中国科学院大学
University of Chinese Academy of Sciences

量子计算简述
Introduction to Quantum Computing

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New methods

- 计算需求永无止境

  结绳→算盘　电子管→晶体管→超级计算机……

  openMP　MPI　CUDA　……

As long as mankind can dream，we can certainly achieve.

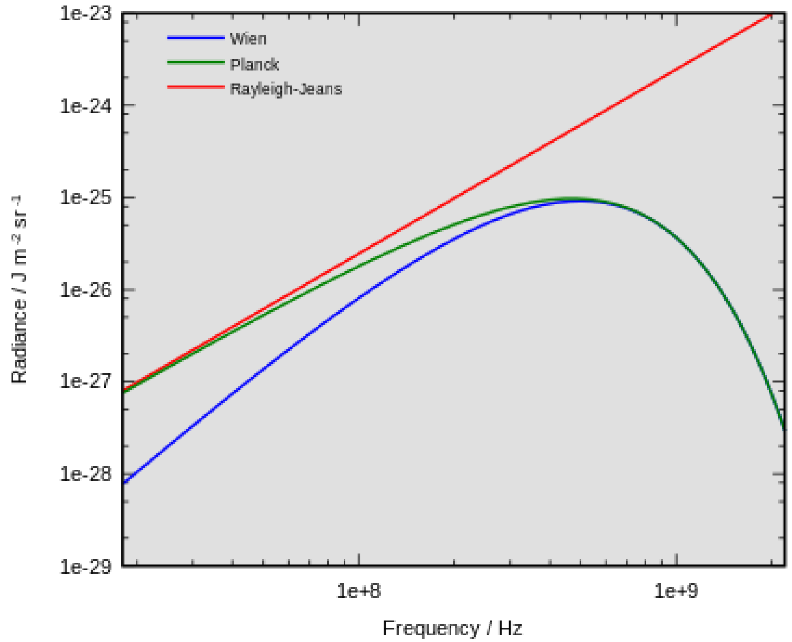
——NASA

- 自然计算：
  - DNA计算
- 自然计算
  - 量子计算

Content

- Background
- What is Quantum Computation?
- Qubits and Quantum Gates
- Quantum Algorithms
- Decoherence and Noise
- Implementations
- Applications

量子起源(1)

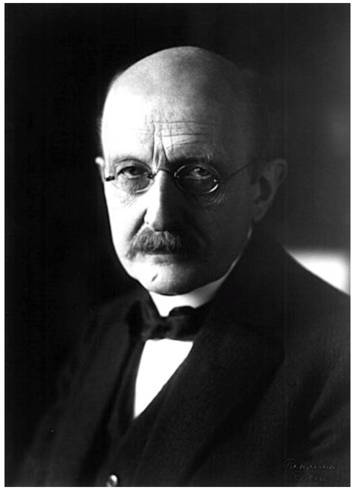


In 1900, Max Planck proposed a model in which the thermal radiation was in equilibrium with a set of harmonic oscillators, and energy emitted by an oscillator was *quantized.*

量子起源

The quantum of energy for each oscillator, according to Planck, was proportional to the frequency of the oscillator; the constant of proportionality is now known as the Planck constant.

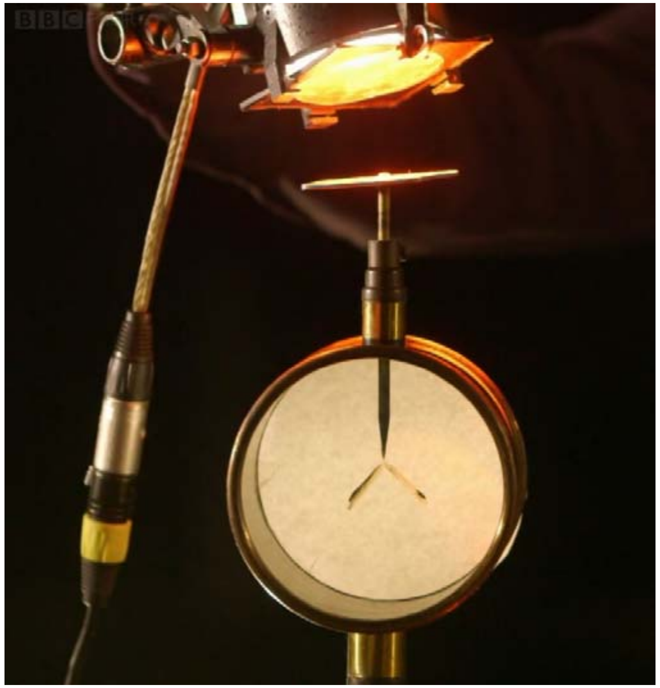
$$E = nhf, \quad \text{where} \quad n = 1, 2, 3, \ldots$$



Max Planck

Planck's law was the first quantum theory in physics, and Planck won the Nobel Prize in 1918 “ in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".

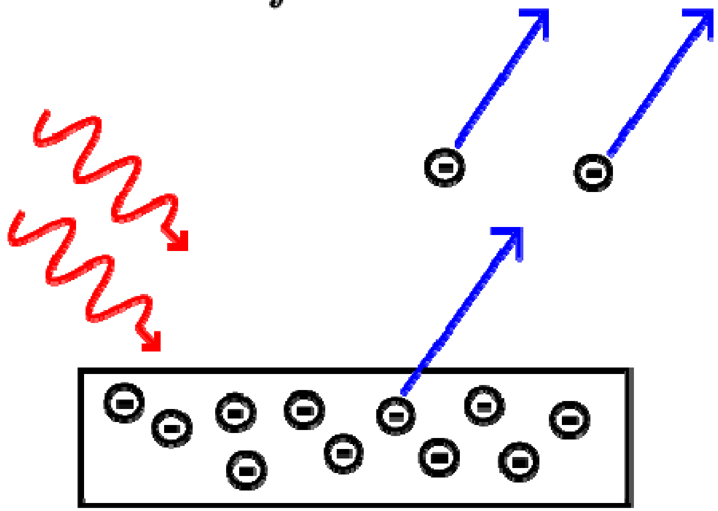
量子起源(2)



量子起源

In 1905, Albert Einstein suggested the concept of photons, The energy of a single photon is given by its frequency multiplied by Planck's constant:

$$E = hf$$



Albert Einstein

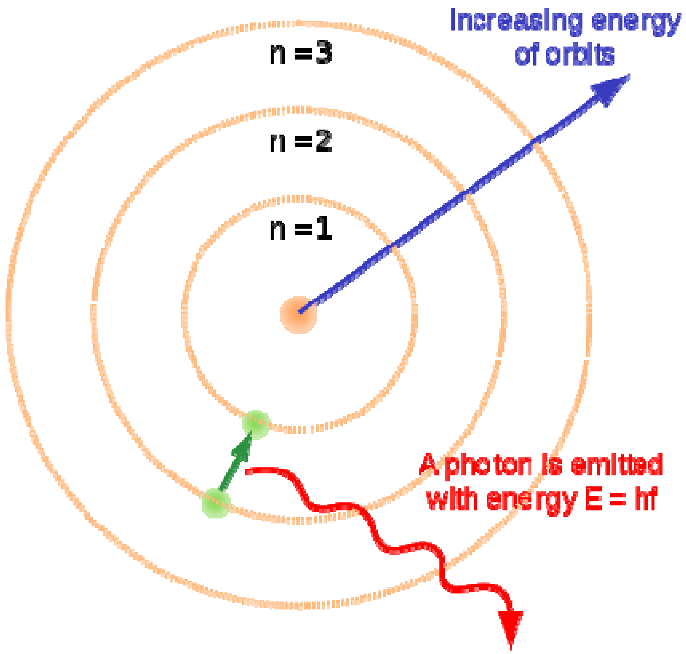
量子起源 (3)

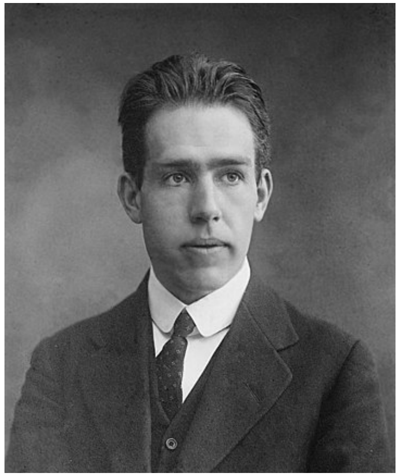
By the dawn of the 20th century, evidence required a model of the atom with a diffuse cloud of negatively charged electrons surrounding a small, dense, positively charged nucleus, just like planets orbiting a sun.

A second, related, puzzle was the emission spectrum of atoms. When a gas is heated, it gives off light only at discrete frequencies.

Emission spectrum of hydrogen

量子起源



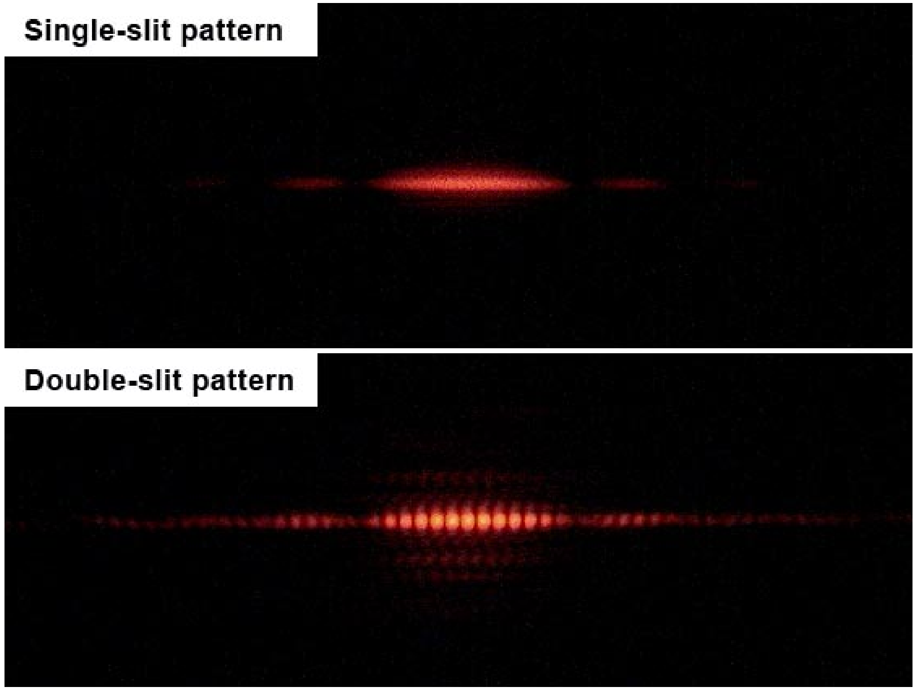


Niels Bohr

In 1913 Niels Bohr proposed a new model of the atom that included quantized electron orbits: electrons still orbit the nucleus much as planets orbit around the sun, but they are only permitted to inhabit certain orbits, not to orbit at any distance.

量子起源 (4)

Just as light has both wave-like and particle-like properties, matter also has wave-like properties.



Variations of the double-slit experiment have been performed using electrons, atoms, and even large molecules, and the same type of interference pattern is seen.

量子起源

In 1924, de Broglie. The wavelength, λ, associated with any object is related to its momentum, p, through the Planck constant, h:

$$p = \frac{h}{\lambda}.$$

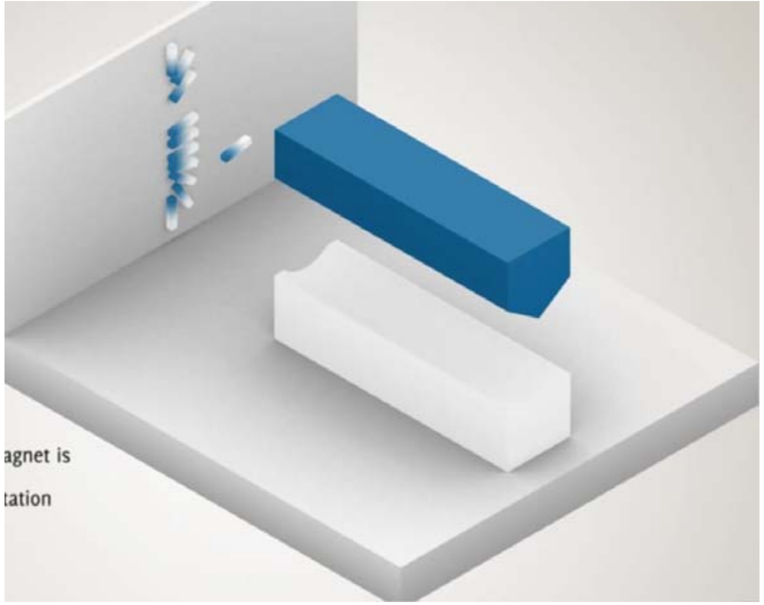
Louis de Broglie

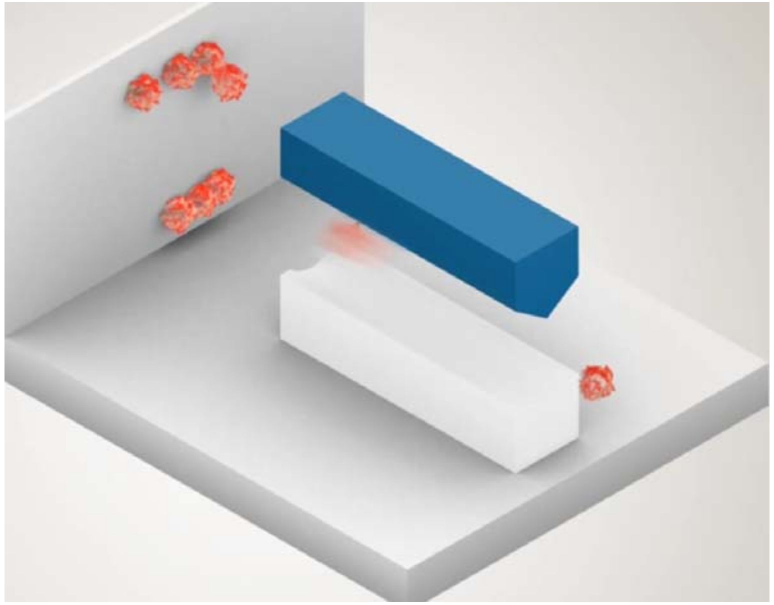
The relationship, called the de Broglie hypothesis, holds for all types of matter: **all matter exhibits properties of both particles and waves.**

De Broglie expanded the Bohr model of the atom by showing that an electron in orbit around a nucleus could be thought of as having wave-like properties. This served as a starting point for Schrödinger.

量子起源 (5)

In 1922, Otto Stern and Walther Gerlach





This implied that the property of the atom that corresponds to the magnet's orientation must be quantised, taking one of two values (either up or down)

Ralph Kronig originated the theory that particles such as atoms or electrons behave as if they rotate, or "spin", about an axis.

量子起源

In 1922, Otto Stern and Walther Gerlach

The Stern-Gerlach experiment demonstrates a number of important features of quantum mechanics:

- a feature of the natural world has been demonstrated to be quantised, and only able to take certain discrete values;
- particles possess an intrinsic angular momentum that is closely analogous to the angular momentum of a classically spinning object
- measurement changes the system being measured in quantum mechanics.
- quantum mechanics is probabilistic

The Pauli exclusion principle

- In 1924, Wolfgang Pauli proposed a new quantum degree of freedom (or quantum number), with two possible values, to resolve inconsistencies between observed molecular spectra and the predictions of quantum mechanics.

Wolfgang Pauli

Uhlenbeck and Goudsmit identified Pauli's new degree of freedom with the property called spin whose effects were observed in the Stern–Gerlach experiment.

量子起源 (6)

In 1925, Werner Heisenberg, Max Born realized that Heisenberg's method of calculating the probabilities for transitions between the different energy levels could best be expressed by using the mathematical concept of matrices.

In the same year, building on de Broglie's hypothesis, Erwin Schrödinger developed the equation that describes the behavior of a quantum mechanical wave.

Time-dependent Schrödinger equation *(general)*

$$i\hbar\frac{\partial}{\partial t}|\Psi(\mathbf{r},t)\rangle = \hat{H}|\Psi(\mathbf{r},t)\rangle$$

Wave function collapse

- Wave function collapse:
  - is a forced expression for whatever just happened
  - when it becomes appropriate to replace the description of an uncertain state of a system
  - by a description of the system in a definite state.

Copenhagen interpretation

- Bohr, Heisenberg and others tried to explain what these experimental results and mathematical models really mean.

Copenhagen interpretation:

Their description of quantum mechanics, aimed to describe the nature of reality that was being:
- probed by the measurements and
- described by the mathematical formulations of quantum mechanics.

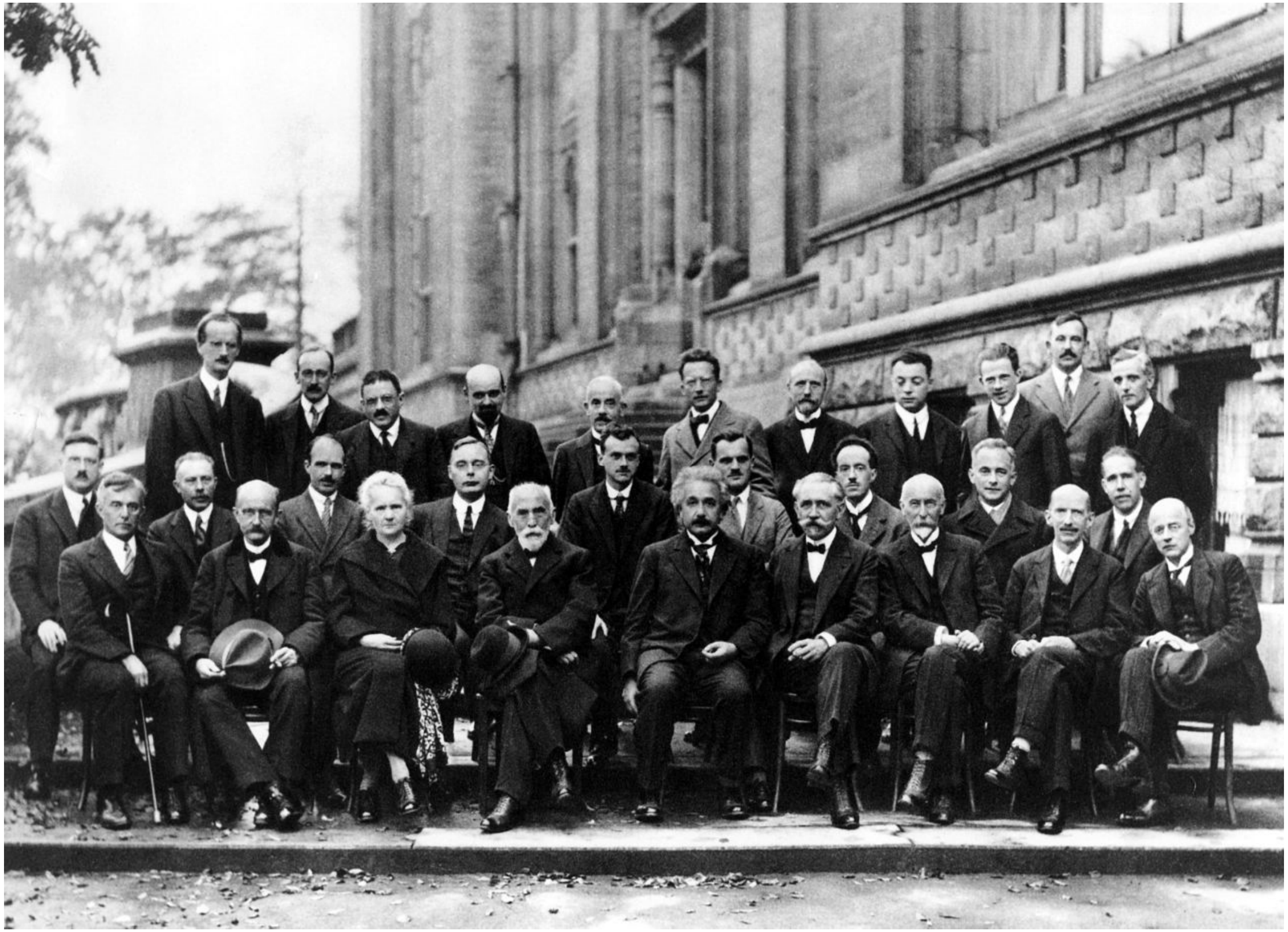
Uncertainty principle

- In 1927, Heisenberg proved that Quantum mechanics shows that certain pairs of physical properties, such as for example position and speed, cannot be simultaneously measured, nor defined in operational terms, to arbitrary precision:

Werner Heisenberg

the more precisely one property is measured, or defined in operational terms, the less precisely can the other.

1927 - the 5th Solvay Conference



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Richard Feynman (1981):

"I think I can safely say that nobody understands quantum mechanics" - Feynman

"...trying to find a computer simulation of physics, seems to me to be an excellent program to follow out...and I'm not happy with all the analyses that go with just the classical theory, because *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."

David Deutsch (1985):

David Deutsch developed the quantum Turing machine, showing that quantum circuits are universal.

“Computing machines resembling the universal quantum computer could, in principle, be built and would have many remarkable properties not reproducible by any Turing machine … Complexity theory for [such machines] deserves further investigation.”

What is a quantum computer

- **Quantum computing:**
  - computing using quantum-mechanical phenomena,
  - such as **superposition** and **entanglement**.

量子叠加　　　　量子纠缠

- **Quantum computer:**
  - a device that performs quantum computing.

Quantum superposition

The principle of quantum superposition:

- if a physical system may be in one of many configurations (arrangements of particles or fields)
- then the most general state is a combination of all of these possibilities,
- where the amount in each configuration is specified by a complex number.

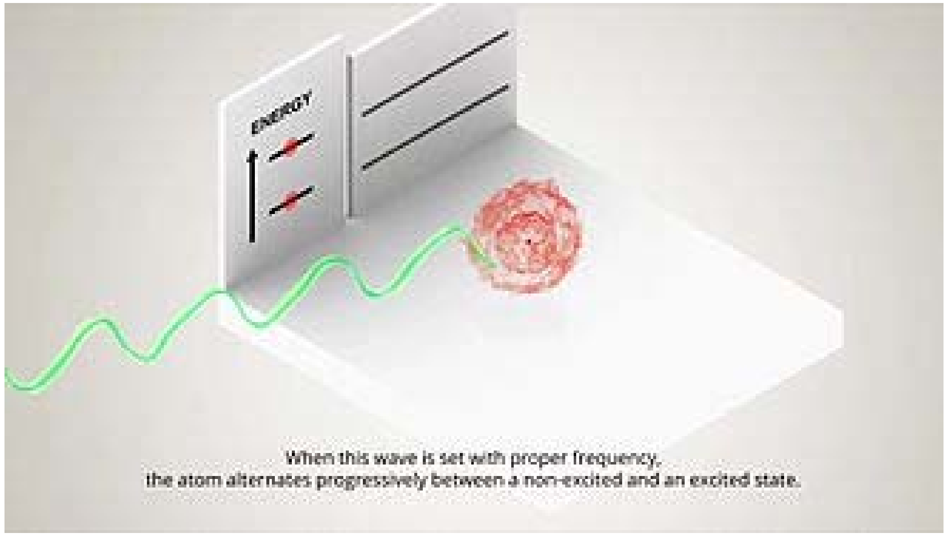
For example, if there are two configurations labelled by 0 and 1, the most general state would be

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \qquad |\alpha|^2 + |\beta|^2 = 1.$$

where the coefficients are complex numbers describing how much goes into each configuration.

Quantum superposition

Consider the superposition of two states, *A* and *B*, such that there exists an observation which is certain to lead to one particular result.



Paul Dirac：
What will be the result of the observation when made on the system in the superposed state?
The answer is that the result will be sometimes *a* and sometimes *b*, according to a probability law depending on the relative weights of *A* and *B* in the superposition process.

Quantum entanglement

Quantum entanglement:

- a physical phenomenon which occurs when pairs or groups of particles are generated, interact, or share spatial proximity in ways such that the quantum state of each particle cannot be described independently of the state of the other(s),
- even when the particles are separated by a large distance;
- —instead, a quantum state must be described for the system as a whole.

- Measurements of physical properties such as position, momentum, spin, and polarization, performed on entangled particles are found to be correlated.

Quantum entanglement

- Measurement of entangled system

Any measurement of a property of a particle performs an irreversible collapse on that particle and will change the original quantum state. In the case of entangled particles, such a measurement will be on the entangled system as a whole.

- paradoxical effects:

one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances.

- EPR paradox

In 1935, a paper by Albert Einstein, Boris Podolsky, and Nathan Rosen, considered such behavior ("spooky action at a distance") to be impossible, formulation of quantum mechanics must therefore be incomplete.

Quantum entanglement

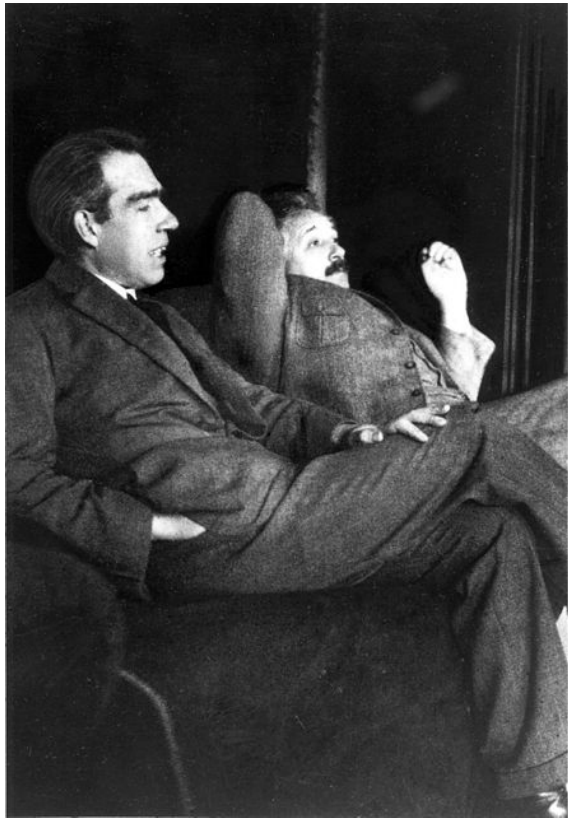
- EPR paradox

The conclusion rested on the seemingly reasonable assumptions of *locality* and *realism* (together called "local realism" or "local hidden variables", often interchangeably).

定域实在论

In the vernacular of Einstein:

- locality meant no instantaneous ("spooky") action at a distance;
- realism meant the moon is there even when not being observed.

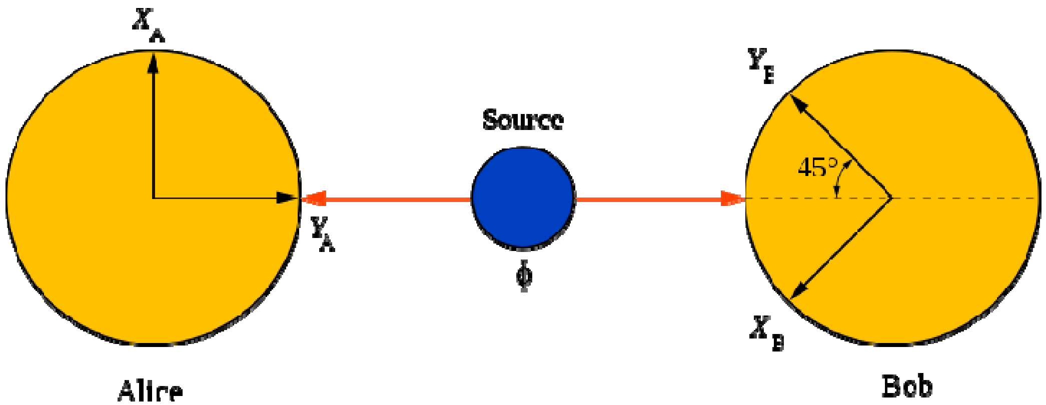


Quantum entanglement

John Bell :

- In 1964 paper "On the Einstein Podolsky Rosen paradox", physicist John Stewart Bell presented an analogy (based on spin measurements on pairs of entangled electrons) to EPR's hypothetical paradox.

- He said, a choice of measurement setting here should not affect the outcome of a measurement there (and vice versa).



Quantum entanglement

Bell inequalities

After providing a mathematical formulation of locality and realism based on this, he showed specific cases where this would be inconsistent with the predictions of quantum mechanics theory.

$$C_h(a,c) - C_h(b,a) - C_h(b,c) \leq 1,$$

CHSH inequality

$$AB + AB' + A'B - A'B' = A(B + B') + A'(B - B') \leq 2.$$

Quantum entanglement

CHSH inequality

$$AB + AB' + A'B - A'B' = A(B + B') + A'(B - B') \leq 2.$$

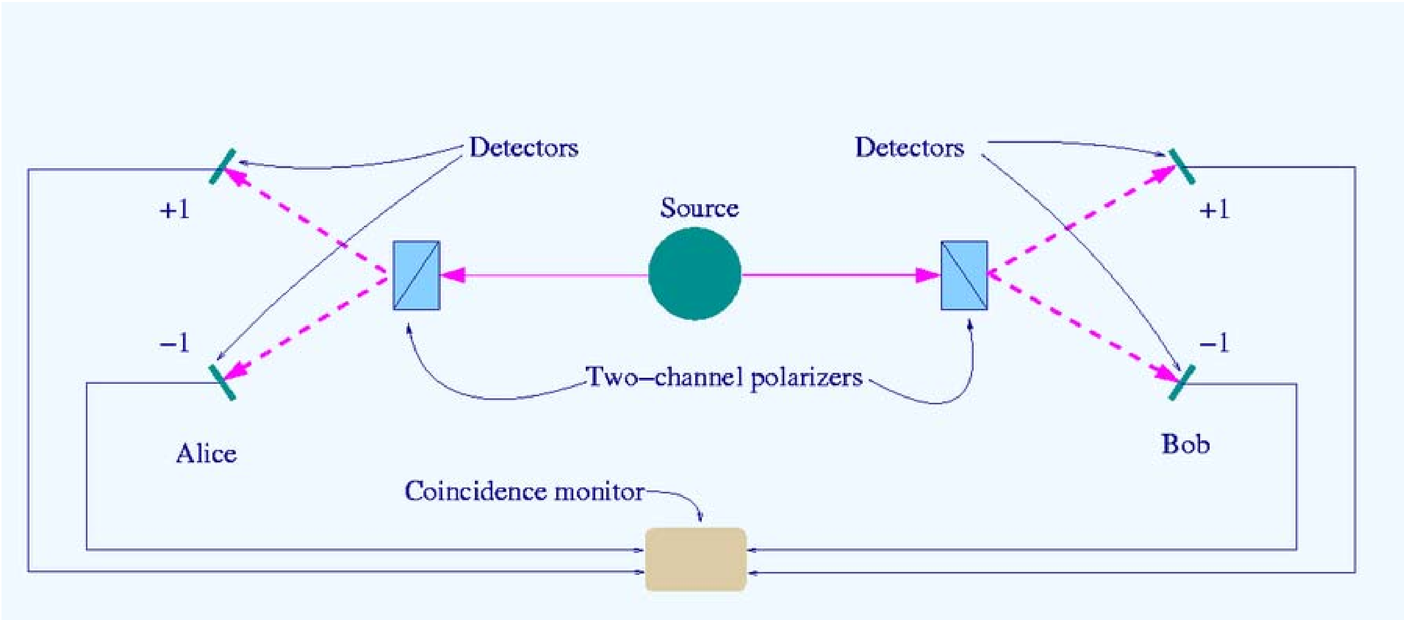
If the quantum mechanical formalism is correct, then the system consisting of a pair of entangled electrons cannot satisfy the principle of local realism.

$$\langle A(a)B(b)\rangle + \langle A(a')B(b')\rangle + \langle A(a')B(b)\rangle - \langle A(a)B(b')\rangle$$

$$= \frac{4}{\sqrt{2}} = 2\sqrt{2} > 2$$

Quantum entanglement

- John Clauser and Stuart Freedman (1972)
- Alain Aspect *et al*. (1981)
- Hensen and co-workers (2015)



Quantum entanglement

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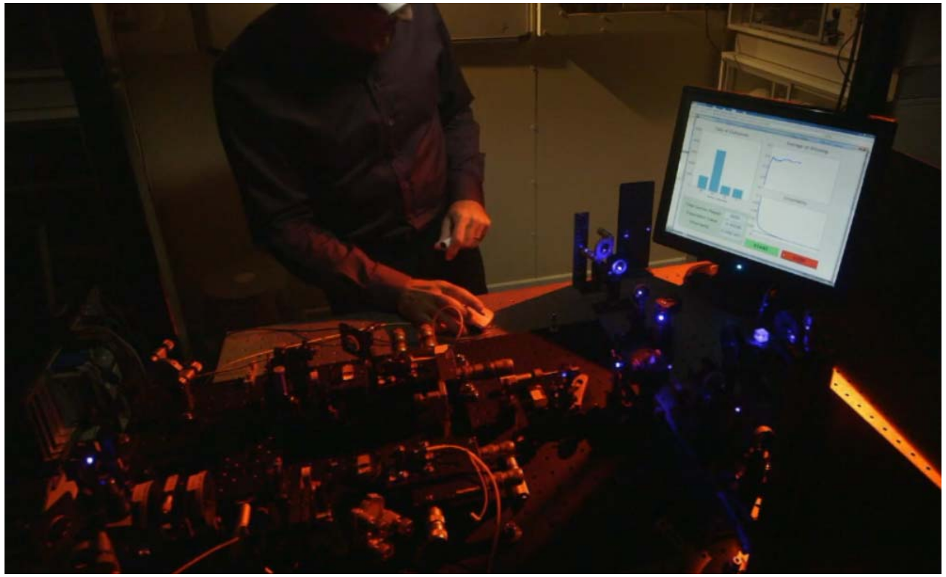
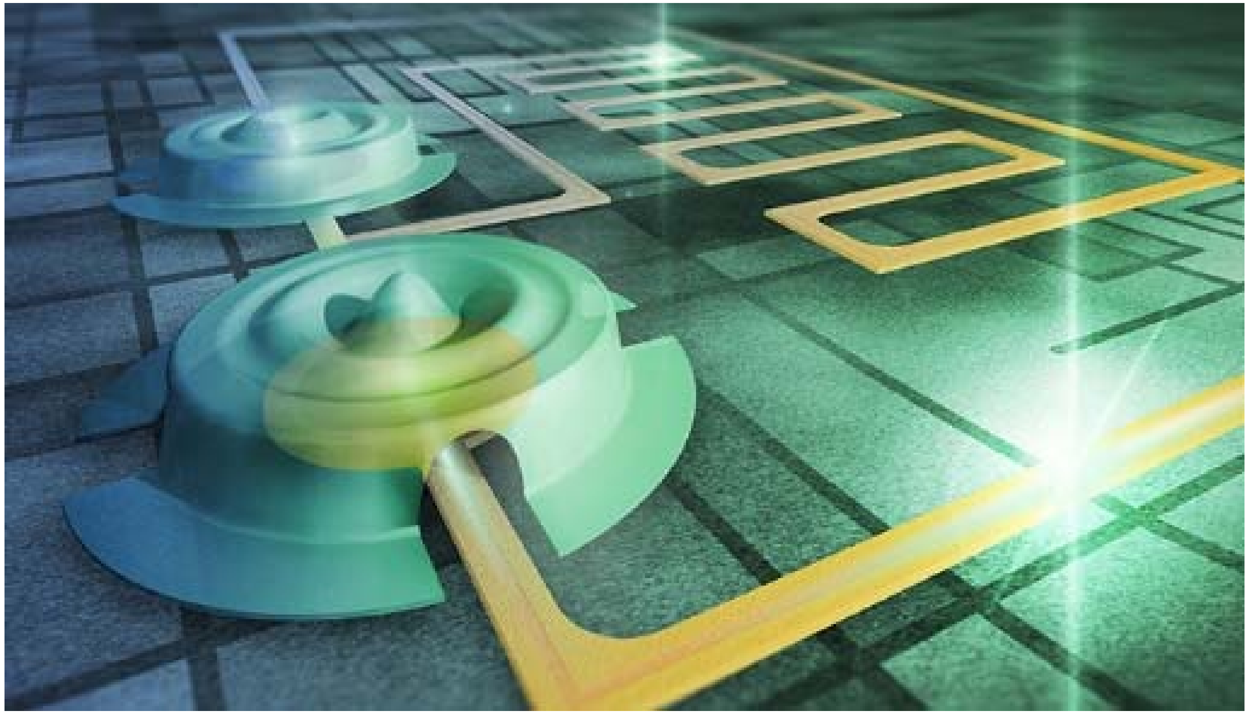


$$\langle A(a)B(b)\rangle + \langle A(a')B(b')\rangle + \langle A(a')B(b)\rangle - \langle A(a)B(b')\rangle \; > 2$$

Quantum entanglement

Mika Sillanpää, Stabilized entanglement of massive mechanical oscillators, Nature, 25 April 2018.



Einstein's "spooky action" goes massive!

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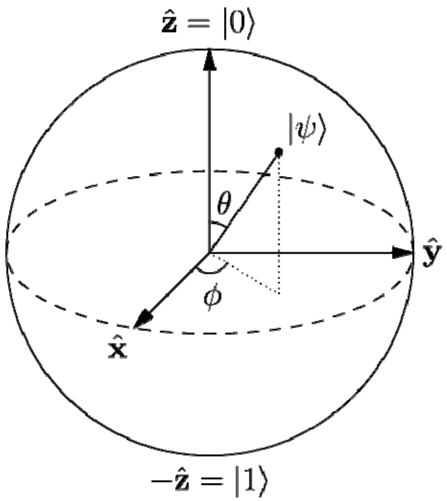
Qubit

A qubit is a two-state (or two-level) quantum system：
such as the polarization of a single photon: here the two states can be taken to be the vertical polarization and the horizontal polarization. 光子偏振

In a classical system, a bit would have to be in one state or the other. However, quantum mechanics allows the qubit to be in a superposition of both states/levels at the same time.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle,$$

$$|\alpha|^2 + |\beta|^2 = 1.$$



The possible states for a single qubit can be visualised using a Bloch sphere

Qubit

Multiple qubits can exhibit quantum entanglement. Take, for example, two entangled qubits in the Bell state

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle).$$

- A single qubit can represent a one, a zero, or any quantum superposition of those two qubit states;
- a pair of qubits can be in any quantum superposition of 4 states,
- and three qubits in any superposition of 8 states.

In general, a quantum computer with n qubits can be in an arbitrary superposition of up to 2^n different states simultaneously.
(This compares to a normal computer that can only be in one of these 2^n states at any one time).

Quantum supremacy

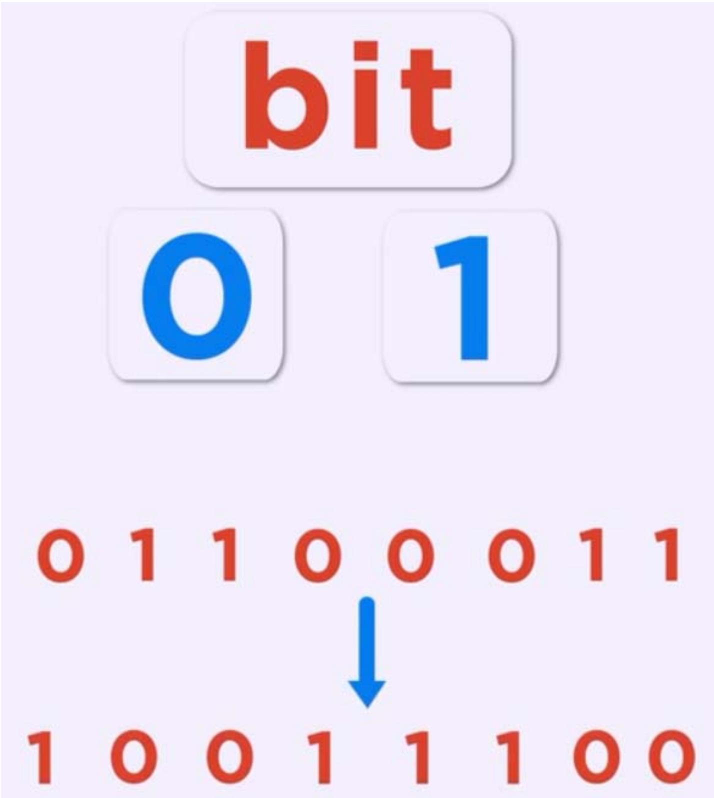
Quantum supremacy 量子霸权（优越性）

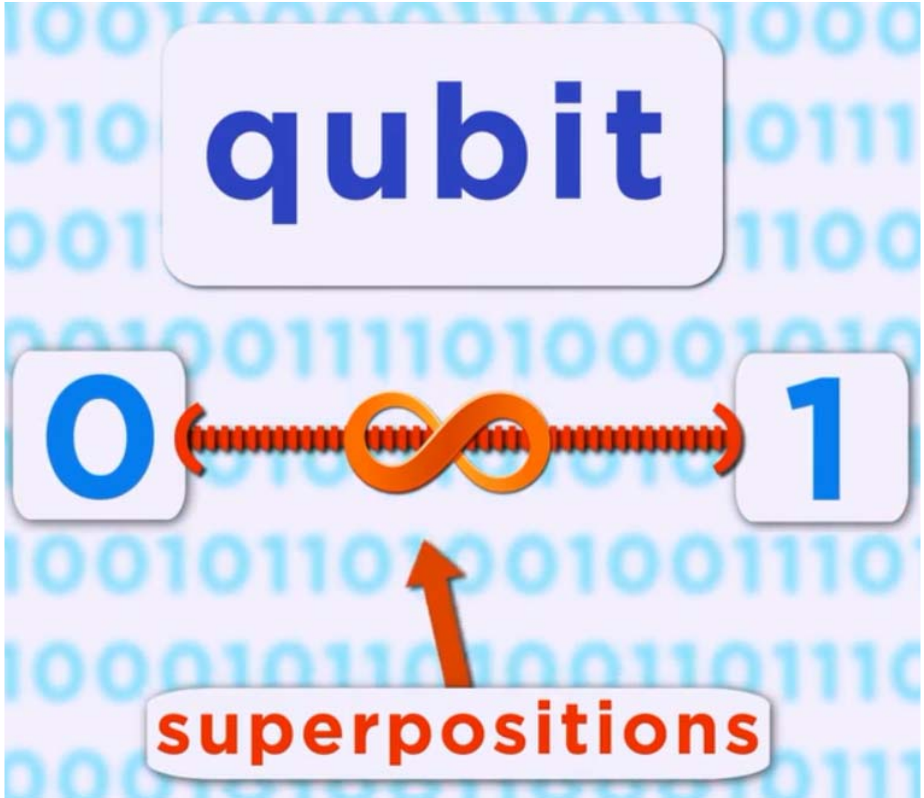
- refer to the hypothetical speedup advantage that a quantum computer would have over a classical computer in a certain field.

Google announced in 2017 that it expected to achieve quantum supremacy by the end of the year, and IBM says that the best classical computers will be beaten on some task within about five years.

Quantum supremacy has not been achieved yet, and some people doubt that it will ever be.

Qubit





Qubit

2 qubits
4 Basic States

$|00\rangle$

$|10\rangle$

$|01\rangle$

$|11\rangle$

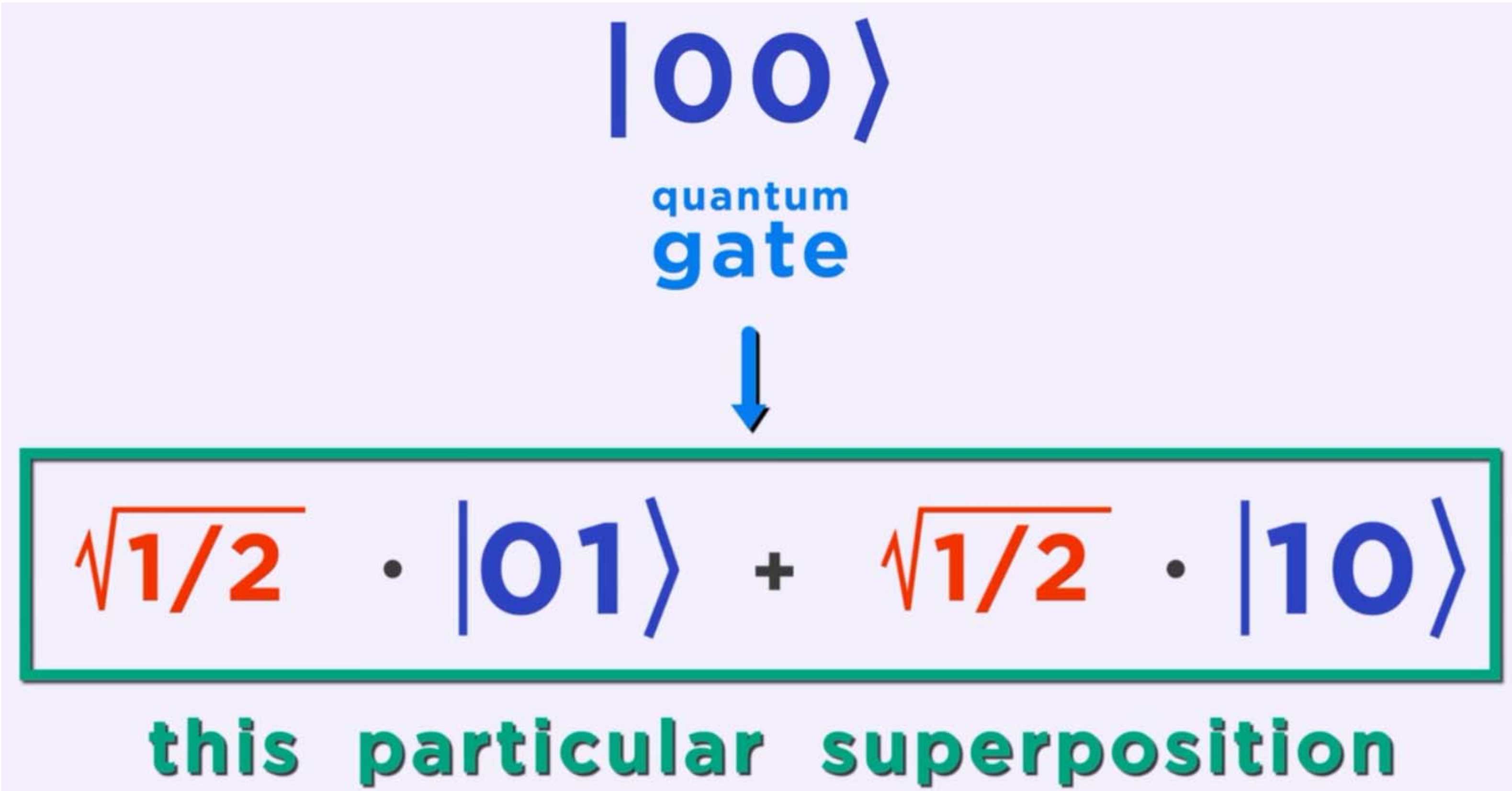
Infinitely many states formed by superpositions

Qubit -- How to build qubits ?

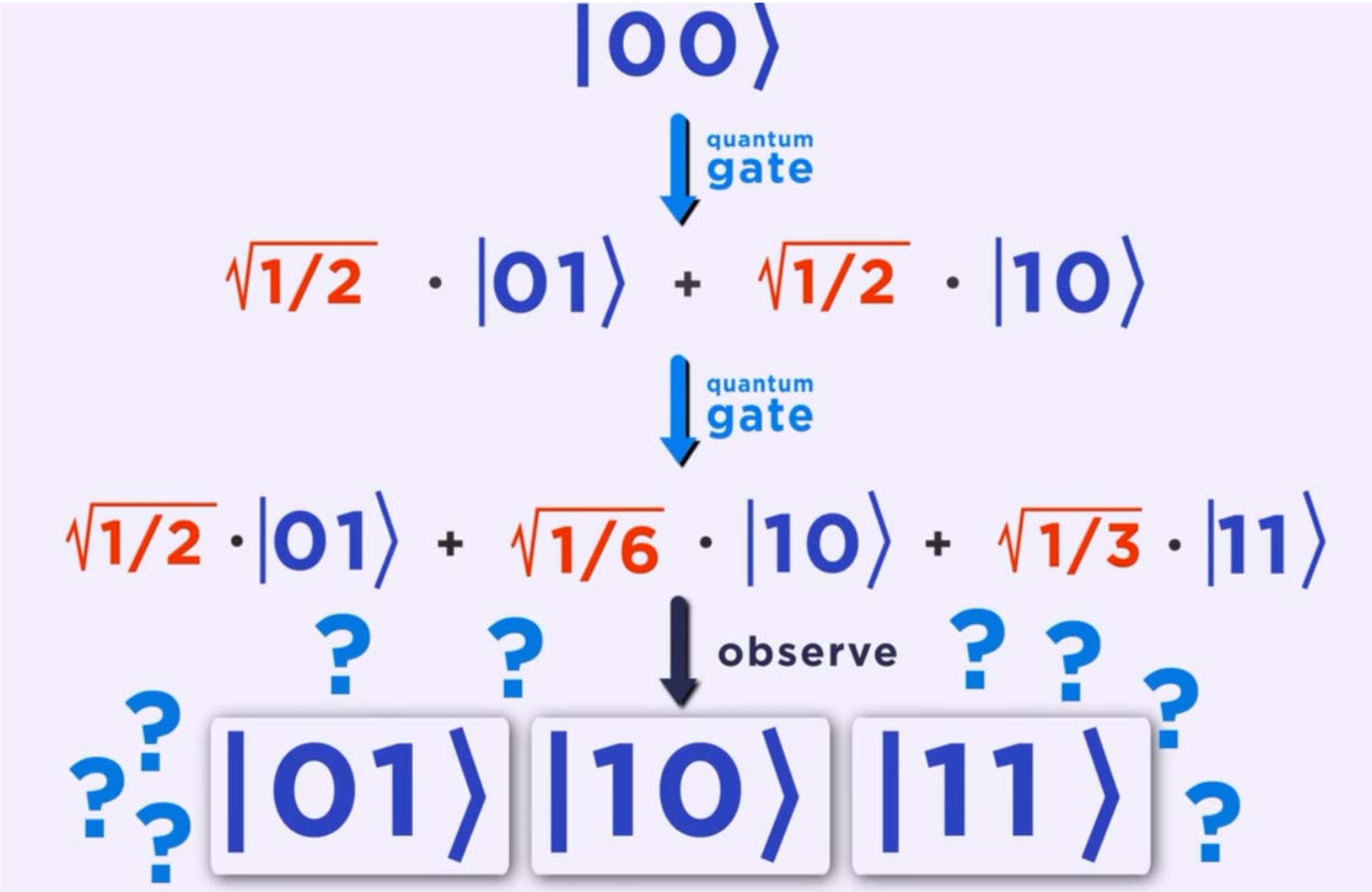
Physical support	Name	Information support	$\|0\rangle$	$\|1\rangle$
Photon	Polarization encoding	Polarization of light	Horizontal	Vertical
	Number of photons	Fock state	Vacuum	Single photon state
	Time-bin encoding	Time of arrival	Early	Late
Coherent state of light	Squeezed light	Quadrature	Amplitude-squeezed state	Phase-squeezed state
Electrons	Electronic spin	Spin	Up	Down
	Electron number	Charge	No electron	One electron
Nucleus	Nuclear spin addressed through NMR	Spin	Up	Down
Optical lattices	Atomic spin	Spin	Up	Down
Josephson junction	Superconducting charge qubit	Charge	Uncharged superconducting island (Q=0)	Charged superconducting island (Q=2e, one extra Cooper pair)
	Superconducting flux qubit	Current	Clockwise current	Counterclockwise current
	Superconducting phase qubit	Energy	Ground state	First excited state
Singly charged quantum dot pair	Electron localization	Charge	Electron on left dot	Electron on right dot
Quantum dot	Dot spin	Spin	Down	Up

October 23, 2008, 1.75 seconds, recently extended to 3 hours

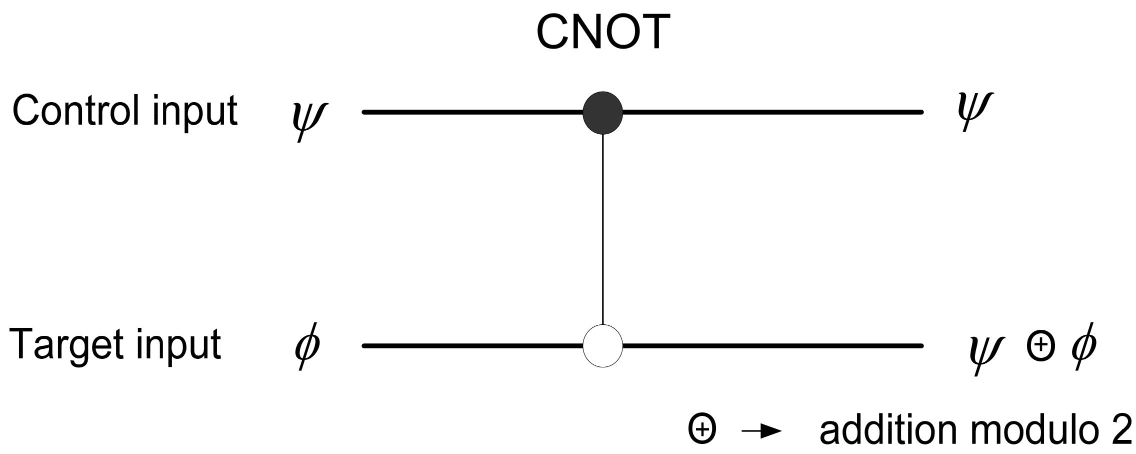
Quantum Gate



Quantum Gate

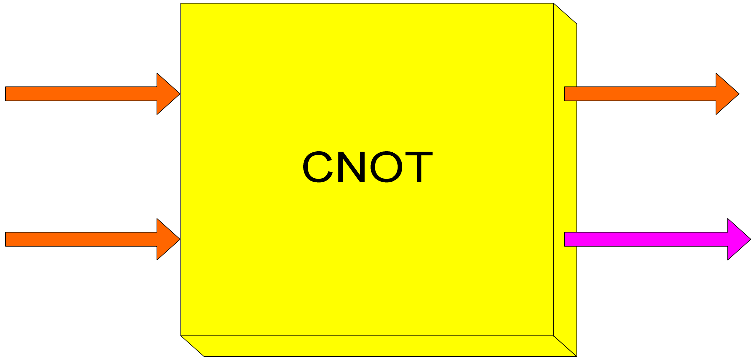


Quantum Gate



- Two inputs
  - Control
  - Target
- The control qubit is transferred to the output as is.
- The target qubit
  - Unaltered if the control qubit is 0
  - Flipped if the control qubit is 1.

Quantum Gate



$$\left|V_{CNOT}\right\rangle = \left|\psi\right\rangle \otimes \left|\phi\right\rangle \qquad \left|W_{CNOT}\right\rangle = G_{CNOT}\left|V_{CNOT}\right\rangle$$

$$\left|G_{CNOT}\right\rangle = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Quantum Gate

Unitary Matrix 酉矩阵

$$\begin{bmatrix} 0 & 1 & 0 & 1 \\ \sqrt{1/2} & 0 & -\sqrt{1/2} & 0 \\ \sqrt{1/2} & 0 & \sqrt{1/2} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \sqrt{1/2} \\ \sqrt{1/2} \\ 0 \end{bmatrix}$$

Quantum Gate

2nd State

Quantum Gate

$$|010001\rangle$$

$$\downarrow$$

$$\sqrt{1/6}\cdot|010100\rangle + \sqrt{1/6}\cdot|111001\rangle + \sqrt{1/3}\cdot|001110\rangle + \sqrt{1/3}\cdot|101100\rangle$$

$$\downarrow$$

$$\sqrt{1/5}\cdot|010110\rangle + \sqrt{1/10}\cdot|110001\rangle + \sqrt{2/5}\cdot|001110\rangle + \sqrt{1/20}\cdot|010100\rangle + \sqrt{1/5}\cdot|111001\rangle + \sqrt{1/20}\cdot|110110\rangle$$

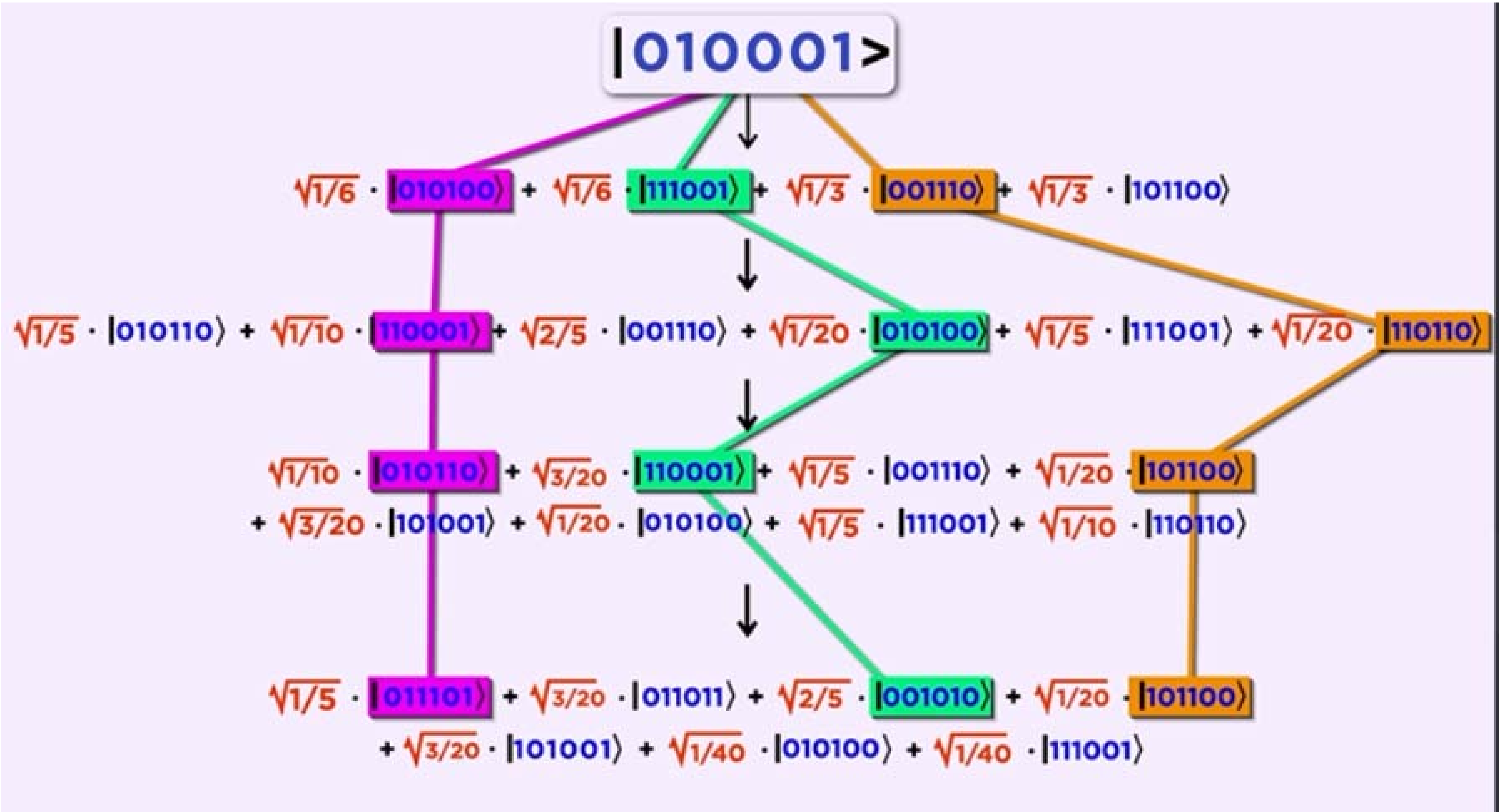
$$\downarrow$$

$$\sqrt{1/10}\cdot|010110\rangle + \sqrt{3/20}\cdot|110001\rangle + \sqrt{1/5}\cdot|001110\rangle + \sqrt{1/20}\cdot|101100\rangle$$
$$+ \sqrt{3/20}\cdot|101001\rangle + \sqrt{1/20}\cdot|010100\rangle + \sqrt{1/5}\cdot|111001\rangle + \sqrt{1/10}\cdot|110110\rangle$$

$$\downarrow$$

$$\sqrt{1/5}\cdot|011101\rangle + \sqrt{3/20}\cdot|011011\rangle + \sqrt{2/5}\cdot|001010\rangle + \sqrt{1/20}\cdot|101100\rangle$$
$$+ \sqrt{3/20}\cdot|101001\rangle + \sqrt{1/40}\cdot|010100\rangle + \sqrt{1/40}\cdot|111001\rangle$$

Quantum Gate



Quantum Gate

$$|010001\rangle$$

$$\downarrow$$

$$\sqrt{1/6}\cdot|010100\rangle + \sqrt{1/6}\cdot|111001\rangle + \sqrt{1/3}\cdot|001110\rangle + \sqrt{1/3}\cdot|101100\rangle$$

$$\downarrow$$

$$\sqrt{1/5}\cdot|010110\rangle + \sqrt{1/10}\cdot|110001\rangle + \sqrt{2/5}\cdot|001110\rangle + \sqrt{1/20}\cdot|010100\rangle + \sqrt{1/5}\cdot|111001\rangle + \sqrt{1/20}\cdot|110110\rangle$$

$$\downarrow$$

$$\sqrt{1/10}\cdot|010110\rangle + \sqrt{3/20}\cdot|110001\rangle + \sqrt{1/5}\cdot|001110\rangle + \sqrt{1/20}\cdot|101100\rangle$$
$$+ \sqrt{3/20}\cdot|101001\rangle + \sqrt{1/20}\cdot|010100\rangle + \sqrt{1/5}\cdot|111001\rangle + \sqrt{1/10}\cdot|110110\rangle$$

$$\downarrow$$

$$\sqrt{1/5}\cdot|011101\rangle + \sqrt{3/20}\cdot|011011\rangle + \sqrt{2/5}\cdot|001010\rangle + \sqrt{1/20}\cdot|101100\rangle$$
$$+ \sqrt{3/20}\cdot|101001\rangle + \sqrt{1/40}\cdot|010100\rangle + \sqrt{1/40}\cdot|111001\rangle$$

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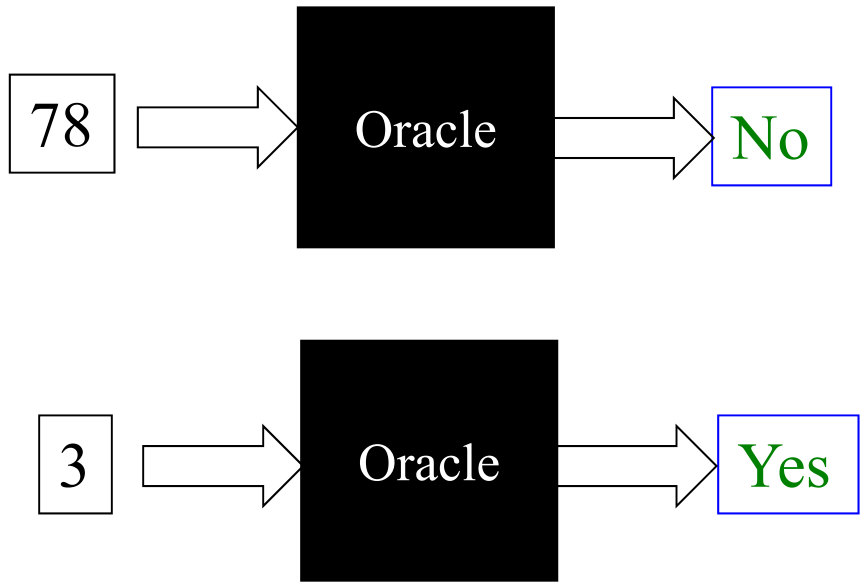
Grover’s Search Algorithm

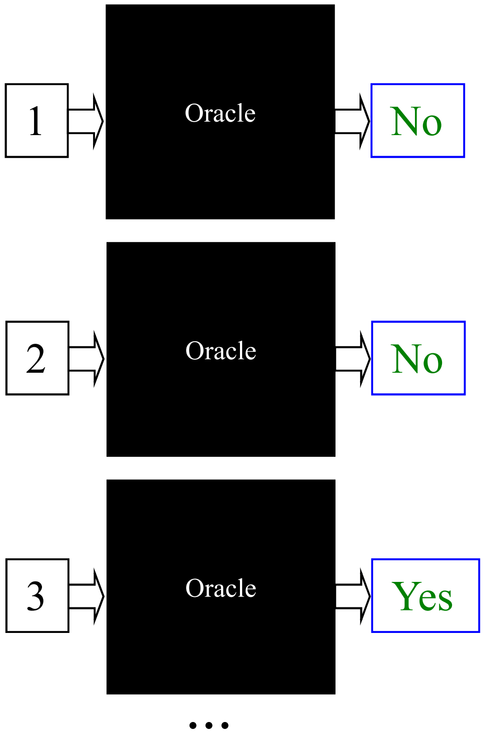
Imagine we are looking for the solution to a problem with N possible solutions. We have a black box (or ``oracle”) that can check whether a given answer is correct.

Question: I’m thinking of a number between 1 and 100. What is it?



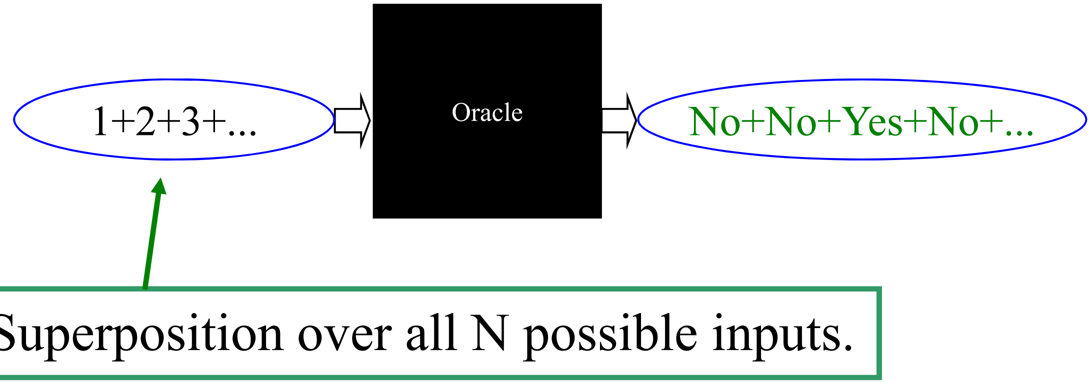
Grover’s Search Algorithm

Classical computer



The best a classical computer can do on average is N/2 queries.

Quantum computer



Using Grover’s algorithm, a quantum computer can find the answer in $\sqrt{N}$ queries!

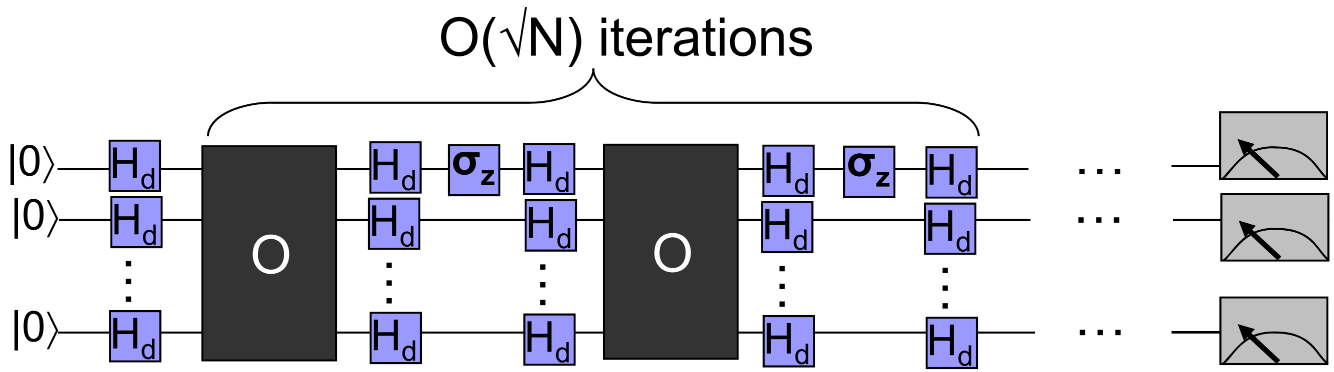
Grover's Search Algorithm

Pros:

Can be used on any unstructured search problem, even NP-complete problems.

Cons:

Only a quadratic speed-up over classical search.

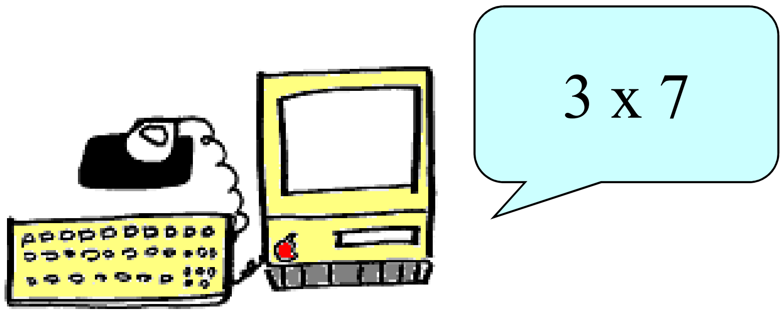


The circuit is not complicated, but it doesn't provide an immediately intuitive picture of how the algorithm works. Are there any more intuitive models for quantum search?

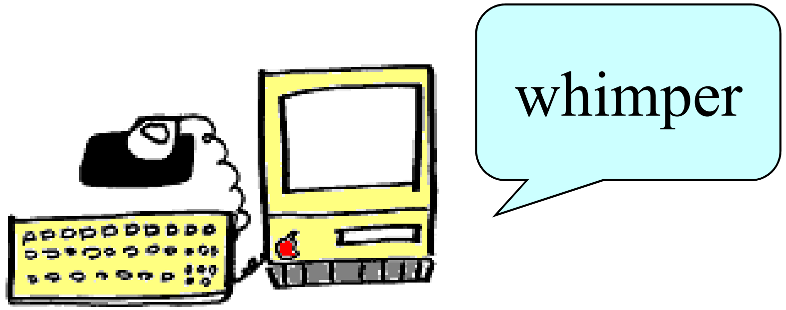
Shor's Factoring Algorithm

Makes use of quantum Fourier Transform, which is exponentially faster than classical FFT.

Find the factors of: 21



Find the factors of:
1623847601650176238761076269172261217123987210397462187618712073623846129873982634897121861102379691863198276319276121



All known algorithms for factoring an n-bit number on a classical computer take time proportional to O(n!).

But Shor's algorithm for factoring on a quantum computer takes time proportional to $O(n^2 \log n)$.

Shor's Factoring Algorithm

The details of Shor's factoring algorithm are more complicated than Grover's search algorithm, but the results are clear:

with a classical computer

# bits	1024	2048	4096
factoring in 2006	10^5 years	5×10^{15} years	3×10^{29} years
factoring in 2024	38 years	10^{12} years	7×10^{25} years
factoring in 2042	3 days	3×10^8 years	2×10^{22} years

with potential quantum computer
(e.g., clock speed 100 MHz)

# bits	1024	2048	4096
# qubits	5124	10244	20484
# gates	3×10^9	$2 X 10^{11}$	$X 10^{12}$
factoring time	4.5 min	36 min	4.8 hours

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- Decoherence and Noise
- Implementations
- Applications

DiVincenzo's criteria

- In 1996， David DiVincenzo, of IBM, listed the following requirements for a practical quantum computer:
  - scalable physically to increase the number of qubits;
  - qubits that can be initialized to arbitrary values;
  - quantum gates that are faster than decoherence time;
  - universal gate set;
  - qubits that can be read easily.

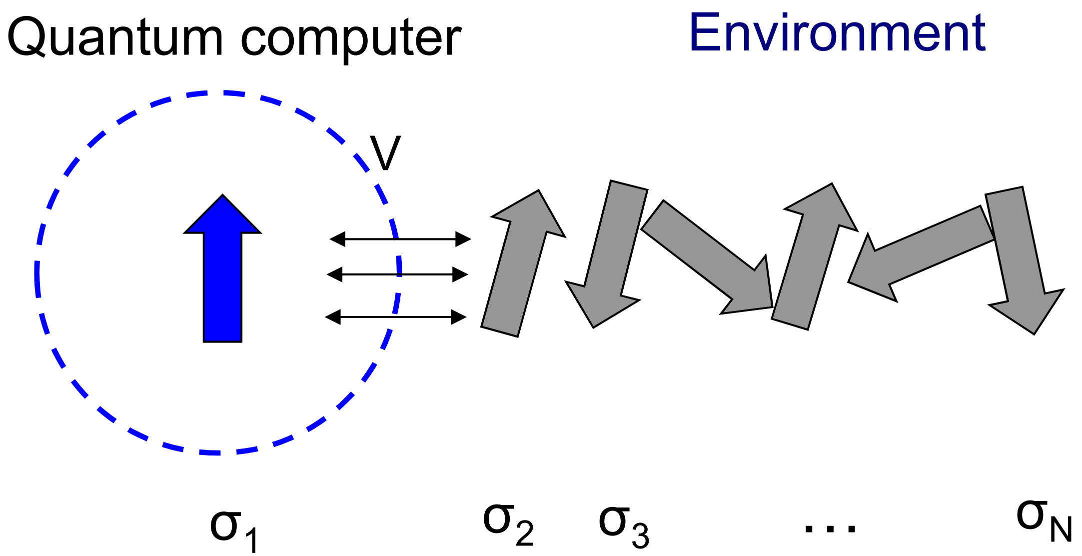
Decoherence and Noise

What happens to a qubit when it interacts with an environment?

$$H = H_0 + V$$

$$H_0 = B\sigma_{1,z}$$

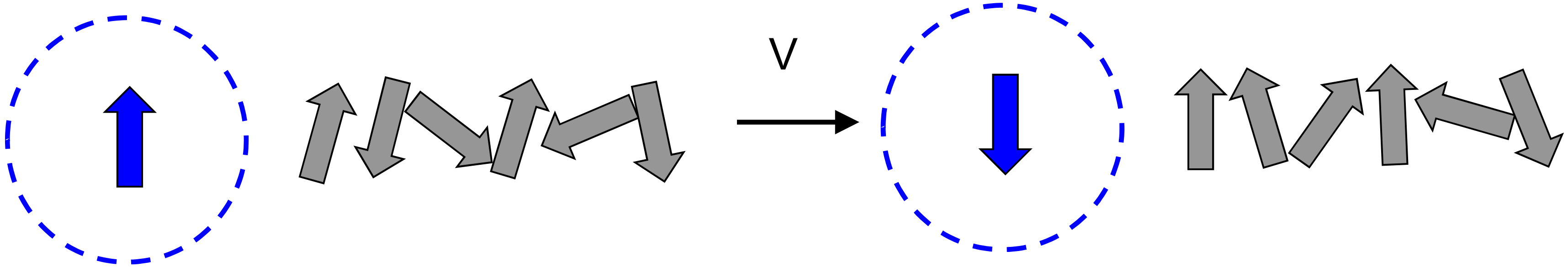
$$V = \sum_j A_j \vec{\sigma}_1 \cdot \vec{\sigma}_j$$



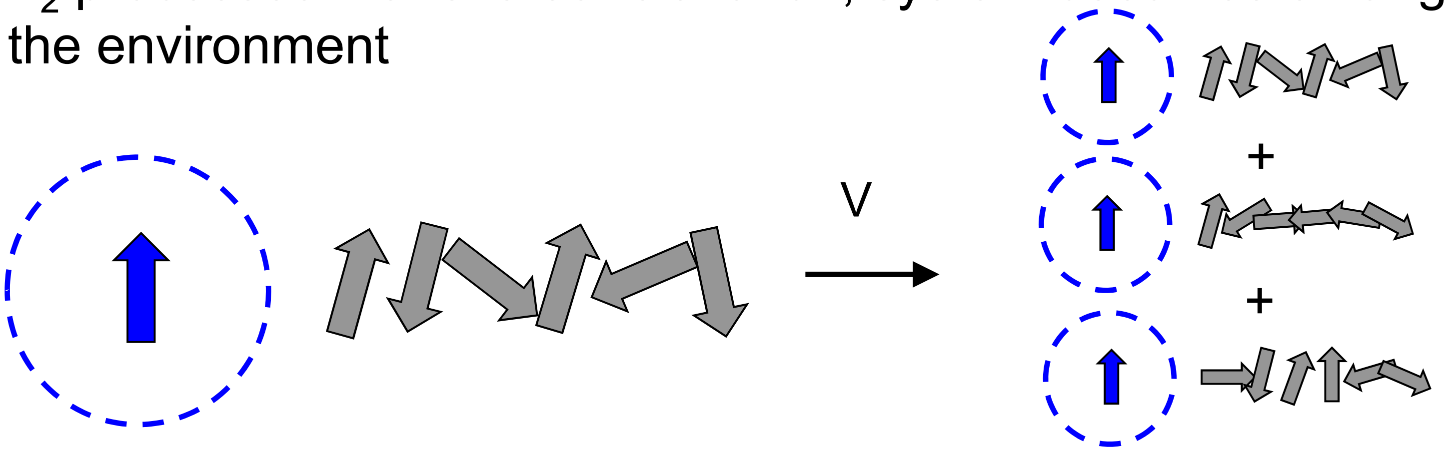
Quantum information is lost through decoherence.

Types of Decoherence

T_1 processes: longitudinal relaxation, energy is lost to the environment

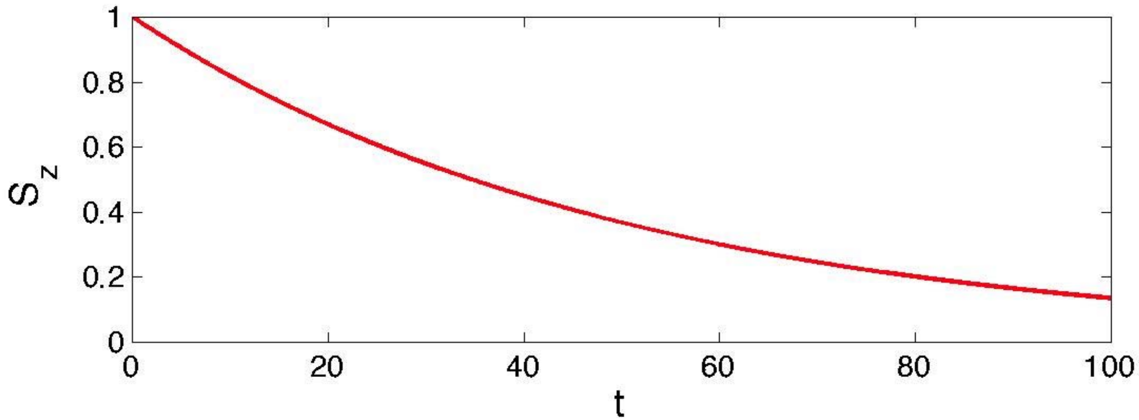


T_2 processes: transverse relaxation, system becomes entangled with the environment

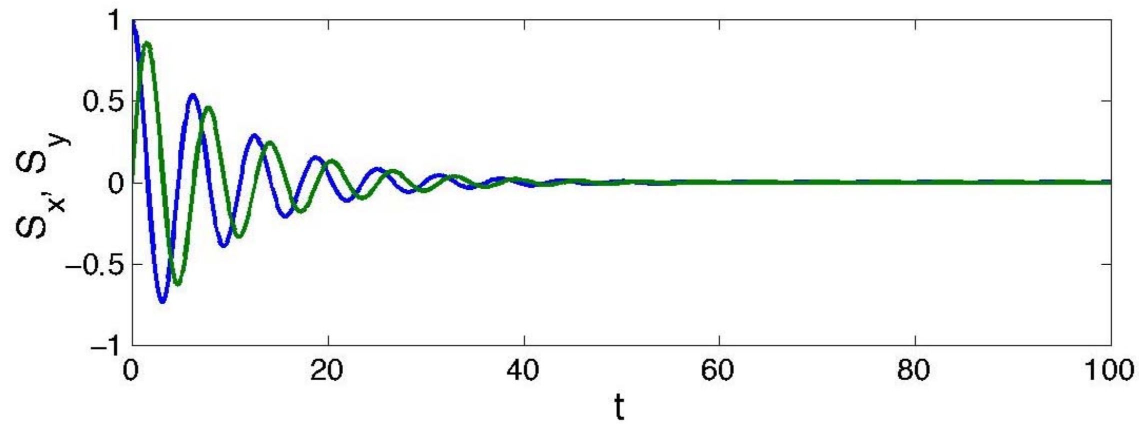


What are the effects of decoherence?

Effects of Environment on Quantum Memory



T_1 – timescale of longitudinal relaxation



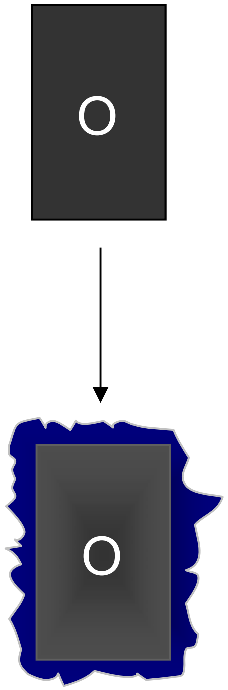
T_2 – timescale of transverse relaxation

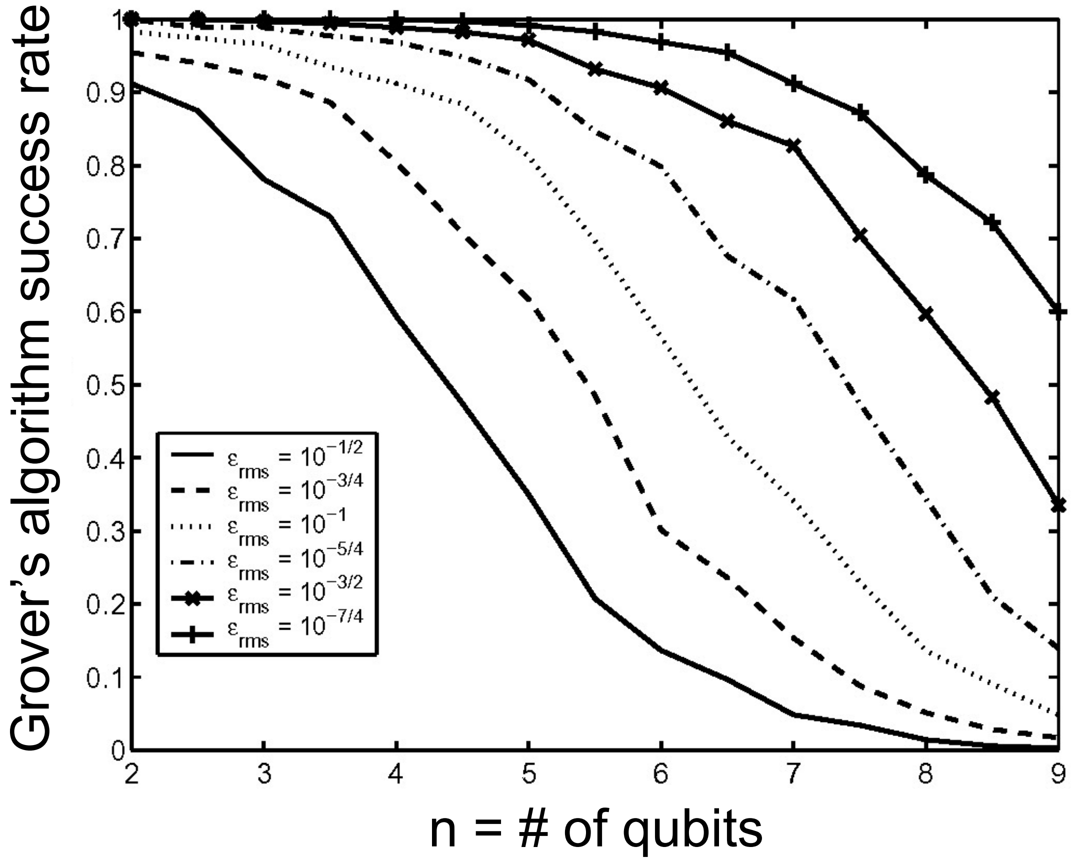
Fidelity of stored information decays with time.

Effects of Environment on Quantum Algorithms

Ideal oracle

Noisy oracle

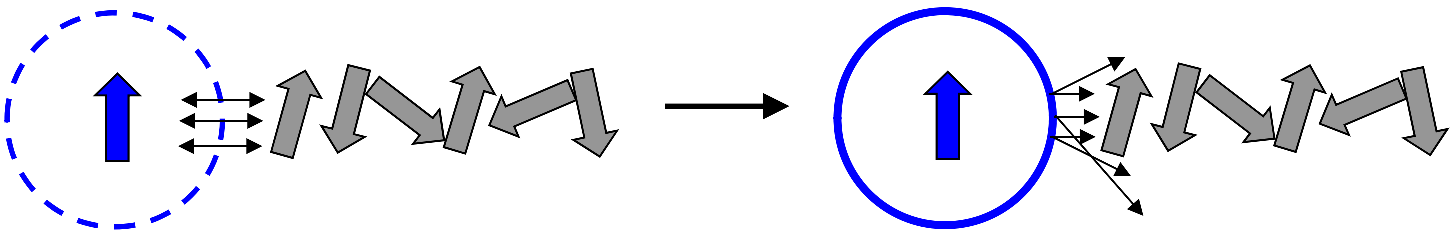




Errors accumulate, lowering success rate of algorithm

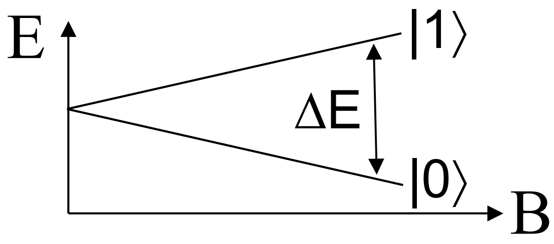
Suppressing Decoherence

1. Remove or reduce V, i.e. build a better computer



System isolated from environment

2. Increase B, i.e. increase level splitting



When $\Delta E >> V$, decoherence is small

3. Use decoherence free subspace (DFS)
4. Use pulse sequence to remove decoherence
5. Use topological quantum computer

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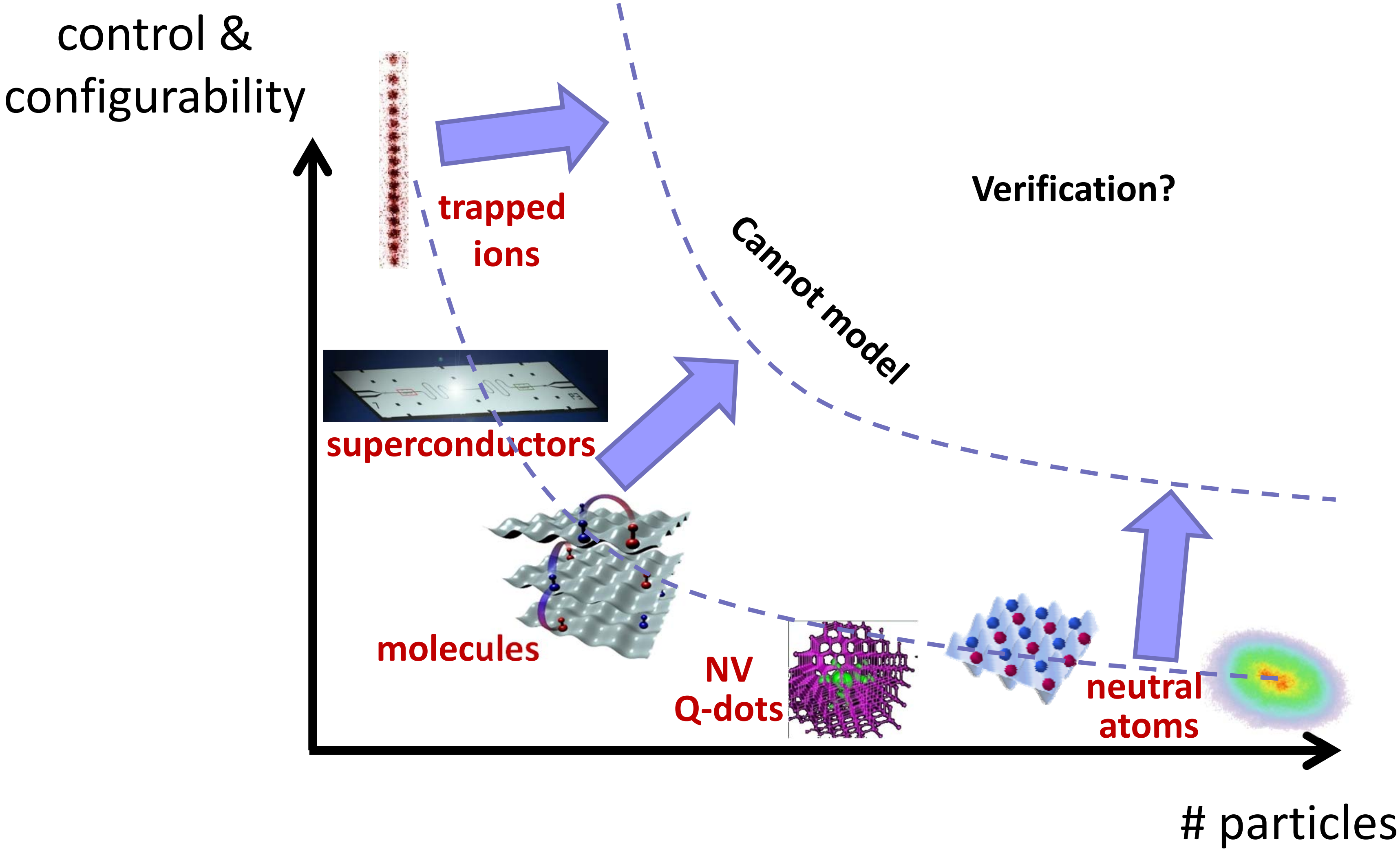
quantum computing models

- Quantum gate array
  - computation decomposed into sequence of few-qubit quantum gates
- One-way quantum computer
  - computation decomposed into sequence of one-qubit measurements applied to a highly entangled initial state or cluster state
- Adiabatic quantum computer, based on quantum annealing
  - computation decomposed into a slow continuous transformation of an initial Hamiltonian into a final Hamiltonian, whose ground states contain the solution
- Topological quantum computer

Implementation of Quantum Hardware



Quantum Computer implementing

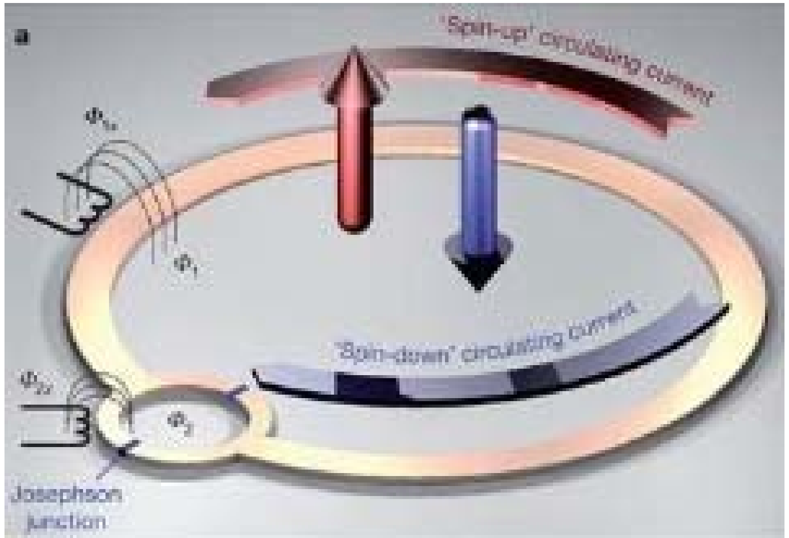
Superconducting Circuits

FEATURES & STATE-OF-ART

- connected with wires
- fast gates
- 5-10 qubits demonstrated
- **printable circuits and VLSI**

CHALLENGES

- short (10^{-6} sec) memory
- 0.05K cryogenics
- **all qubits different**
- **not reconfigurable**



Superconducting qubit:
right or left current

Research in superconducting quantum computing is conducted by Google, Microsoft, IBM and Intel.

Quantum Computer implementing

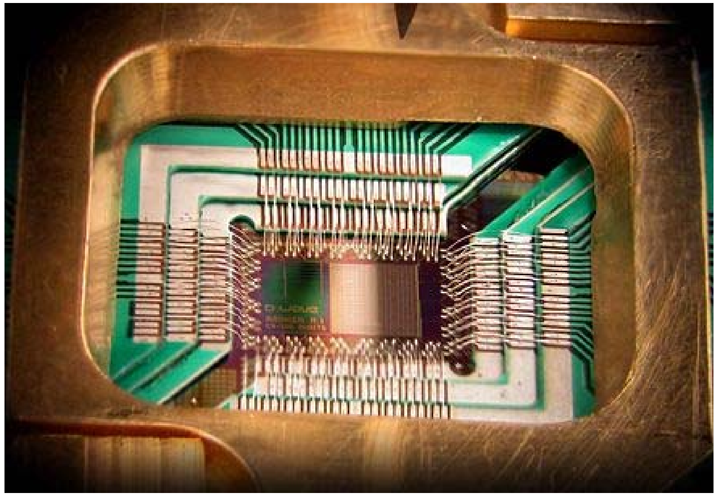
Superconducting Circuits

In May 2013, Google announced that it was launching the Quantum Artificial Intelligence Lab, with a 512-qubit D-Wave quantum computer studying quantum computing for machine learning.

In December 2015 NASA publicly displayed D-Wave at the Quantum AI Laboratory

Their architectures are suitable for solving some problems in optimization, molecular dynamics, and even deep learning training and inference tasks.

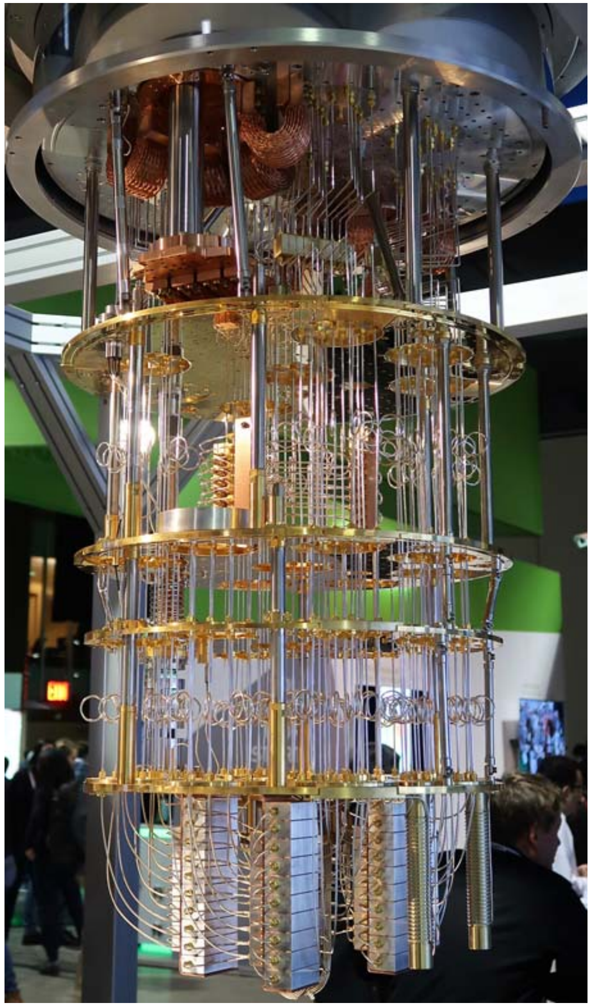
D:Wave
The Quantum Computing Company™



128-qubit superconducting adiabatic quantum optimization processor, mounted in a sample holder.

Quantum Computer implementing

IBM’s quantum computer I/O subsystem for getting electrical signals in and out of a millikelvin liquid helium bath (Source: TIRIAS Research)

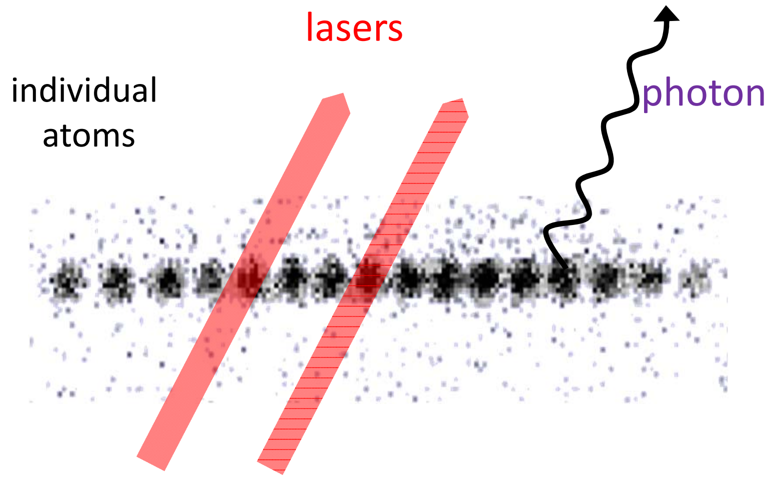


Quantum Computer implementing

Trapped Atomic Ions

FEATURES & STATE-OF-ART
- very long (>>1 sec) memory
- 5-20 qubits demonstrated
- **atomic qubits all identical**
- **connections reconfigurable**

CHALLENGES
- lasers & optics
- high vacuum
- 4K cryogenics
- **engineering needed**



Atomic qubits connected through laser forces on motion or photons

	IARPA	Lockheed
Investments:	DoD	Honeywell
	Sandia	UK Gov't

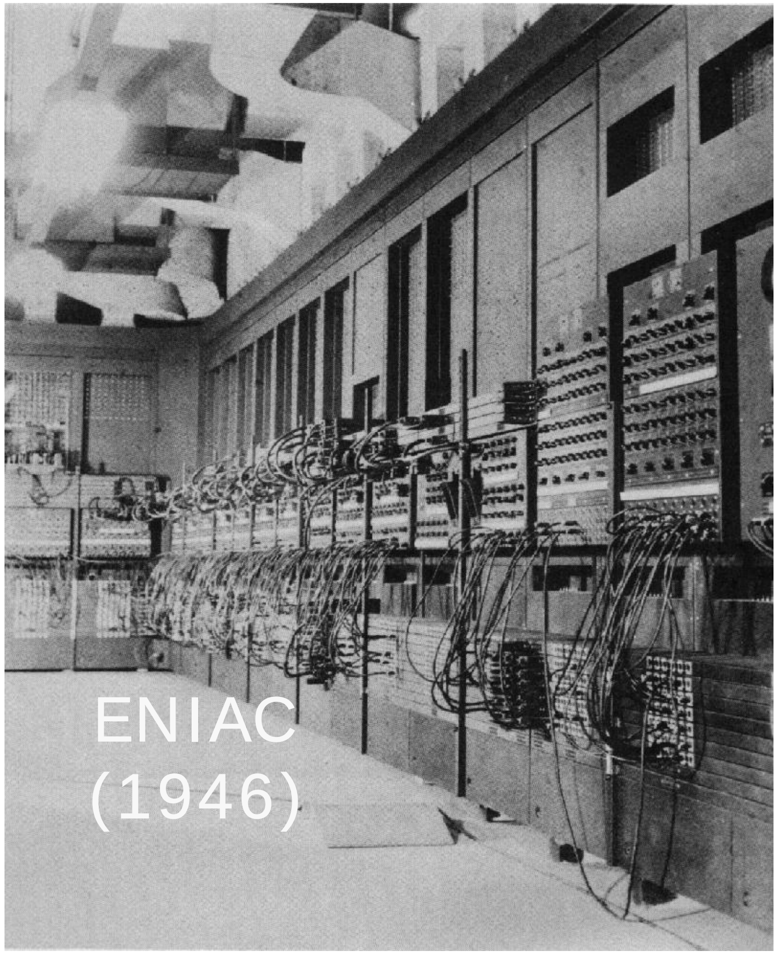
Quantum Computer implementing

Many others

- Optical lattices
- Quantum dot computer,
- Nuclear magnetic resonance on molecules in solution (liquid-state NMR)
- Solid-state NMR Kane quantum computers
- Electrons-on-helium quantum computers (qubit is the electron spin)
- Molecular magnet (qubit given by spin states)
- Fullerene-based ESR quantum computer
- Linear optical quantum computer
- Diamond-based quantum computer
- Bose–Einstein condensate-based quantum computer
- Transistor-based quantum computer

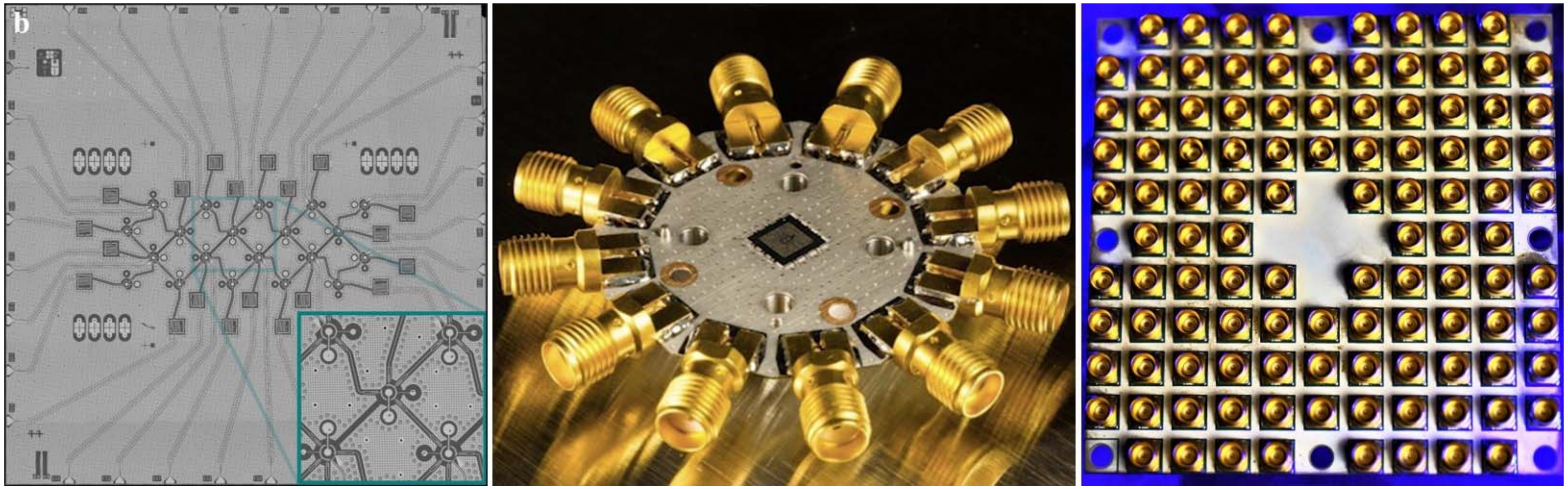
Quantum Computer trends

Quantum Computing Enters 2018 Like the semiconductor landscape 50 years ago in **1968.**



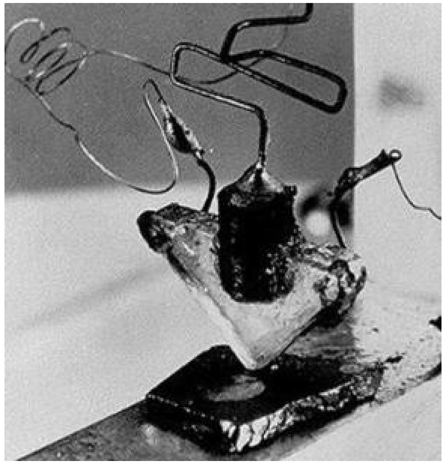
Quantum Computer trends

Quantum Computing Enters 2018 Like the semiconductor landscape 50 years ago in **1968.**



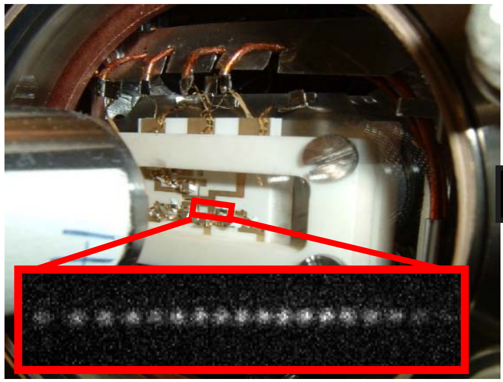
Rigetti 20-qubit silicon (left), Google 6-qubit silicon plus carrier (middle), Intel 49-qubit carrier (right)

Quantum Engineering Needed!

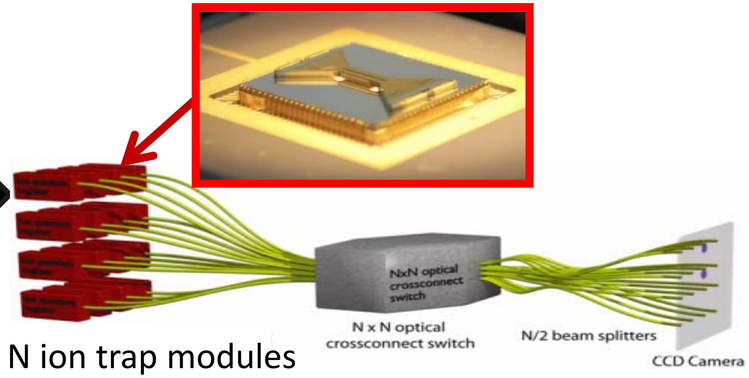


1947: first transistor

2000: integrated circuit



2015: qubit collection



Large scale quantum network?

Quantum Software

IBM

In May 2016, IBM Research announced that for the first time ever it is making quantum computing available to members of the public via the cloud, who can access and run experiments on IBM's quantum processor.

The service is called the IBM Quantum Experience.

The company also released a new API for the IBM Quantum Experience that enables developers and programmers to begin building interfaces between its existing five quantum bit (qubit) cloud-based quantum computer.

IBM says its Q Experience tools are used by over 1,500 universities, 300 private education institutions. Like Nvidia's successful strategy of educational outreach with CUDA tools.

Quantum Software

Microsoft

In December 2017, Microsoft released a preview version of a “Quantum Development Kit” QDK. Open sourced 2019.

It includes a programming language in Visual Studio, Q#, which can be used to write programs that are run on an emulated quantum computer.

QsharpVSIX.vsix

It is basing its quantum computing program on Majorana Fermions, which were found in 2012.

Quantum Software

In 2018:

- IBM open sourced its **QASM** (Quantum ASseMbler), a key component of IBM's QISKit (Quantum Information Software Kit).

- **XACC** (EXtreme scale ACCelerator) interfaces to Rigetti's simulator and prototype chips, and to D-Wave's production systems.

- **QuTiP** (Quantum Toolbox in Python) is an open source quantum computing simulator in use across a wide swath of the quantum computing hardware community (logos for Alibaba, Amazon, Google, Honeywell, IBM, Intel, Microsoft, Northrup Grumman, Rigetti, and RIKEN appear on its site).

- Google partnered with Rigetti to open source **OpenFermion**, a software package for compiling and analyzing quantum chemistry problems.

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Application 1. Quantum Factoring

P. Shor (1994)

A quantum computer can factor numbers **exponentially faster** than classical computers

15 = 3 × 5 (… easy)
3864788462100938762143232563 1 = **?** × **?**

Importance: cryptanalysis

public key cryptography relies on inability to factor large numbers

Application 2: Quantum Search

L. Grover (1997)

A quantum computer can finding a marked entry in an unsorted database **quadratically faster** than classical computers

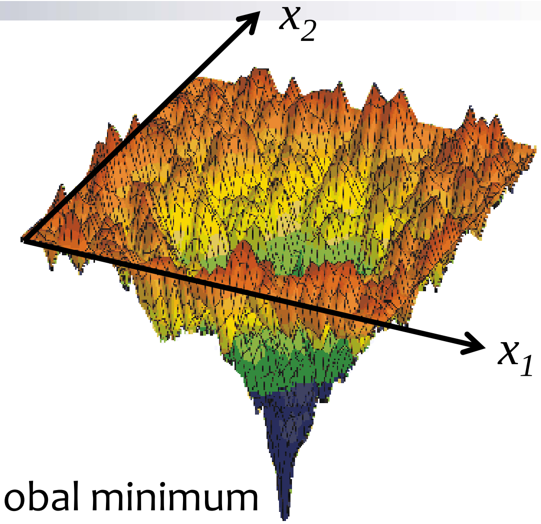
(e.g., given a phone number, finding the owner's name in a phonebook)

Importance: "satisfiability" problems

- fast searching of big data
- inverting complex functions
- determining the median or other global properties of data
- pattern recognition; machine vision

Application 3: Quantum Optimization

Minimizing complex (nonlinear) functions by "simultaneously sampling" entire space through quantum superposition



global minimum of $f(x_1,x_2)$

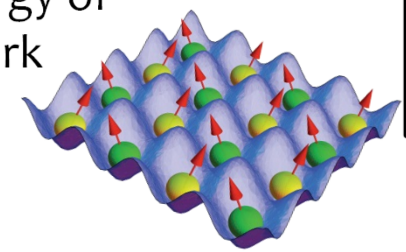
Relevant to

- Logistics
- Operations Research
- VLSI design
- Finance

Example: quadratic optimization

Minimize $f(x_1, x_2, \ldots) = \sum_{i<j} q_{ij} x_i x_j + \sum_i c_i x_i$

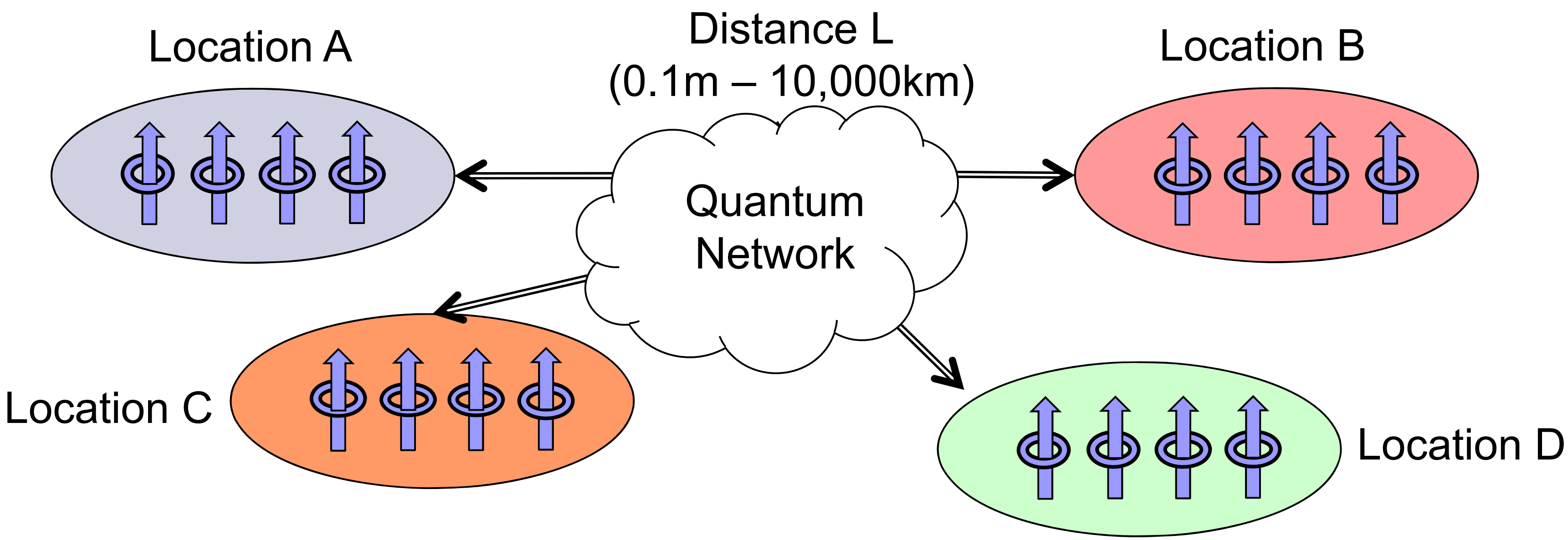
this function maps to energy of quantum magnetic network



Killer Application?

- could crack a large class of intractable problems: factoring, "traveling salesman" problem, etc..
- BUT not known if there is always a quantum speedup

Application 4: Quantum Networks



Uses of a quantum network

- Secret key generation: cryptography
- Certifiable random number generation
- Quantum repeaters ("amplifiers")
- Distributed quantum entanglement for optimal decision making
- *Large-scale quantum computing*

Application 5: Artificial Intelligence

AI is based on the principle of learning from experience, becoming more accurate as feedback is given, until the computer program appears to exhibit "intelligence."

This feedback is based on calculating the probabilities for many possible choices, and so AI is an ideal candidate for quantum computation.

For example,

- Lockheed Martin, using D-Wave quantum computer to test autopilot software that is currently too complex for classical computers;
- Google is using a quantum computer to design software that can distinguish cars from landmarks;
- Tsinghua, Quantum generative adversarial learning in a superconducting quantum circuit, QGAN.

Application 6: Financial Modeling

Feature of finance simulation: there's no controlled setting in which to run experiments.

To solve this, investors and analysts have turned to quantum computing.

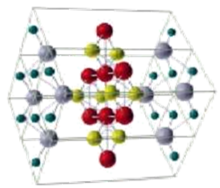
- One immediate advantage is that the randomness inherent to quantum computers is congruent to the stochastic nature of financial markets.
- Investors often wish to evaluate the distribution of outcomes under an extremely large number of scenarios generated at random.

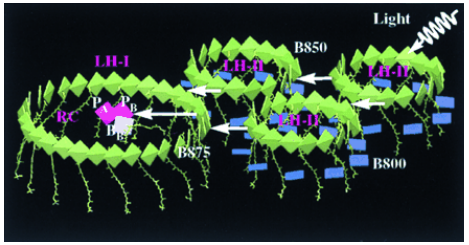
Application 7: Quantum Simulation

Quantum modelling is hard: *N* quantum systems require solution to 2^N coupled eqns

Alternative approach: Implement model of interacting system on a ***quantum simulator***, or "standard" set of qubits with programmable interactions

Quantum Material Design Understand exotic material properties or design new quantum materials from the bottom up





Energy and Light Harvesting Use quantum simulator to program QCD lattice gauge theories, test ideas connecting cosmology to information theory (AdS-CFT etc..)

Quantum Field Theories Program QCD lattice gauge theories, test ideas connecting cosmology to information theory (AdS-CFT etc..)

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I am looking at the future with concern, but with good hope.

-- -- Albert Schweitzer