Feynman’s Computer

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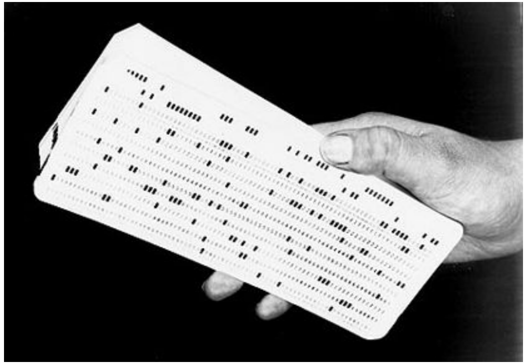
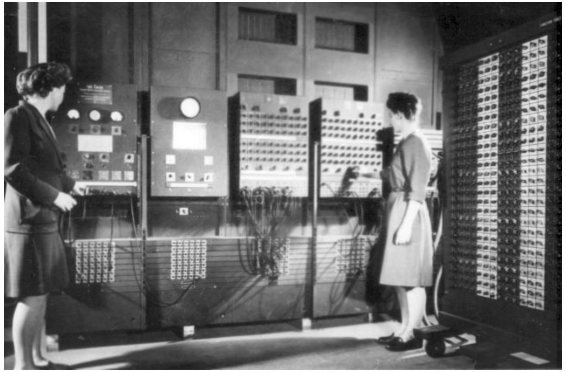
“Simulating Physics with Computers”

Feynman 1981 (published 1982)

- Can a computer efficiently simulate quantum mechanics (QM)?
- Can the “computing way of thinking” teach us about nature?
    - Why does QM exhibit randomness?
    - Which physics problems are computationally equivalent (“intersimulable”)?



IBM punchcard
pininterest.com



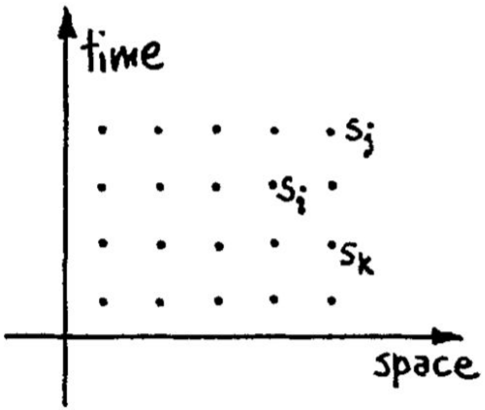
ENIAC, 1946
atomicheritage.org

IBM PC, 1981
computerhope.com

1st Conference on Physics and Computing, MIT 1981

Feynman’s Rules for a quantum simulator

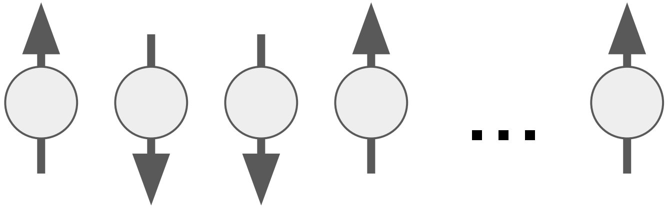
1. **Locality** - the parts only interact with nearby parts
2. **Linear growth** - size of computer proportional to space-time volume of the problem
3. **Discretizing** space and time is allowed



Feynman 1982

Exponential Scaling

N spin ½ particles (N = 128)



state	ψ
0000… 0	0.01
0000… 1	0.01 + 0.02i
...	...
1001… 1	0.05 - 0.01 i
...	...

Classical: N bits, i.e. (1 0 0 1 … 1)

128 bits ~ 13 x 

Quantum: $\psi(n_1, n_2,.. n_N)$

$\rightarrow 2^N$ complex values $\rightarrow$ e.g. 128×2^N bits

43556142965880123323311949751266331066368 ~ 10^{41} bits

10^8 x 

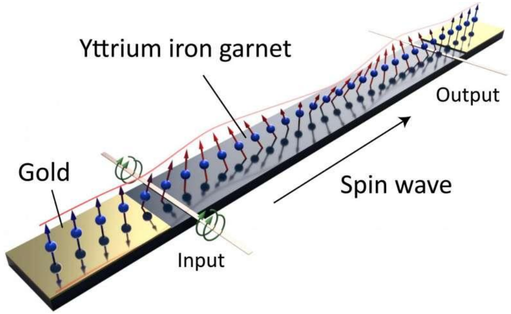
10^{33} atoms

Quantum Simulators

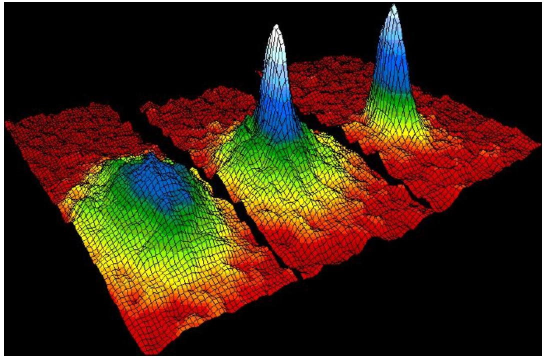
"Let the computer itself be built of quantum mechanical elements"

Feynman's Conjecture:

- Quantum systems can simulate other quantum systems
- Possibility of a "universal quantum simulator"
    - suggests array of spin ½ particles (now called qubits)



Spin wave
Toyohashi University Of Technology



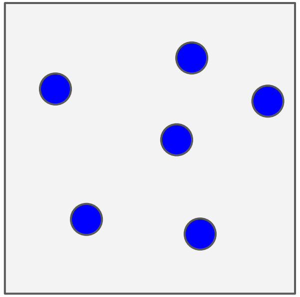
Bosons (BEC)
wikipedia.org

Aside:
BEC of magnons
Dzyapko et al 2011

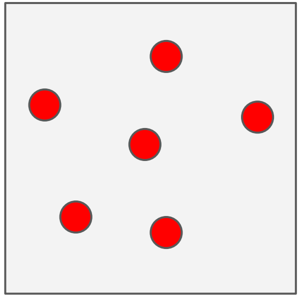
Analog Quantum Simulation

Model quantum systems using, e.g. atoms

Neutron star
NASA



Fermions w/
contact interactions



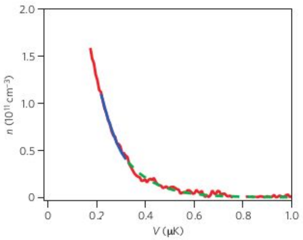
Atoms i.e. ^{6}Li
Scattering length *a*

Also: metals,
Superconductors,
Mott insulators,...

Thermodynamics

image:

density



potential

Resonance ($a \rightarrow \infty$)

$\mu = 0.376(4)\ E_F$

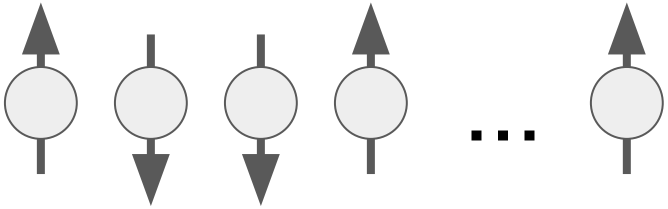
(Bertsch parameter)

Ku et al Science 2012

Digital Quantum Simulation

Program quantum bits

Simulate other quantum systems



R. Feynman 1982 - “... you could imitate any quantum system”

S. Lloyd 1996 - Trotter expansion leads to linear scaling

$$H = \Sigma_{i=1}^{\ell} H_i$$

Local interactions

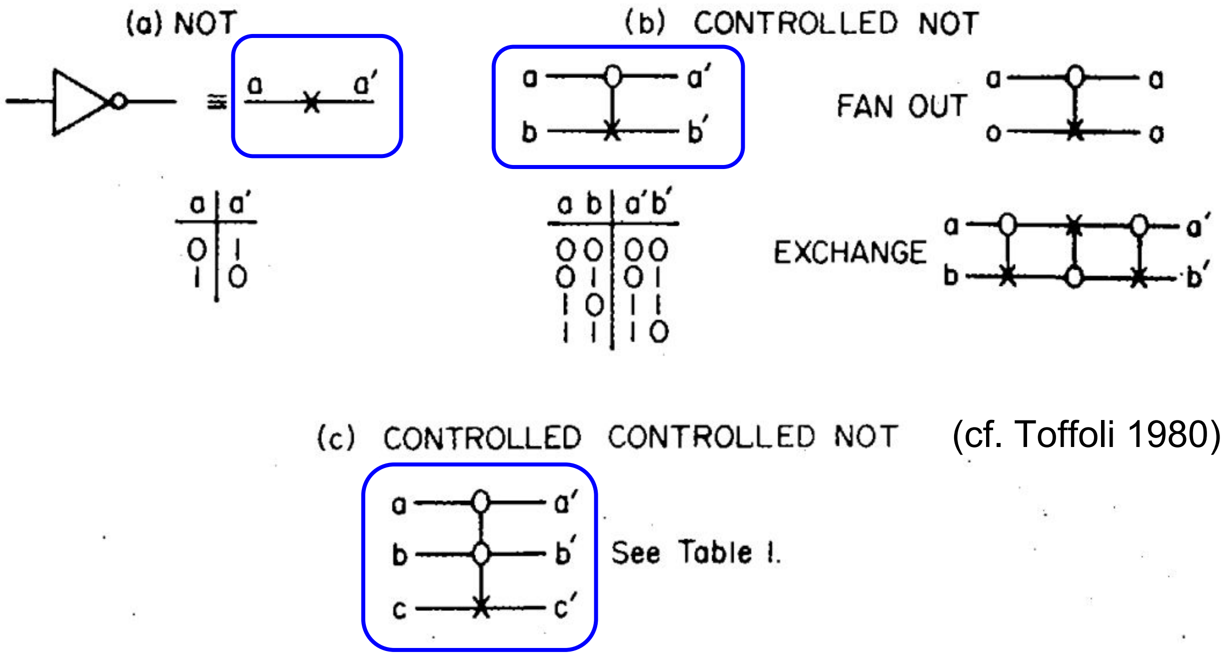
$$e^{iHt} \approx \left(e^{iH_1 t/n} \ldots e^{iH_\ell t/n}\right)^n$$

Product of local unitaries

6 qubit realization: trapped Ca^+ ions, Innsbruck 2011

Feynman’s diagrams for quantum circuits

Feynman 1985 “Quantum Mechanical Computers”

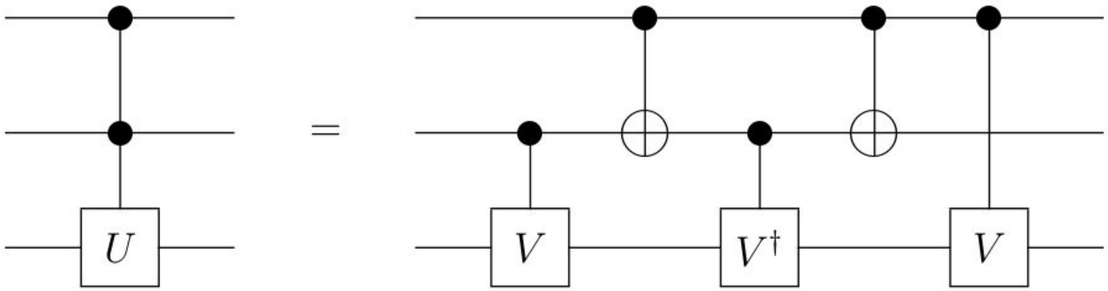


(cf. Toffoli 1980)

Feynman's diagrams for quantum circuits

Standard notation for quantum circuits

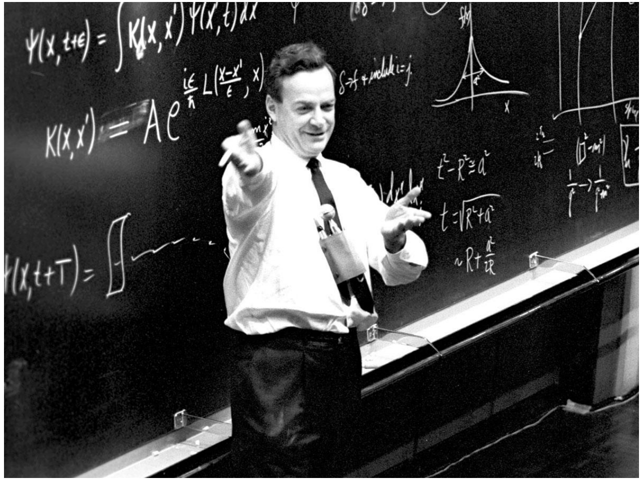
Random example:



(from Barenco 1995 proof of universality of 1-qubit + CNOT)

Feynman’s contributions

- Conjectured the existence of universal quantum simulators
- Stimulated research on quantum computers
- Drew some diagrams!



CERN

CNOT