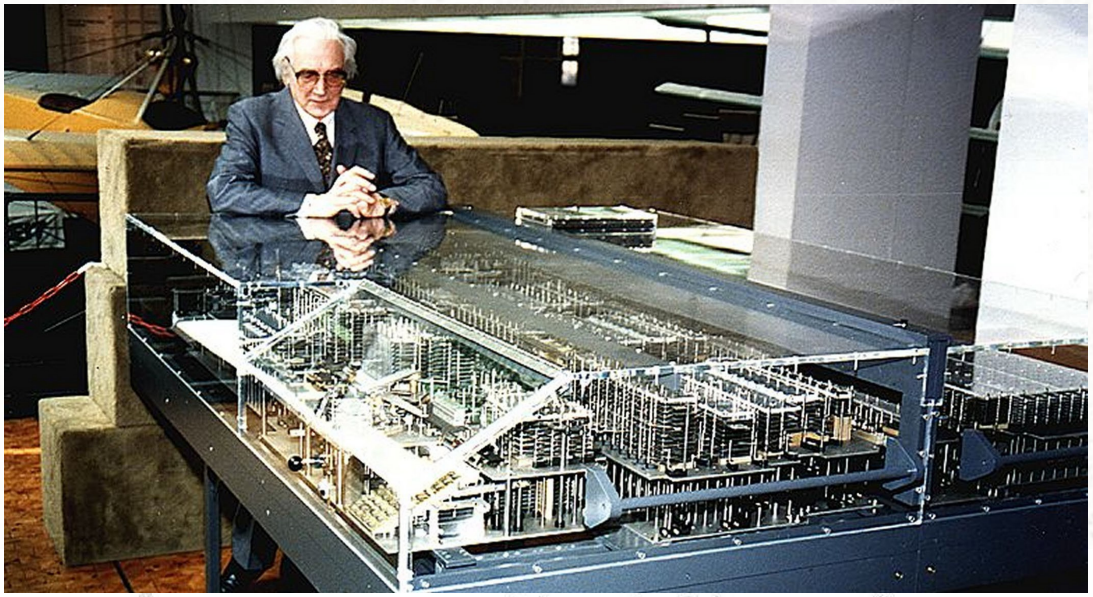
History of Computers

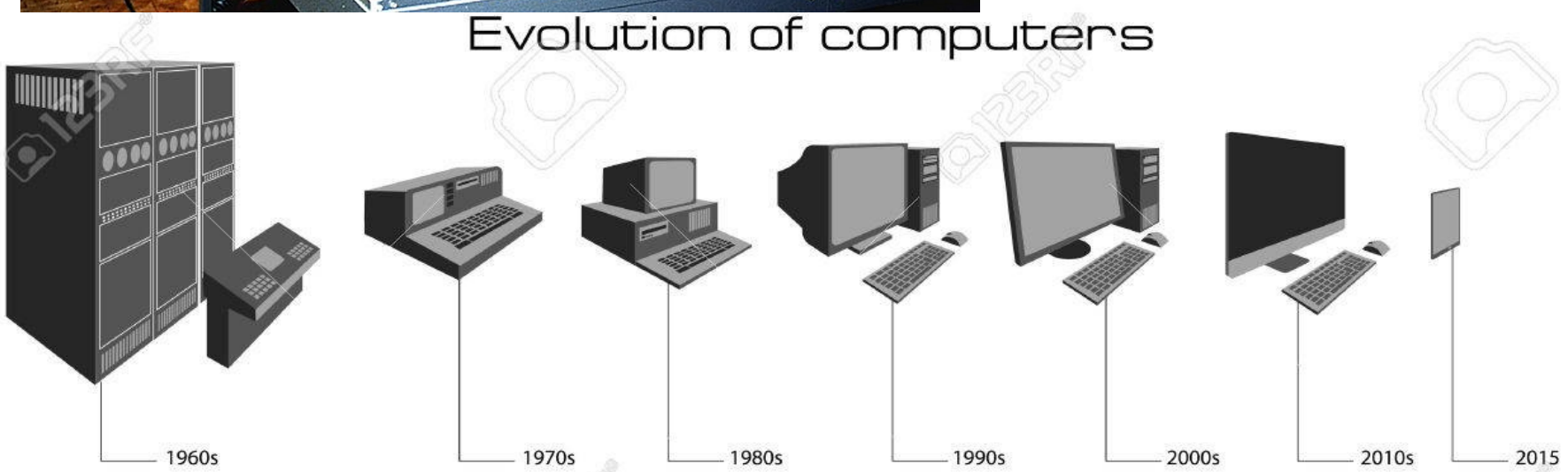
- 1944 Mark I, 1946 ENIAC – Vacuum Tubes
- 1947 Transistor – Use QM to make switches
- 1964 IC (Integrated Circuits) – a number of components being placed on a chip



Miniaturization of Computers

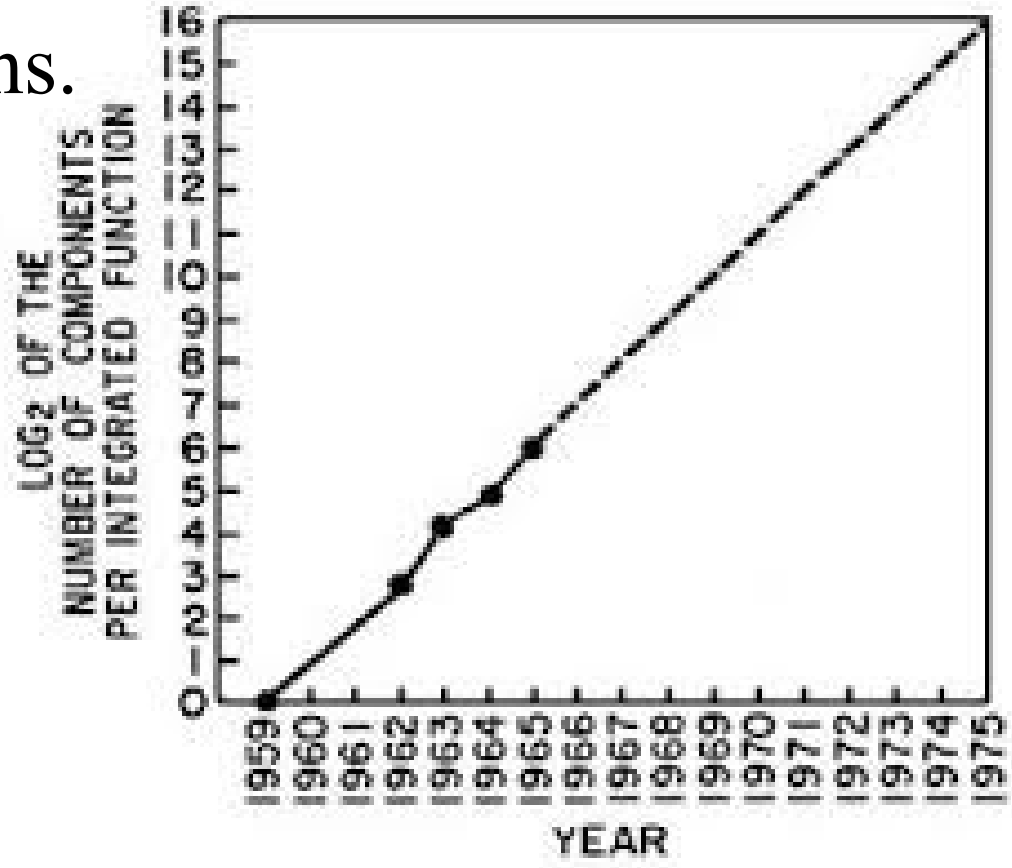
- From Z1 to 1981 IBM PC to ...



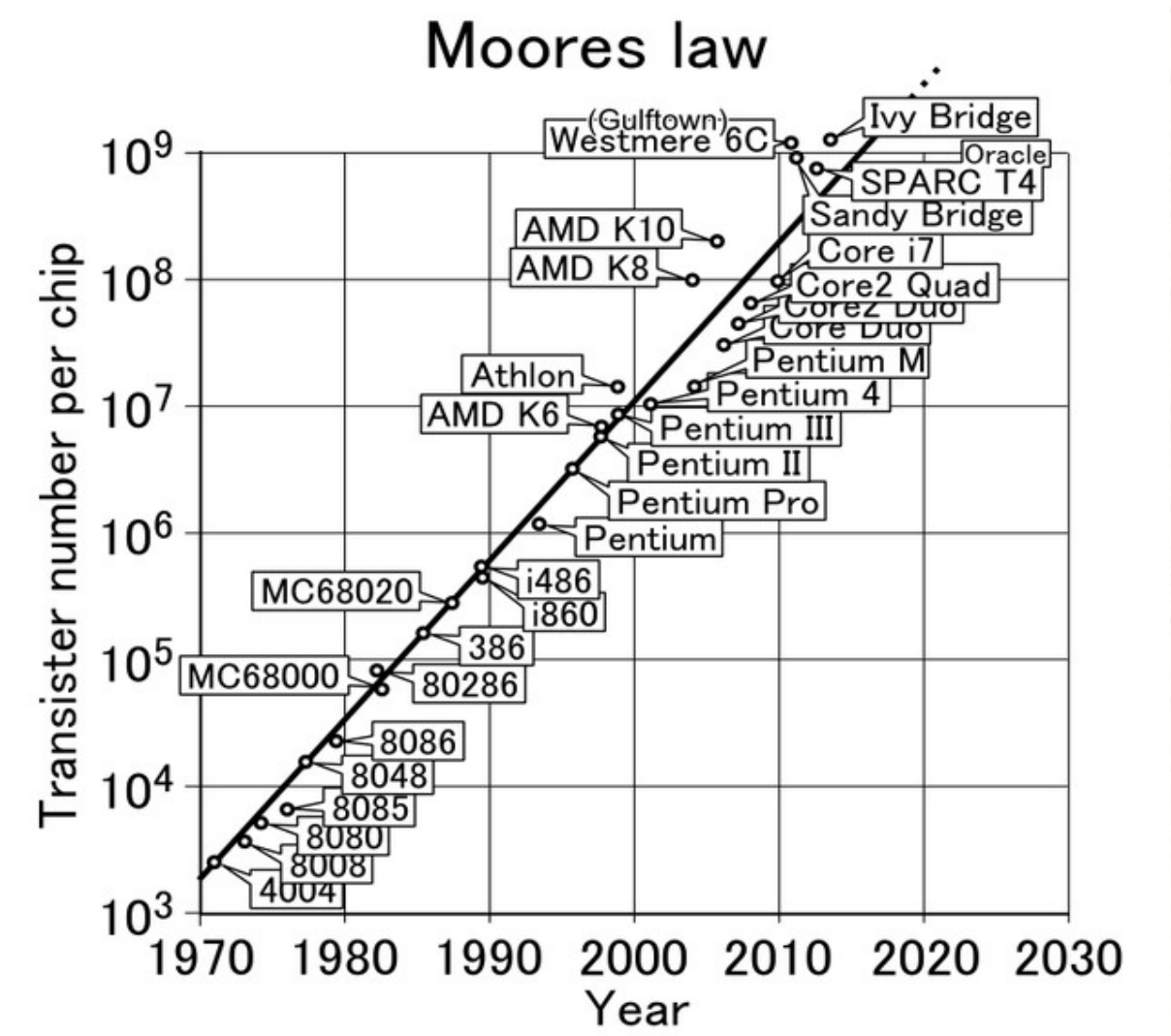


Moore's Law -1965

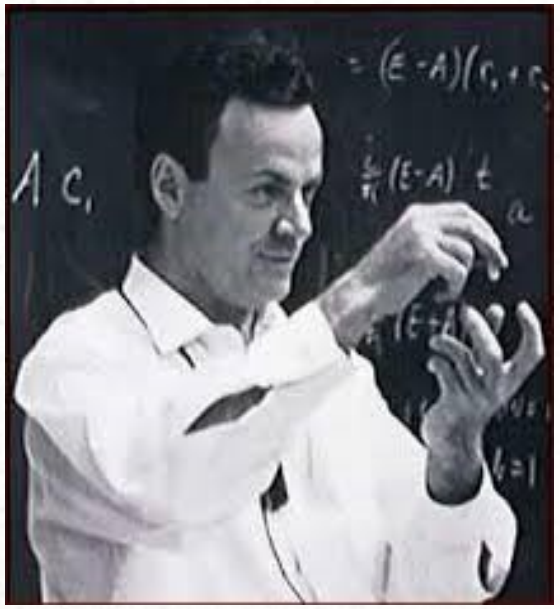
- Cofounder of Intel
- Number of components double every 18 months.
- 1981 IBM PC
- Now – 14 Billion transistors on a few square inch chip
- Cloud computing
  - FB, Google



The Limit of Moore's Law



Richard Feynman (1918-1988)



- 1939 MIT
- 1941-2 Atomic Bomb Project
- 1942 Ph. D. Princeton
- 1965 Nobel Prize - QED
- 1981-2 - "Its impossible to efficiently simulate the evolution of a quantum system on a classical computer." - ***Need quantum mechanics!***
- 1986 Rogers Commission - Challenger

Quantum Theory - 1900-1930

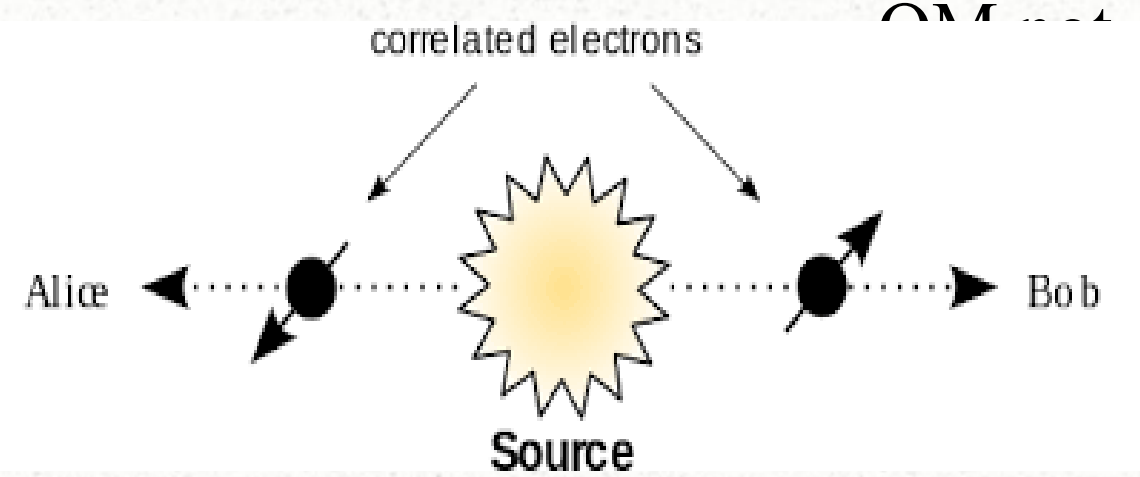
Quantum Theory

- 1900 Max Planck – A better light bulb?
- 1905 Albert Einstein – Photo detectors
- 1913 Neils Bohr – Atomic Model
- 1924 Louis deBroglie – Do electrons wave?
- 1925/6 Werner Heisenberg – QM/Uncertainty
- 1926 Erwin Schrodinger – Wave equation
- 1926 Max Born – Probability interpretations
- 1927-1935 Einstein – Bohr debates

Entanglement - EPR

- 1935 Einstein, Podolsky, Rosen

QM not complete!

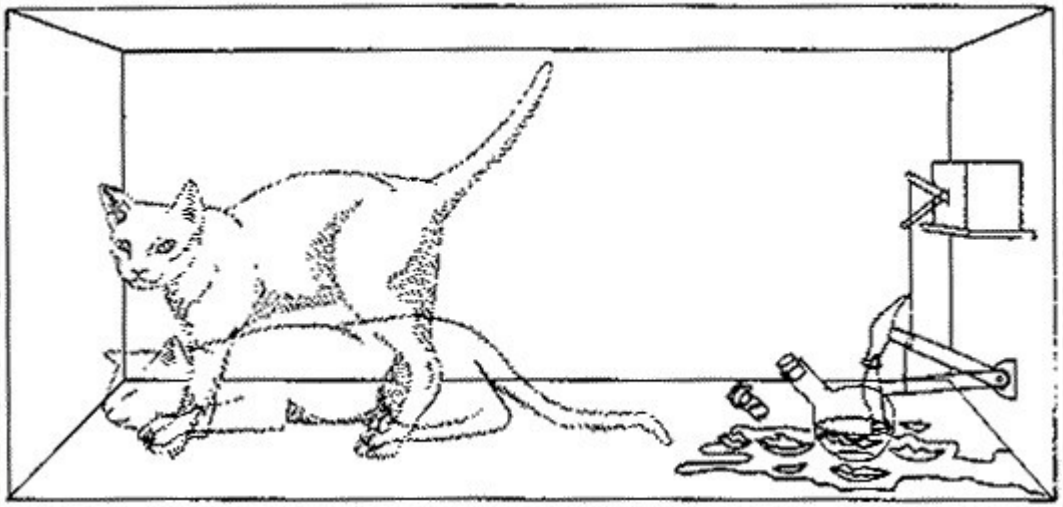


- Entanglement – two particles can be linked

  change in one results in change in the other
  without interaction.

- Termed “spooky action at a distance.”

Schrodinger's Cat – Born 1935



- Exhibits superposition and decoherence once measured.
- 1964 John S. Bell ('28-'90), CERN, Switzerland

History of Quantum Computing

- 1984 Charles H. Bennett and Gilles Brassard
  Quantum Cryptography
- 1985 David Deutsch – Quantum computer theory
- 1991 Artur Ekert – Cryptography - Entanglement
- 1994 Peter Schor – Factoring Algorithm
- 1996 Lov Grover – Quantum Search Algorithm
- 1997 First papers on quantum computers
- 2001 Factored 15 [used 7-qubit NMR computer]

What is Quantum Computing?

Computer components getting smaller -

Have to use properties of quantum mechanics

- Based on quantum states (qubits)
- Use quantum operations to manage states
- Operations done on an atomic scale
    - Moving atoms, electrons, or photons

Example

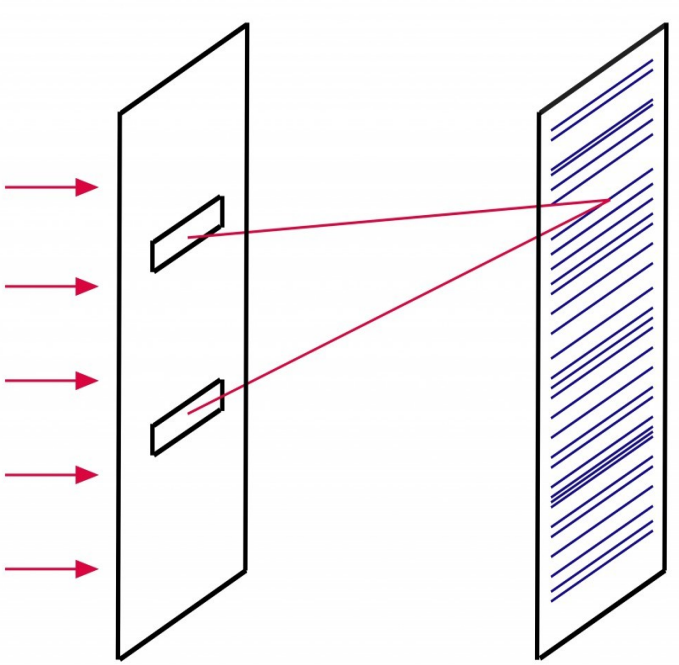
10 people come to a dinner party.

How many ways can one seat them?

- Number of ways – 10! = 3,628,800
- Classical – Test each way.
- Quantum –
  - Test all at once – superposition
  - Cancel all wrong answers - interference
  - Accentuates correct answer

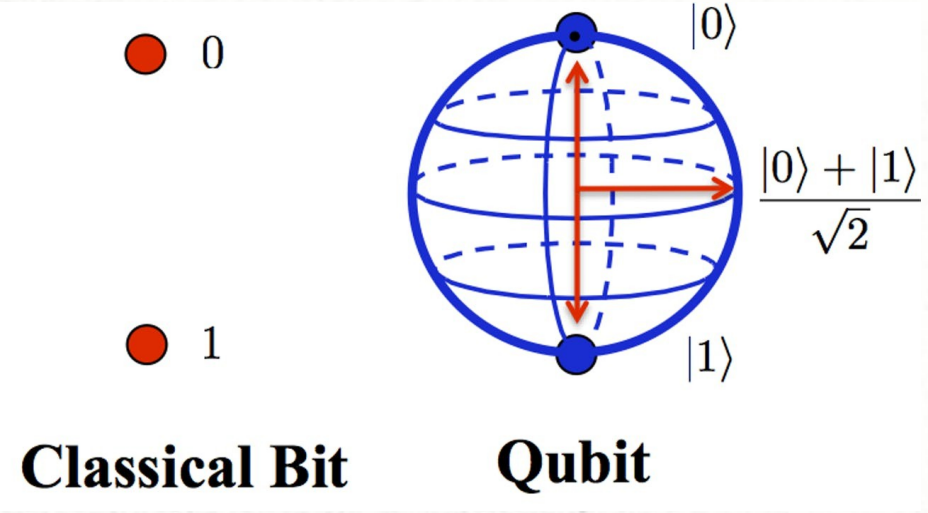
Quantum Properties

- Superposition, Interference,
- Decoherence, Entanglement
- Uncertainty Principle – Measurement
- Mathematics – Linear Algebra
- Notation from Dirac (1902-1984)
- Represent data (states) with qubits
- Atoms in ground vs excited state,
  polarization of photons,
  particle spin – up or down



From Bit to Qubit

- Classical Bit:
  - 0 or 1 (On/Off)
- Quantum Bit:
  - Atoms are |0> and |1>, simultaneously
  - Twice the information stored
- Classical: *n* bits – *n* pieces of information
- Quantum: *n* qubits – 2^n pieces of information



Properties

- Qubits are
  - Dynamic
  - Probabilistic superposition of all states.
  - Accurate measurement is difficult.
  - Measurement collapses state.
  - Requires complex algorithms,
    - Shor's algorithm for factoring.

Logic Gates

Classical (Boolean) – AND, OR, XOR

P AND Q

P	Q	P ^ Q
T	T	T
T	F	F
F	T	F
F	F	F

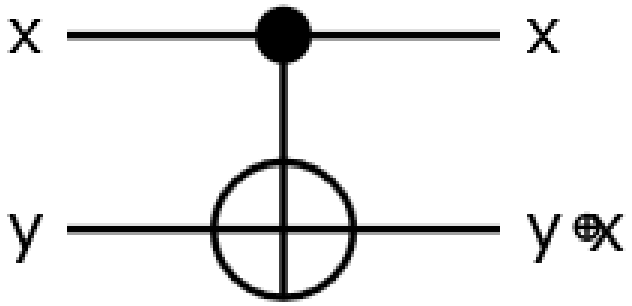
P OR Q

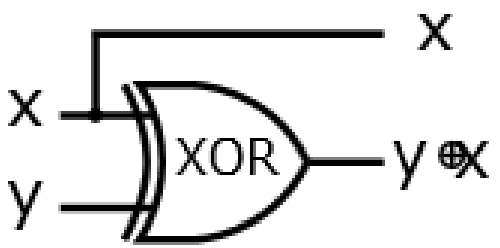
P	Q	P V Q
T	T	T
T	F	T
F	T	T
F	F	F

P XOR Q

P	Q	P XOR Q
T	T	F
T	F	T
F	T	T
F	F	F

CNOT vs XOR





input		output	
x	y	x	y+x
|0⟩	|0⟩	|0⟩	|0⟩
|0⟩	|1⟩	|0⟩	|1⟩
|1⟩	|0⟩	|1⟩	|1⟩
|1⟩	|1⟩	|1⟩	|0⟩

input		output	
x	y	x	y+x
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Quantum Logic Gates

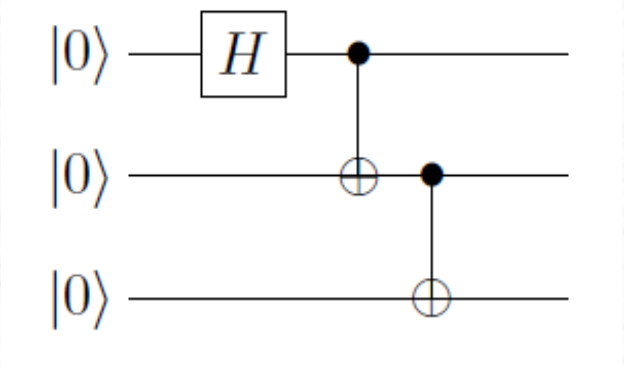
- Operations that preserve probability.
- Types of Gates
  - Hadamard

    $|0\rangle$ to $|0\rangle+|1\rangle$, $|1\rangle$ to $|0\rangle-|1\rangle$
  - Quantum NOT

    $|0\rangle$ to $|1\rangle$, $|1\rangle$ to $|0\rangle$

Quantum Circuits

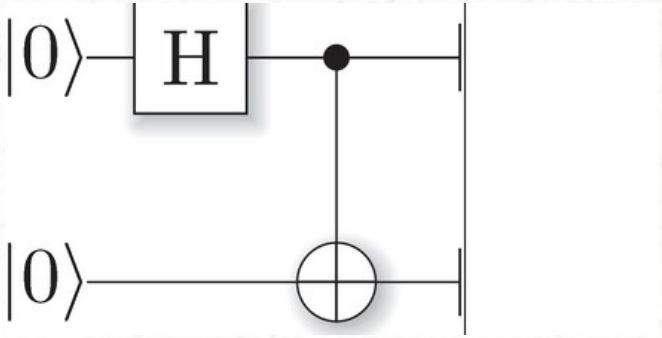
- Start with 3 qubits
- Use H-gate and CNOTs to produce GHZ state

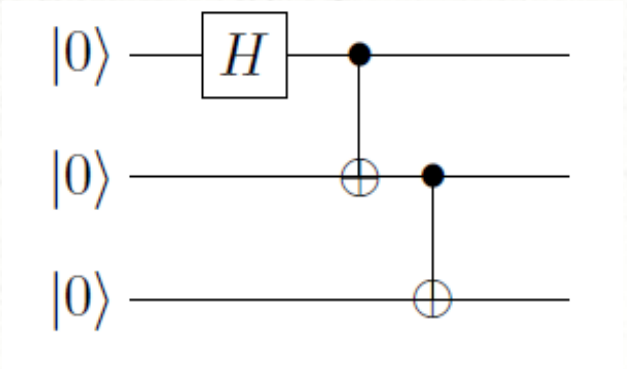


Hadamard and CNOT

- H and CNOT give an Entangler
- Add another qubit to obtain "GHZ state":

$$|000\rangle + |111\rangle$$

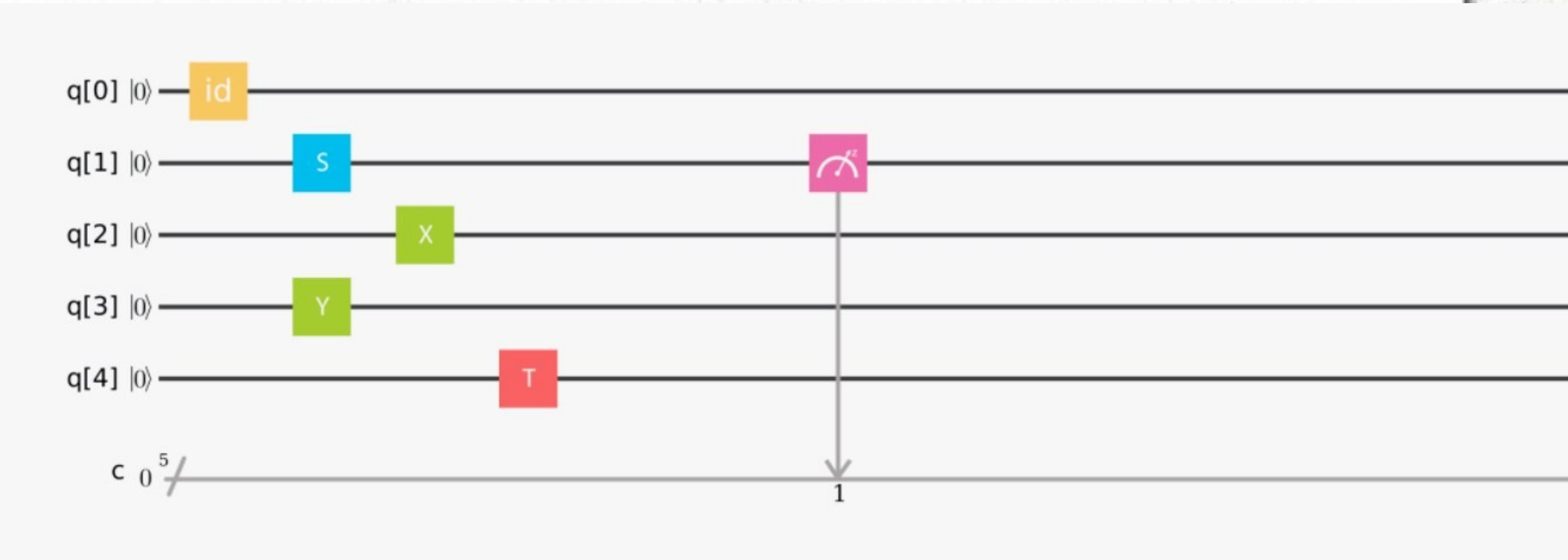




https://algassert.com/quirk#circuit={"cols":[["H"],["•","X"],[1,"•","X"]]}

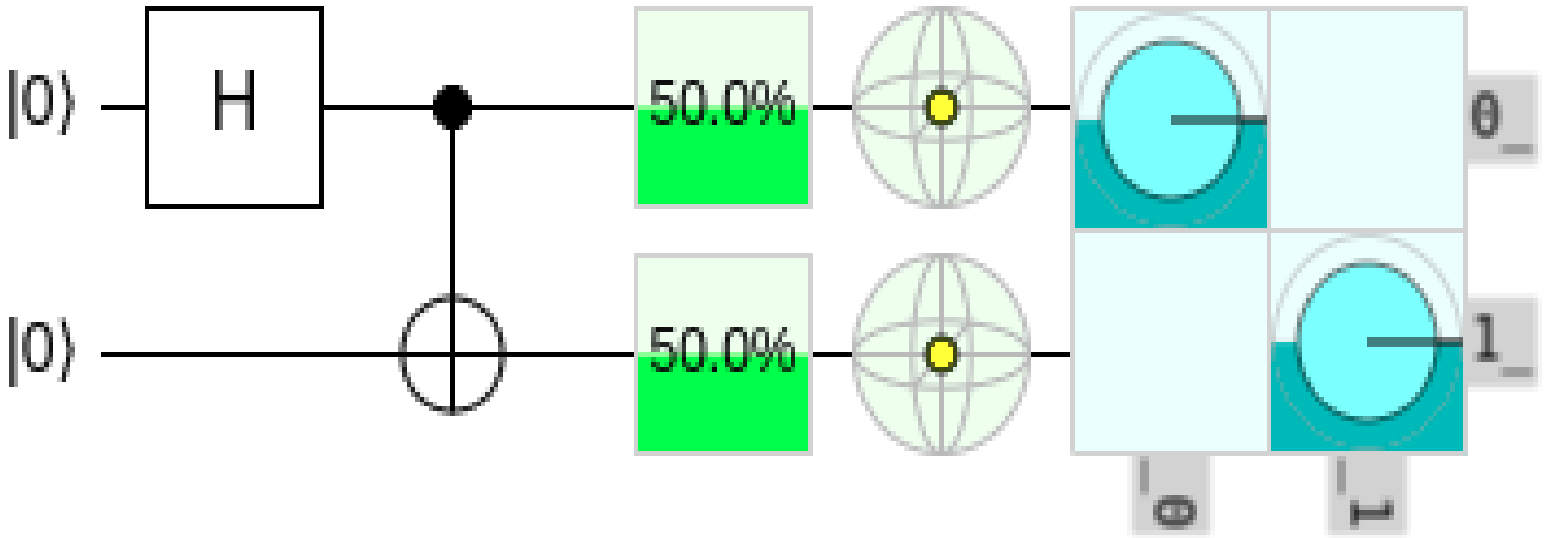
Other Gates

- Quiskit - IBM Q Experience



Quirk

- Entangled State



Quantum Algorithms

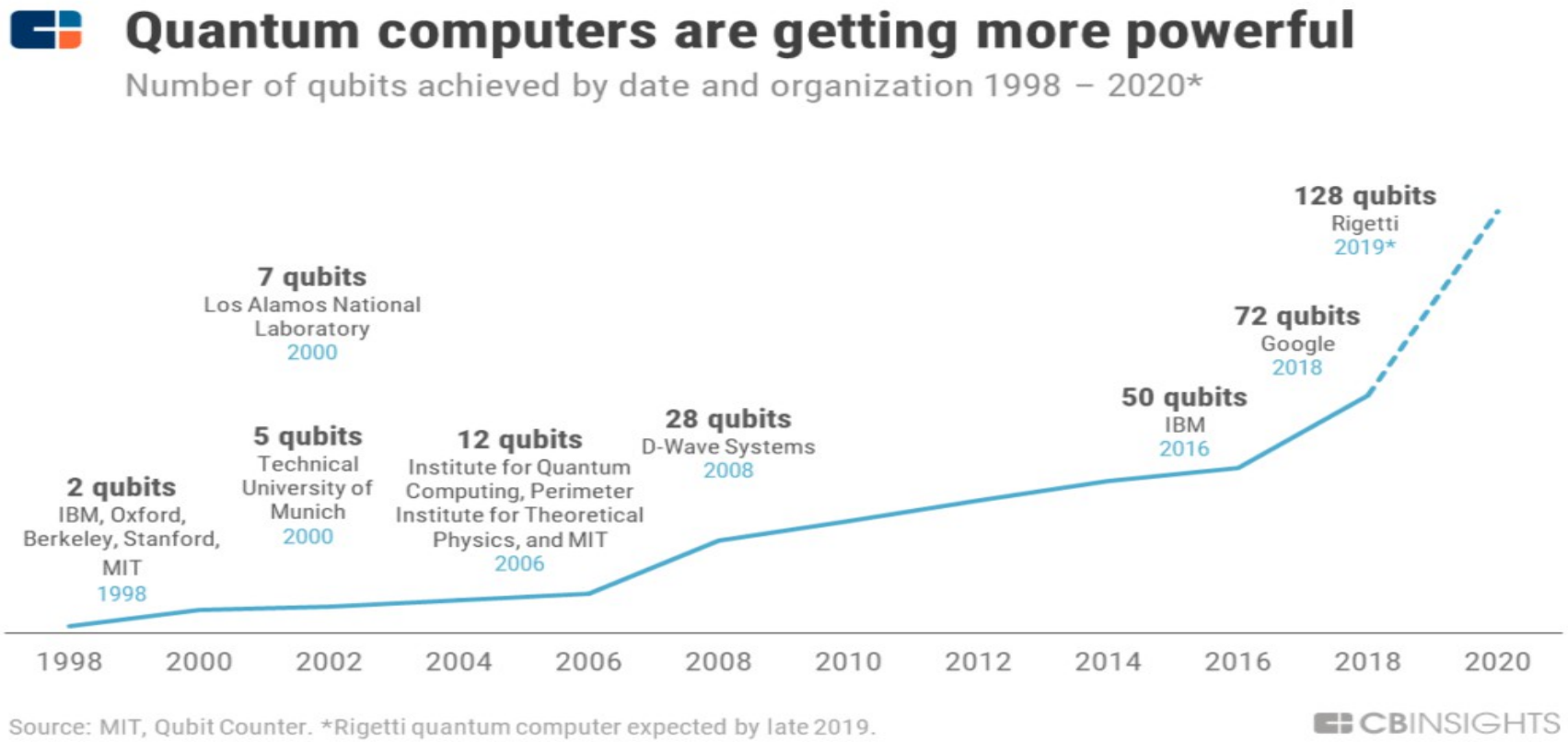
- Search
- FFT
- Factoring
- Solving system of equations

https://goo.gl/v4JbRw

Quantum Computers

- D-Wave 1999
- QuTech, Intel 2015
- Google 2009, 2014 UCSB, 2017 (49 qubit) 2019 (53/72)
- IBM Q Experience, 2016 (5), 2017 (16) quiskit
- 2007 – Orion – superconducting electronics, 16 qubit processor
- Bell Labs Microsoft, Quantum Diamond Tech,
- Quantum Circuits Inc 2015, ION Q
- Rigetti Computing Quantum Cloud Service

Number of Qubits



https://www.cbinsights.com/research/report/quantum-computing/

Current Computers

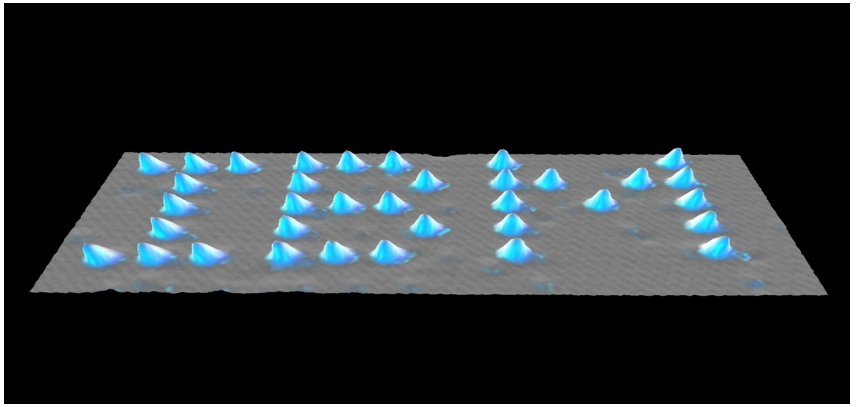
- Supercomputers needed
- Weather forecasting, Genome sequencing
- Encryption
- RSA – depends on factoring large numbers
  - Supercomputer takes years
  - Quantum Computer – days or hours

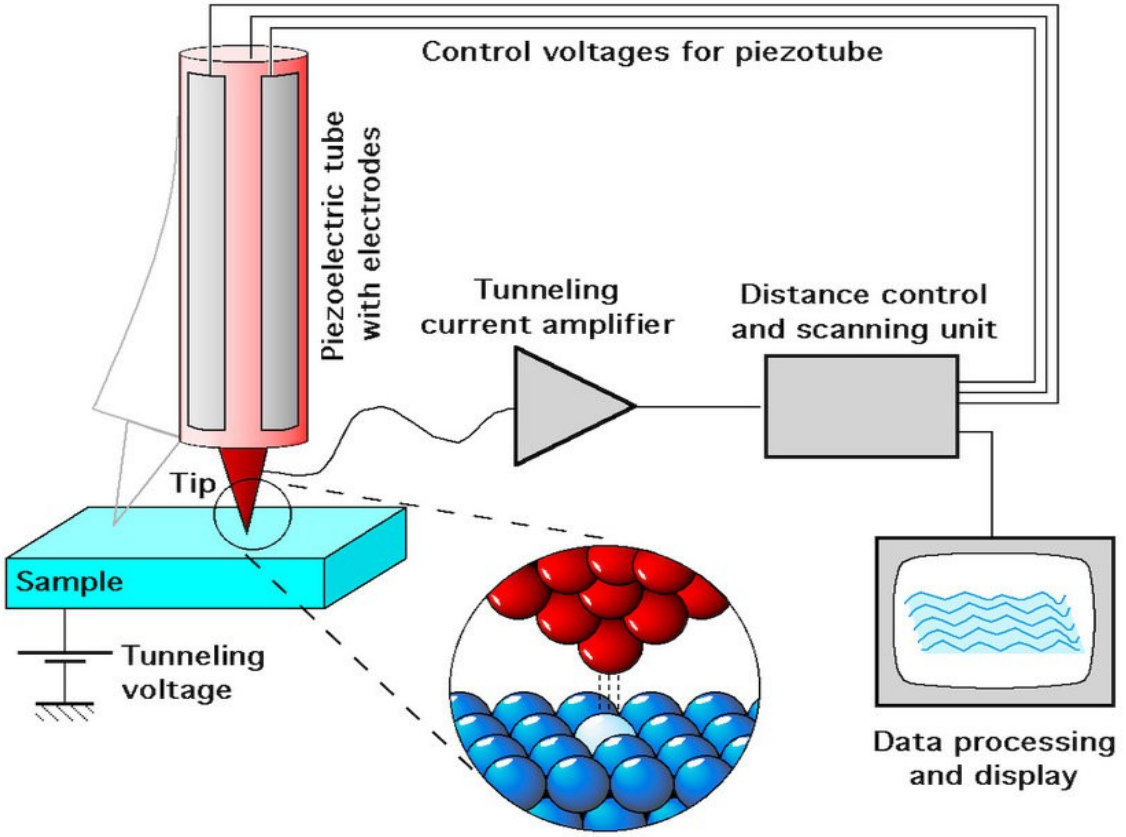
Building Quantum Computers

- Australian and American physicists developed a Single Atom Transistor
- Phosphorous-31 isotope
  - 100 times smaller than 22 nanometer Intel transistor.
  - Scanning Tunneling Microscopy (STM) and
  - Hydrogen-resist Lithography to place single phosphorus dopant atom on the base of Silicon with a accuracy of one lattice site.

STM

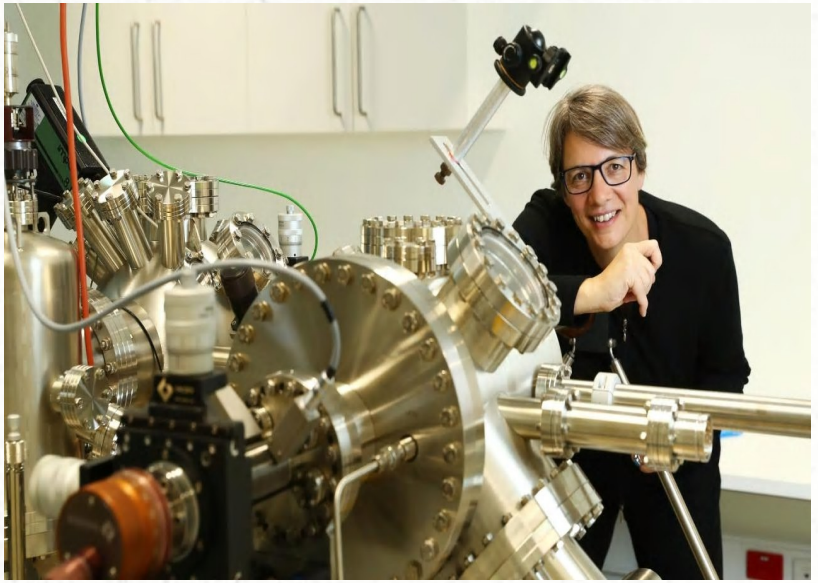
- Scanning Tunneling Microscope – 1981
- Gerd Binnig and Heinrich Rohrer (at IBM Zürich),
- Nobel Prize in Physics in 1986.





Conclusion

- Classical Computers
- Quantum Theory
- Quantum Algorithms
- Quantum Computers



Thank you for attending!