Quantum Computing Trends

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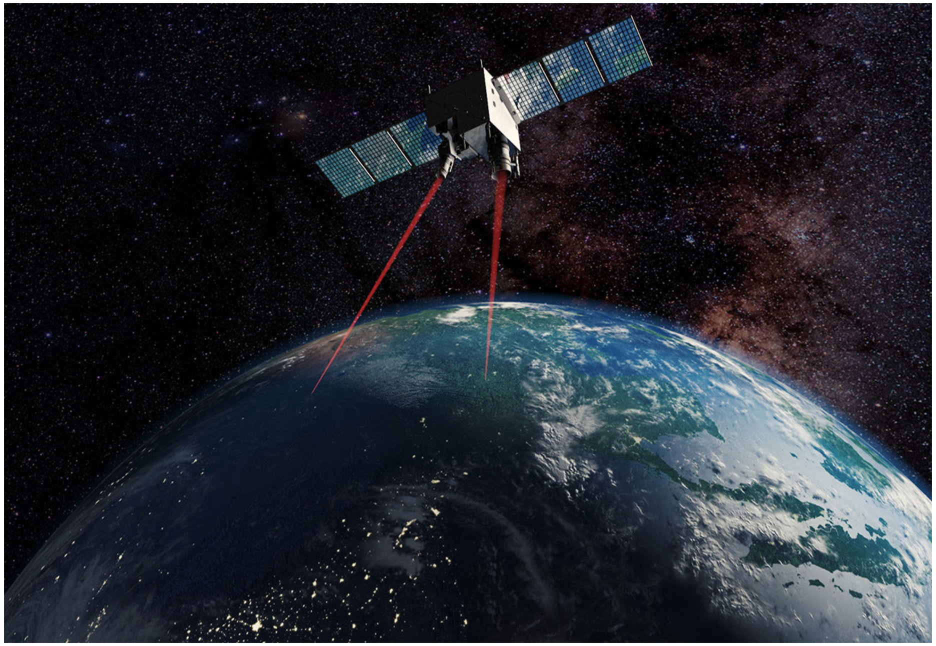
Why Quantum?

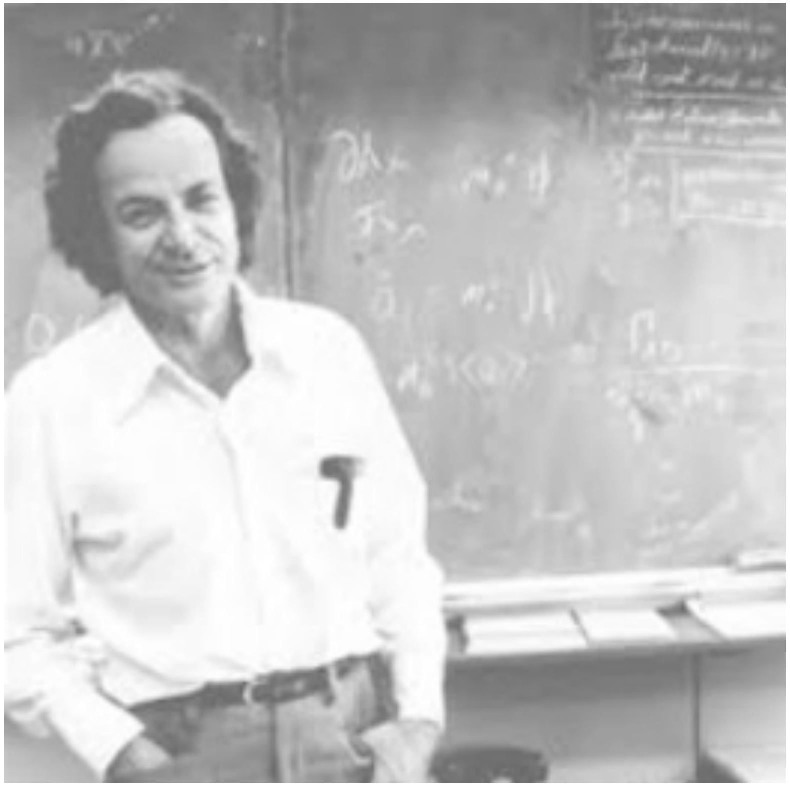
- Scientific problems: a number of NP-hard combinatorial problems can be solved efficiently on quantum computers (i.e. travelling salesman problem and database search). Applications: quantum chemistry, traffic control, real-time risk analysis, financial forecasting etc.
- Secure telecommunication: quantum key distribution is an ultra-secure communication method that requires a key to decipher a message. If the message gets intercepted, no one else can read it.
- Quantum sensors: devices that exploits quantum entanglement to achieve a sensitivity or resolution that is better than can be achieved using only classical systems. Applications: astrophysics, high energy physics, military etc.

Quantum Teleportation

- **“Chinese Scientists Just Set the Record for the Farthest Quantum Teleportation” July 15, 2017**
- **“A quantum physicist says the experiment is "profound" in that it could help lead to super secure and superfast quantum internet”. It is expected to be widely available in ~10-20 years.**
- A new Chinese experiment shows that quantum teleportation works between the ground and space
- It worked at a distance of 870 miles (1,400 kilometers), many times as far as the previous teleportation record
- European Quantum Internet Alliance is building the first genuine quantum network
- UChicago – Argonne – Fermilab quantum network is under construction



Why Quantum Computation?



Richard Feynman, Simulating Physics with Computers, 1982

- “...nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical...”
- "If you think you understand quantum mechanics, you don't understand quantum mechanics.“
- “I think I can safely say that nobody understands quantum mechanics."

What is Quantum Computer?

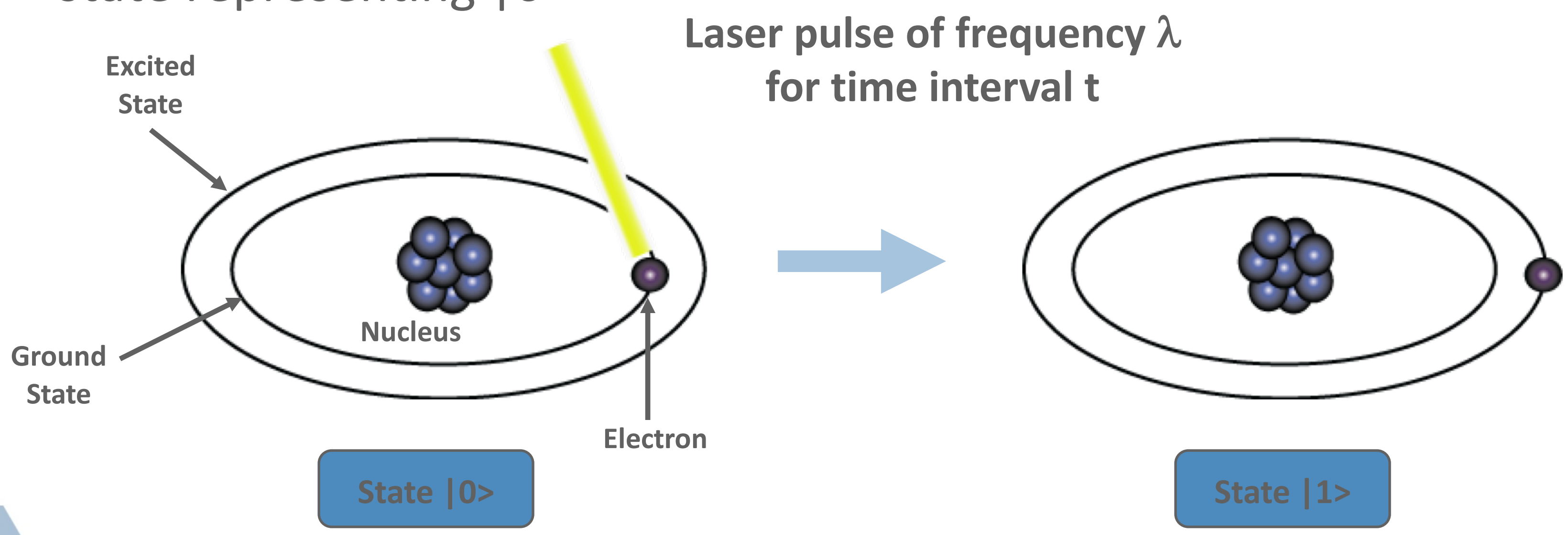
- Feynman’s version: “A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behavior of particles at the sub-atomic level”
- Quantum computer is an “ideal” SIMD special vector co-processor that performs calculations based on the laws of quantum mechanics
- “Ideal” means that a single operation can be performed on all qubits simultaneously at the cost of one operation
- Quantum computers execute unitary reversible operations. During execution of these operations no information is lost to the environment. Such an operation is basically "perfectly" energy efficient. (In contrast classical operations are non-reversible, and therefore wasteful)

Quantum Hype

- Quantum computing might solve World Hunger
- Quantum computing will Save Energy and solve Climate Change
- Quantum computing will help designing New Materials
- Quantum computer can be used as a Time Machine i.e. "reverse time" (https://www.nature.com/articles/s41598-019-40765-6)
- Quantum teleportation for "Long Distance" Space Travel (Chinese experiment to use quantum satellites (http://time.com/4854718/quantum-entanglement-teleport-space)
- Quantum teleportation can be used for "Very Long Space Travel" by use of entanglement between wormholes i.e. black holes (http://meetings.aps.org/Meeting/APR19/Session/B02.2)

Quantum Computing Introduction: Qubit Concept

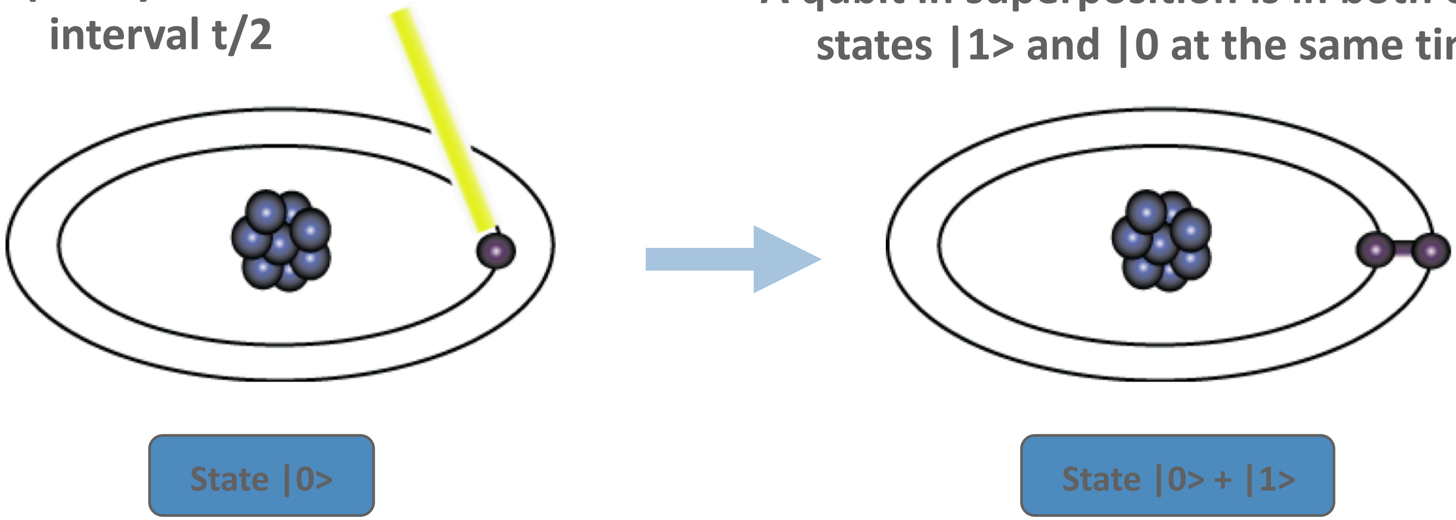
- A qubit is the quantum concept of a bit
- A bit of data is represented by a single atom that is in one of two states denoted by |0> and |1>. A single bit of this type is known as a ***qubit***
- A physical implementation of a qubit could use the two energy levels of an atom. An excited state representing |1> and a ground state representing |0>



Quantum Computing Introduction: Superposition

Laser pulse of frequency λ for time interval t/2

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



- A single qubit can be forced into a ***superposition*** of the two states denoted by the addition of the state vectors:
- **$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$**
- A qubit can be in all possible combinations between states 0 and 1

Quantum Computing Introduction: States

- Qubit states grow as 2^N where N is number of qubits
- Complex coefficients are stored in a very long vector in memory (limits classical simulations)

Number of qubits	Number of states	Memory requirements
2	4	64 Bytes
30	1.0×10^{9}	32 Gigabytes
45	3.5×10^{13}	1.0 Petabytes
300	1.0×10^{90}	*Number of particles in Universe

Quantum parallelism

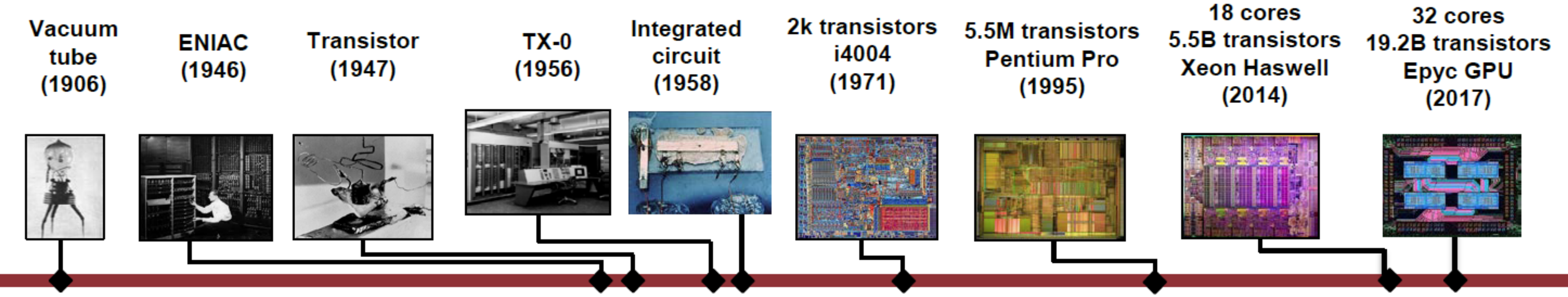
- Quantum parallelism and interference what make quantum computers different from classical
- Consider two qubit system. There are four possible combinations:

Coefficient	State
c_1	$\|00>$
c_2	$\|01>$
c_3	$\|10>$
c_4	$\|11>$

- In classical computing you need perform 4 operations to compute all combinations
- In quantum computing it can be accomplished with just 1 operation i.e. single gate operation on a single qubit will

Hardware timeline

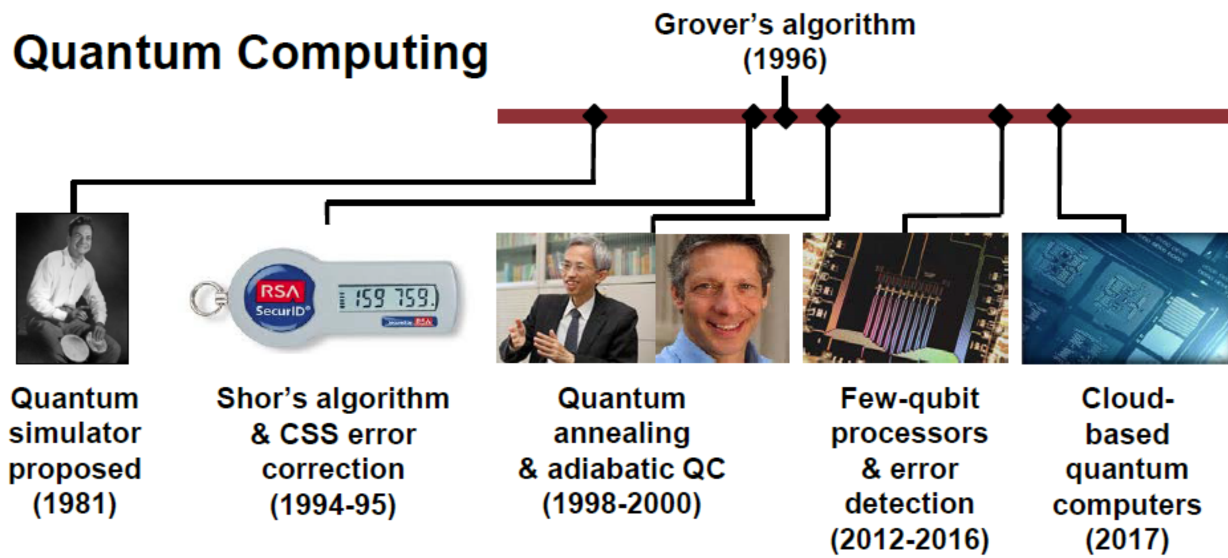
Classical Computing (Electronic)



Quantum computing is transitioning from scientific curiosity to technical reality.

Advancing from discovery to prototype to useful machines takes time.

Quantum Computing



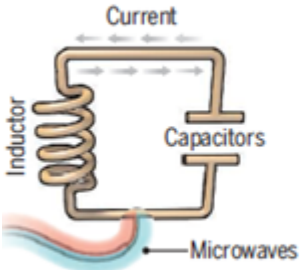
Credit: MIt xPRO I

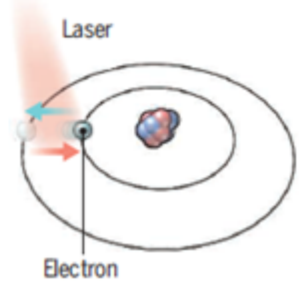
Available and announced quantum computers

Company	Operational	Cloud Access	Framework	Announced
IBM	20 qubits	Open to Q hub members	QISKit	50 qubit chip announced Nov. 2017
Rigetti	19 (8) qubits	Access by request	Forest	128 qubit chip by August 2019
Google	50 qubits?	No access	Cirq	72 qubit chip announced March 2018
Intel	?	No access	?	49 qubit chip announced Jan. 2018
Alibaba	11 qubits	?	Aliyun	50+?
IonQ	7 (20) qubits	No access	Under construction	20+?
DWave	2000Q (~60 qubits)	Open (1 minute per month)	Leap	5000Q delivery target end of 2019

Modern Quantum Computers

Operate at almost absolute zero temperature -460 F or -273 C, colder than deep space



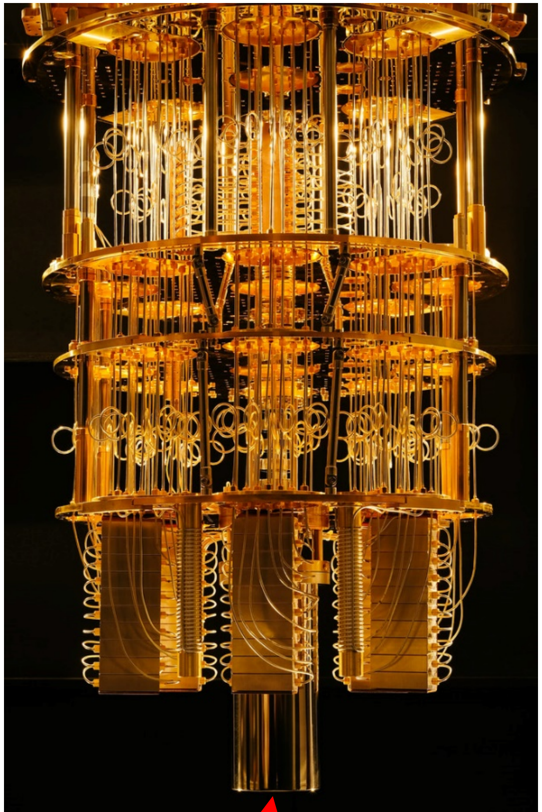


Computers are ranked by number of qubits decoherency time

		Superconducting (IBM, Google, Rigetti)	Trapped ions (IonQ, U. of Innsbruck)
Qubit Modality	Materials	Al on the Si substrate	Yb+, Ca+, Sr+, Be+, Ba+, Mg+
	Type	Transmon	Optical transitions
	Control	Microwaves	Microwaves+optics
	State	Junction phase	Atomic state of electron
Approximate Decoherency Times (ns)		~100-200	Very long
	1qb gate	10	5,000
	2qb gate	40	50,000
Fidelity	1qb gate	99.9%	99.999%
	2qb gate	99.0%	99.5%
Speed (MHz)	1qb gate	100.00	0.20
	2qb gate	25.00	0.02

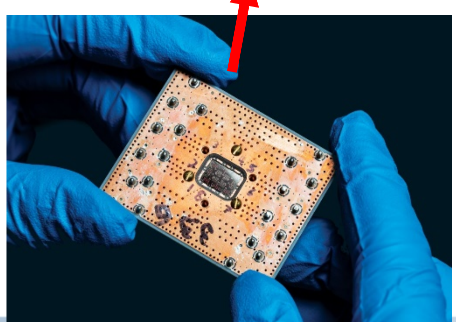
Modern CPUs:
~3 GHz, 100% fidelity

IBM quantum computers



The key piece of the Quantum Computer is the Dilution Refrigerator

Working Temperature 15 mK uses mix of **$^3He/^4He$**



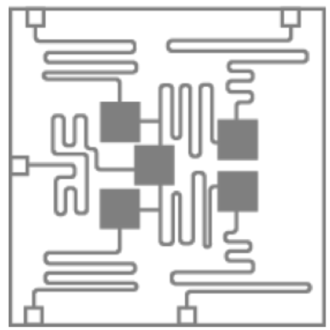
Source: IBM Research

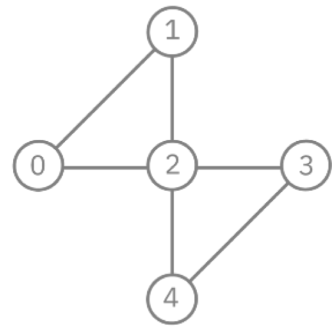
IBM quantum computers

Everybody can get access through cloud
(IBM quantum experience):
https://quantumexperience.ng.bluemix.net/qx/signup

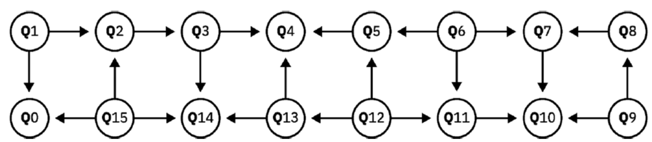
Available devices:

5 qubit computers
Tenerife and Yorktown
(free)

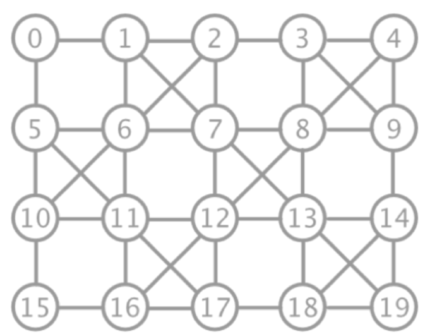




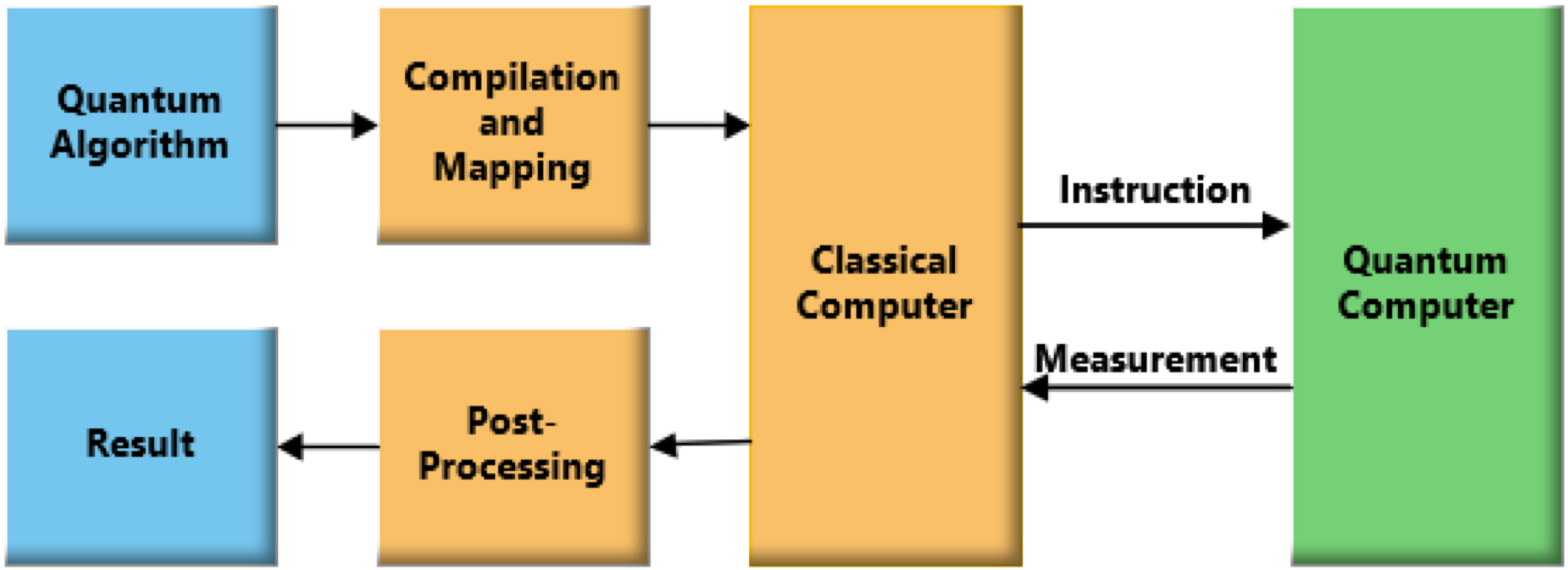
14 qubit computer
Melbourne
(research paper)



IBM Q hub members:
20 (50) qubit computers
Tokyo, Poughkeepsie ($$$)

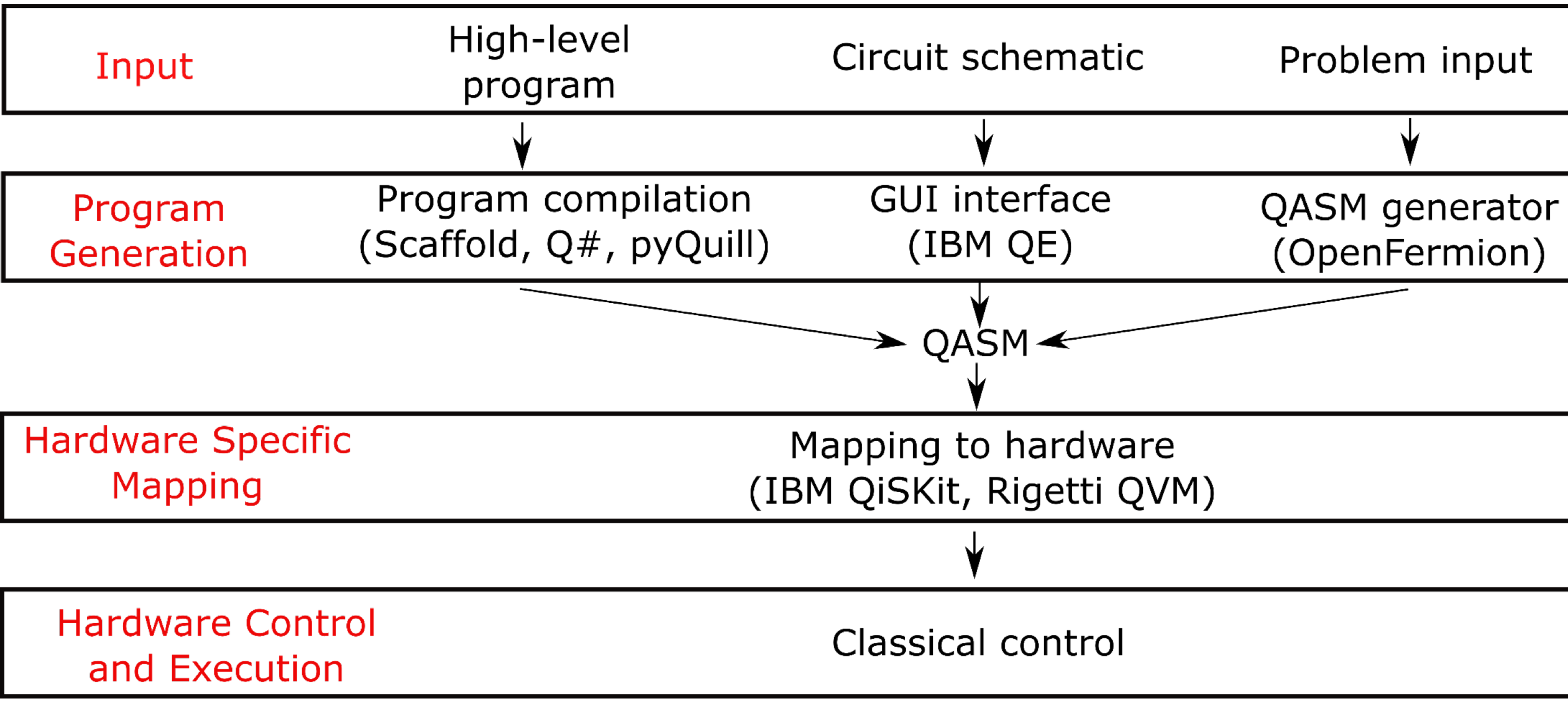


Hybrid Quantum/Classical Computing System

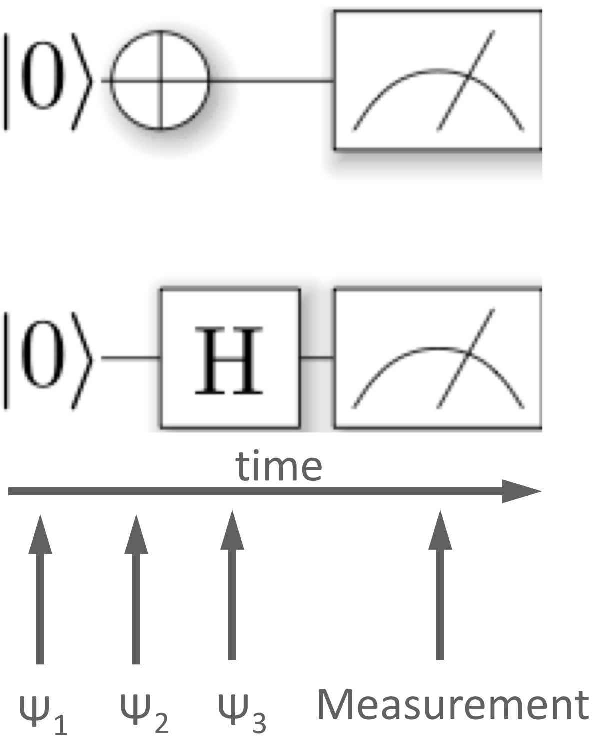


A high-level block diagram of a quantum computing system, where colors represent different levels of abstractions. Typically three levels are involved: a user level (blue), classical computation and control (yellow), and QC system (green). A quantum algorithm is compiled and mapped into a native set of instruction for the target quantum computer. The measurement of quantum register after postprocessing becomes the result.

Quantum software stack



Quantum circuits



Quantum computers are programmed by using Quantum Assembly (QASM)
QASM standards: MIT QASM, IBM OpenQASM 2.0, LANL QASM, Atos QASM etc.

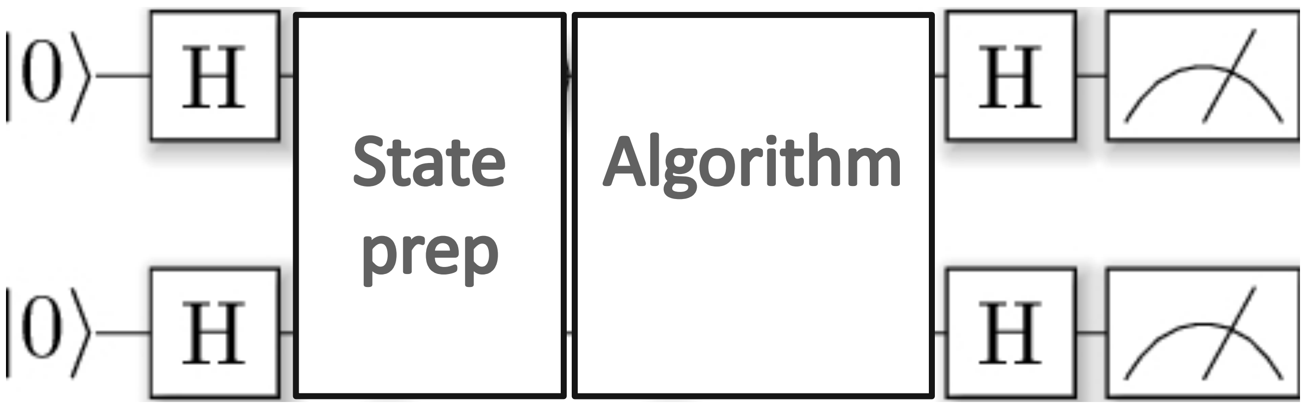
MIT QASM code:

```
qbit q0
qbit q1
not q0
h q1
measure q0
measure q1
```

Ψ_1 = **1.0**|00> + **0.0**|01> + **0.0**|10> + **0.0**|11>
Ψ_2 = **0.0**|00> + **0.0**|01> + **1.0**|10> + **0.0**|11>
Ψ_3 = **0.0**|00> + **0.0**|01> + **0.7**|10> + **0.7**|11>
Output is $(0.7)^2$ =½=50% for states|10> or |11>

A typical structure of a quantum algorithm

Initialize → Maximum superposition → State preparation → Logic Gates → Minimum superposition → Measurement



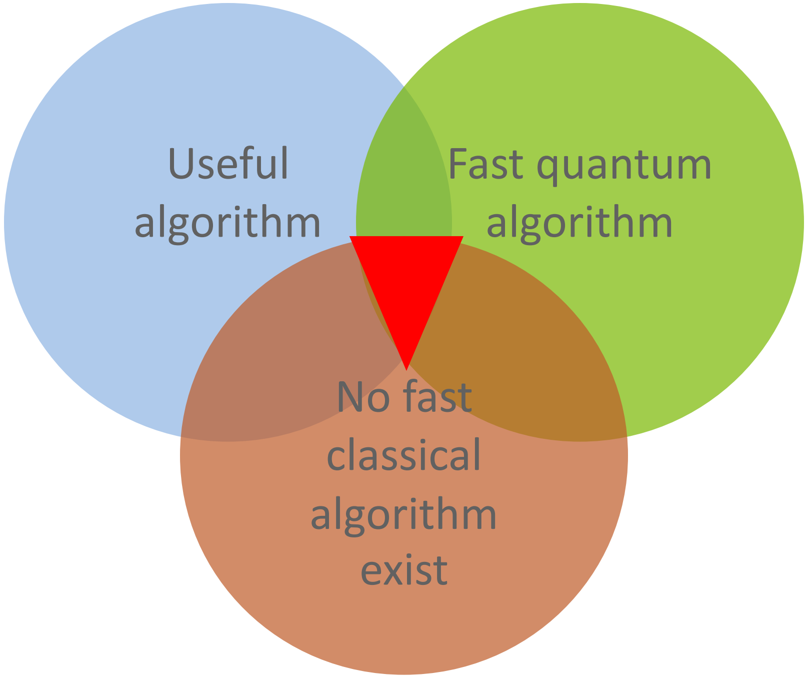
c1|00>
c2|01>
c3|10>
c4|11>

c1'|00>
c2'|01>
c3'|10>
c4'|11>

if c2'=1
c1'=c3'=c4'=0

$\lvert c1' \rvert^2=0$
$\lvert c2' \rvert^2=1$
$\lvert c3' \rvert^2=0$
$\lvert c4' \rvert^2=0$

Quantum Algorithms



- There are two known classes algorithms hitting all three circles:
- Four main fundamental algorithms expected to provide a speedup over their classical counterparts: Shor's factoring algorithm, Grover's search algorithm, HHL’s linear system solver, and quantum simulation
- Quantum machine learning?

Quantum speedup

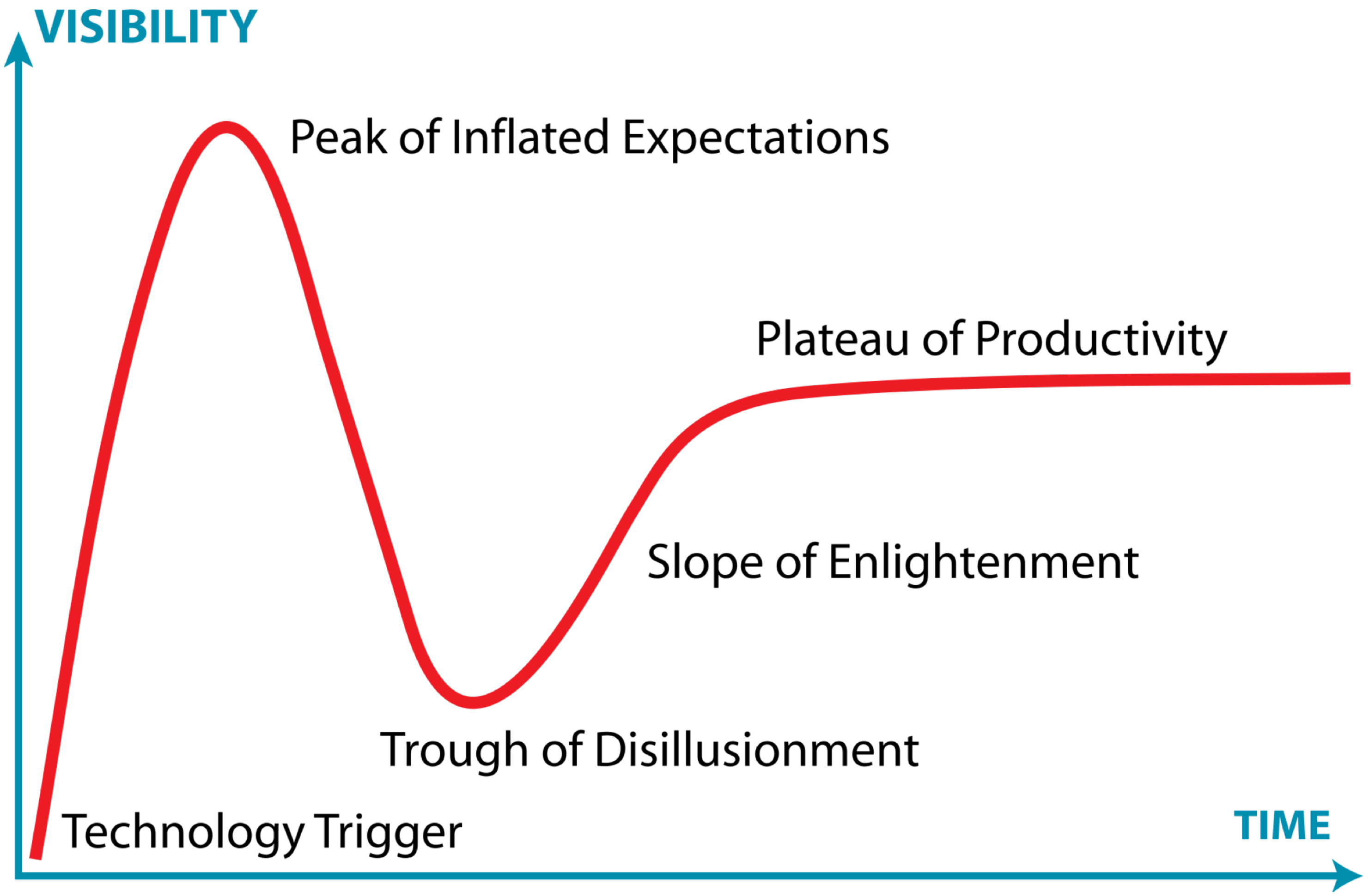
Algorithm	Classical resources	Quantum resources	Quantum speedup	Requirements
Quantum simulation	2^N	$\sim N^6$	Exponential	100+ qubits, millions of gates
Factorization	2^N	N^3	Exponential	200+ qubits, millions of gates
Solving linear systems	N^2	Log(N)	Exponential	Millions of gates and qubits
Unstructured search	N	$\sqrt{N}$	$\sqrt{N}$	Millions of gates and qubits

N-complexity of the problem

Reality check

- We have 20 (50?) noisy qubits (need millions)
- Short decoherency time to run up to 30-200 gates maximum (need millions)
- Slow gates MHz (need GHz)
- Poor connectivity (for superconducting quantum computers)
- Slow I/O
- Quantum Winter II?

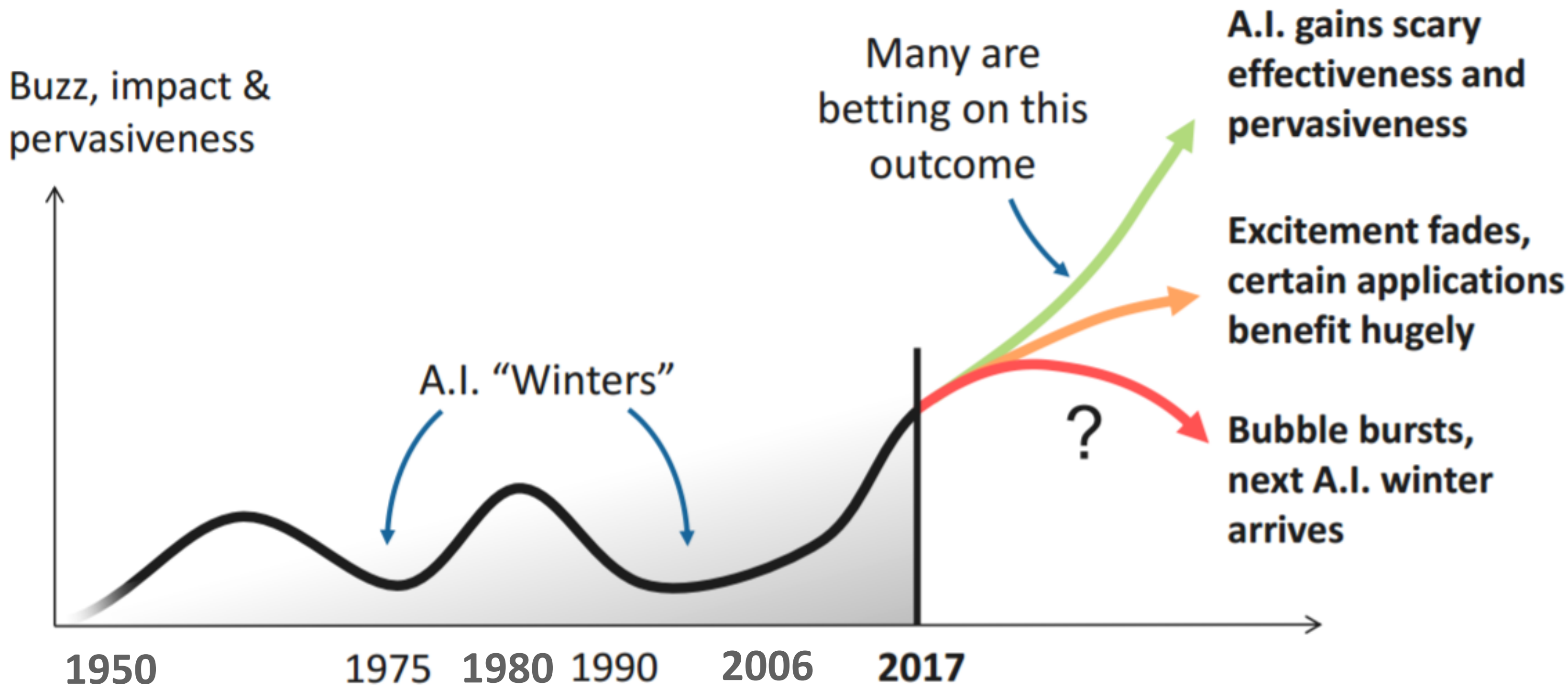
Hype Cycle



Credit: Wikipedia

Artificial Intelligence Hype Cycles

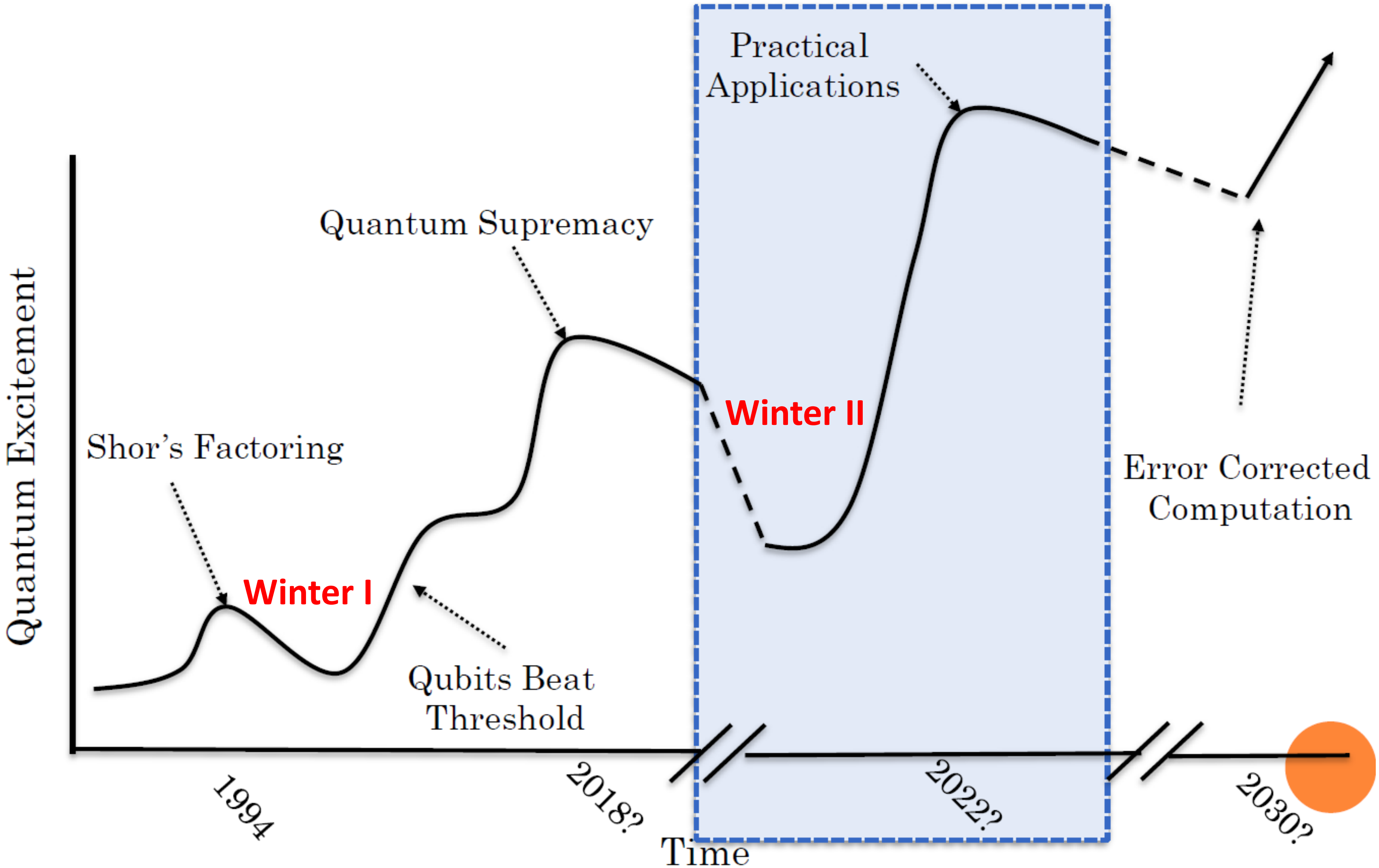
AI is enjoying significant hype and investment



1980: expert systems

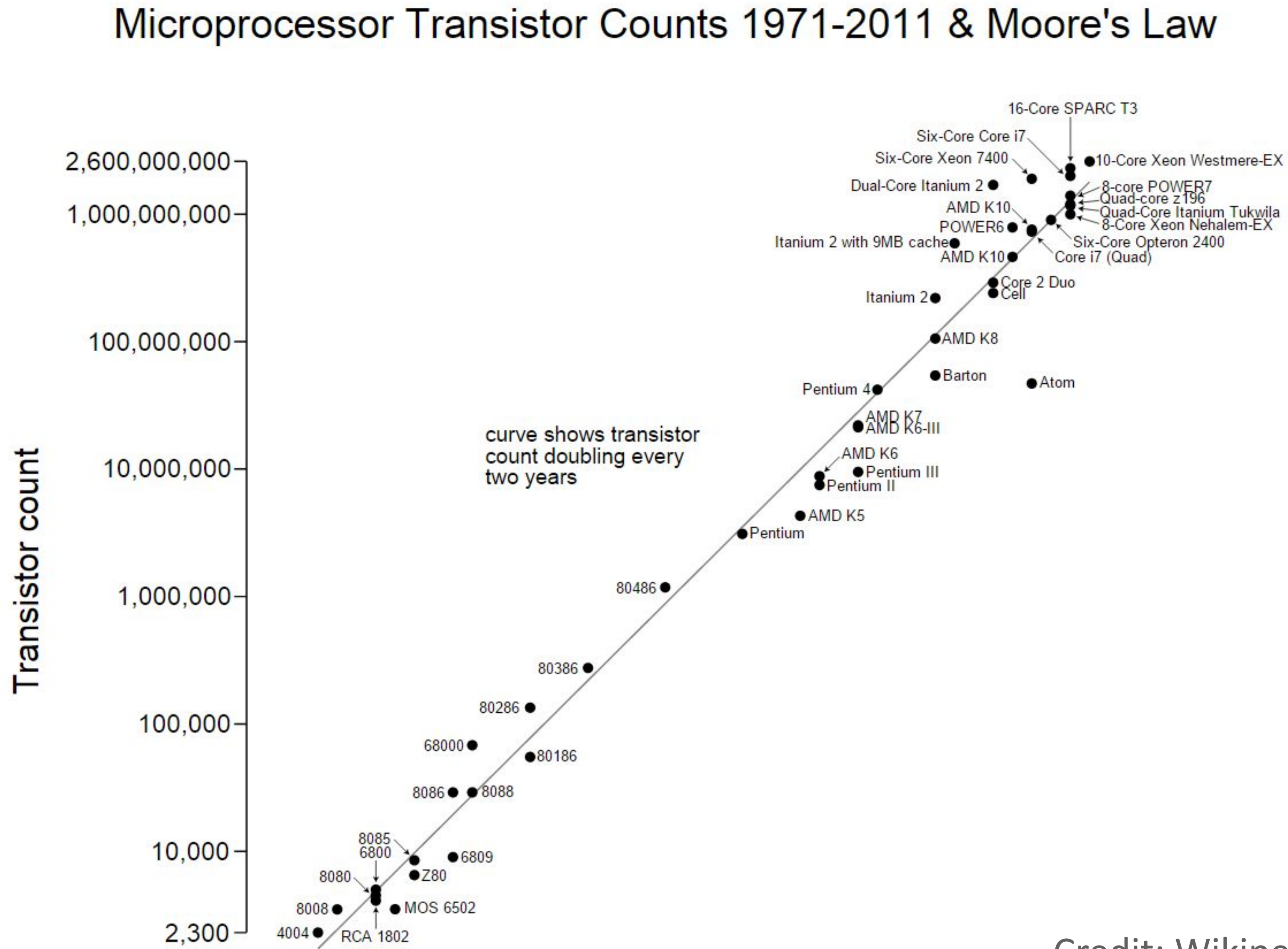
2006: U. of Toronto develops Deep ML + rise of GPUs

Quantum Computing Hype Cycles



Credit: Jarrod McClean

Moore's Law

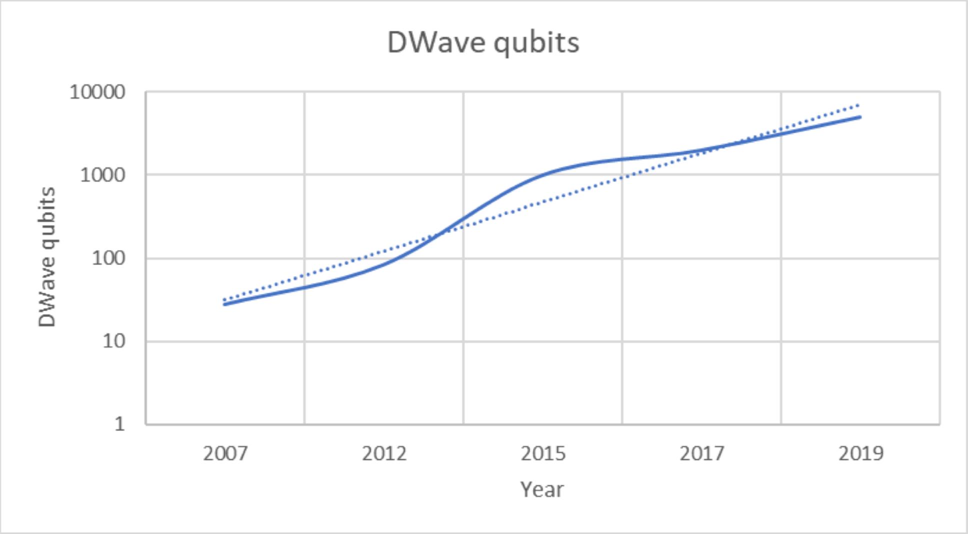


Credit: Wikipedia

Quantum Moore's Law

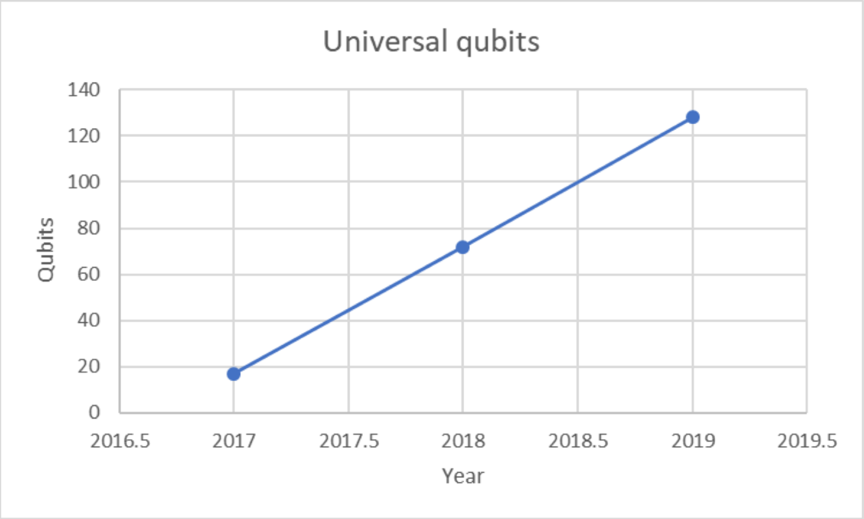
Doubles up every two years

Year	DWave qubits
2007	28
2012	84
2015	1000
2017	2000
2019	5000

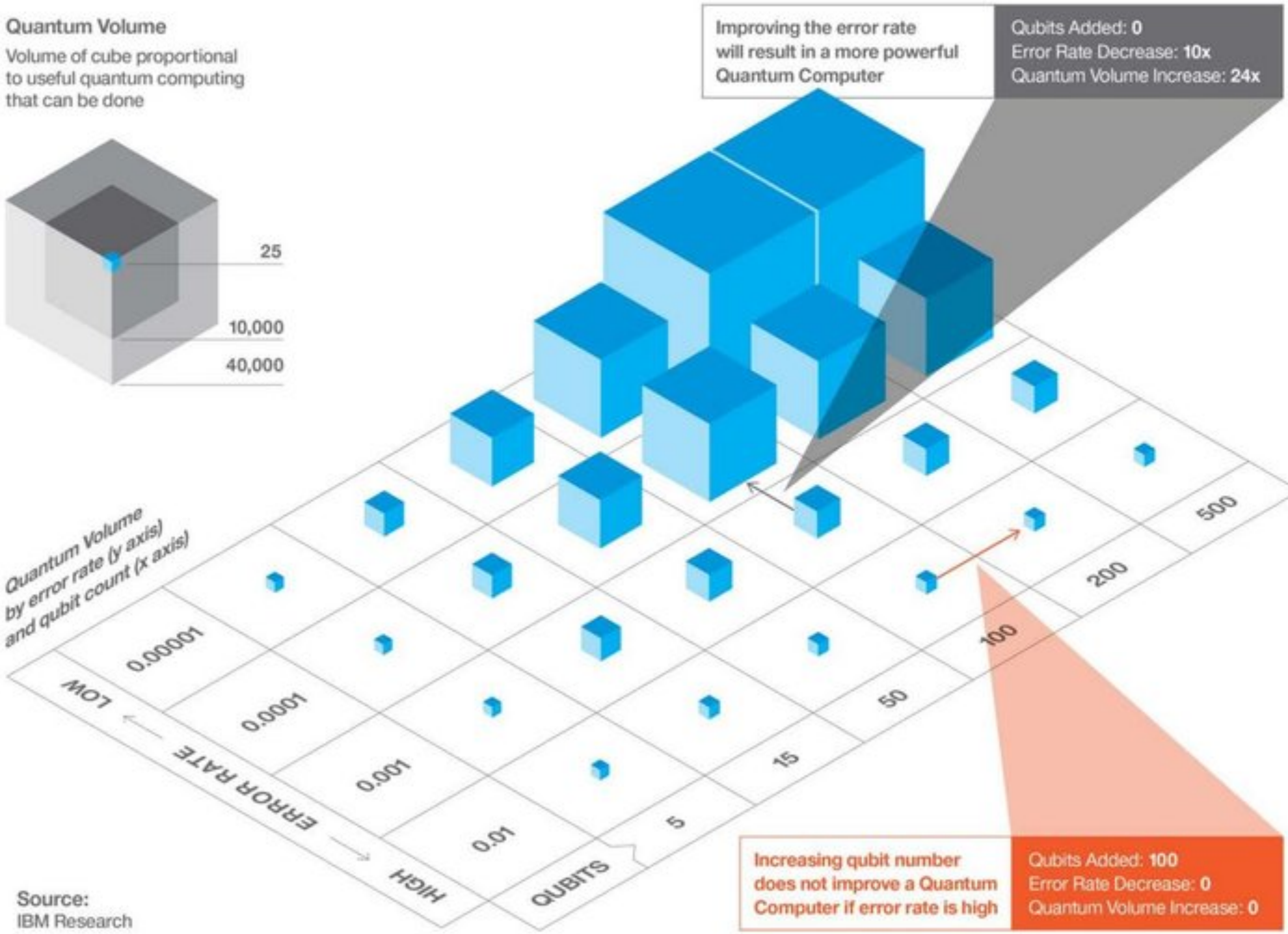


Doubles up every year

Year	Universal qubits
2017	17
2018	72
2019	128?



Quantum Volume



Quantum Simulators

Simulator	Advantages	Disadvantages
Intel-QS	highly scalable C++ HPC code (MPI/OpenMP), freely available from Git	under development, no documentation, lacking sophisticated error models
ProjectQ	easy to use Python code, freely available from Git, works with OpenFermion	no MPI implementation, lacking documentation, lacking error models
QuaC	time dynamics, scalable code, freely available from Git, error models	under development, poor documentations, depends on PETSc
Atos	robust commercial package, easy to use, excellent documentation, error models	not freely available, no MPI implementation

Simulating Quantum Computers On Classical Computers

- Simulating a quantum gate acting on N qubits needs $O(2^N)$ memory and operations

Qubits	Memory	Time per operation
10	16 KB	Microseconds on a smartwatch
20	16 MB	Milliseconds on a smartphone
30	16 GB	Seconds on a laptop
40	16 TB	Seconds on a PC cluster
50	16 PB	Minutes on modern supercomputers
60	16 EB	Hours on post-exascale supercomputers?
70	16 ZB	Days on supercomputers in distant future?

Upcoming Events

- Quantum tutorial December 2019
- SIAM PP20 tutorial and workshop
- SC19 Birds of Feather

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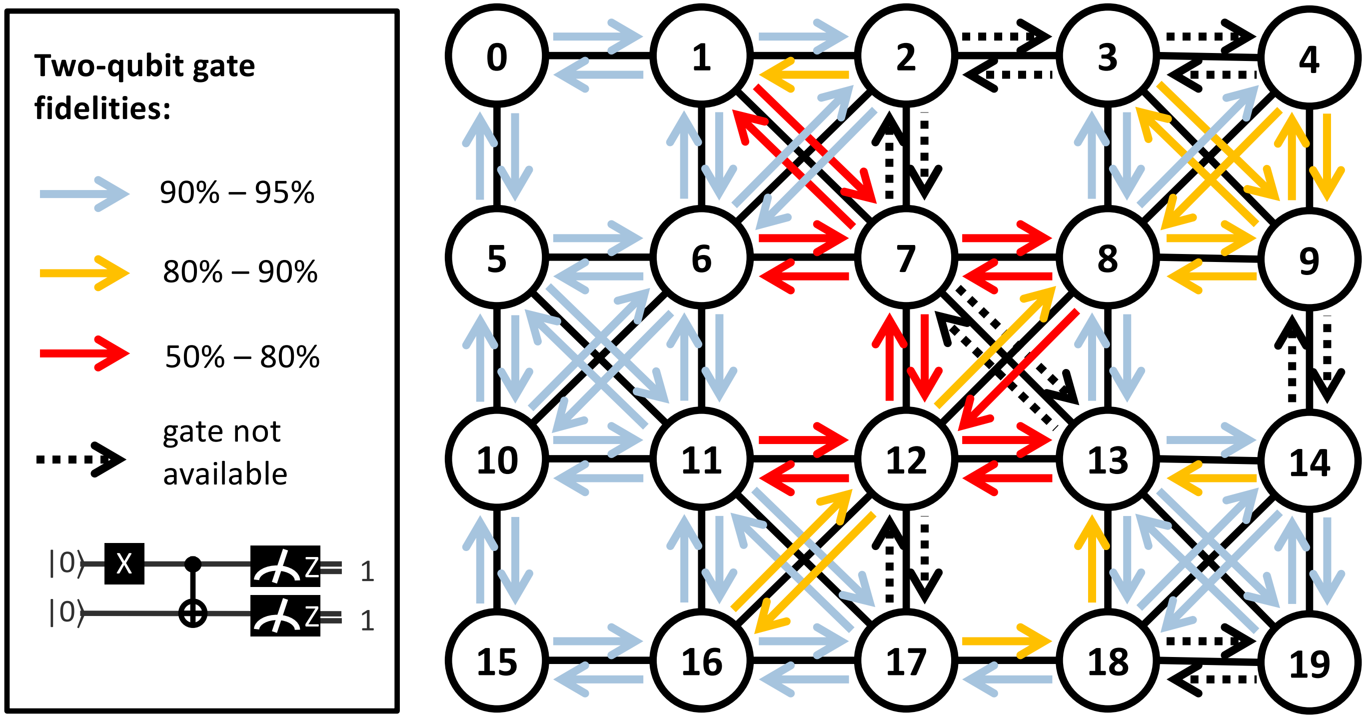
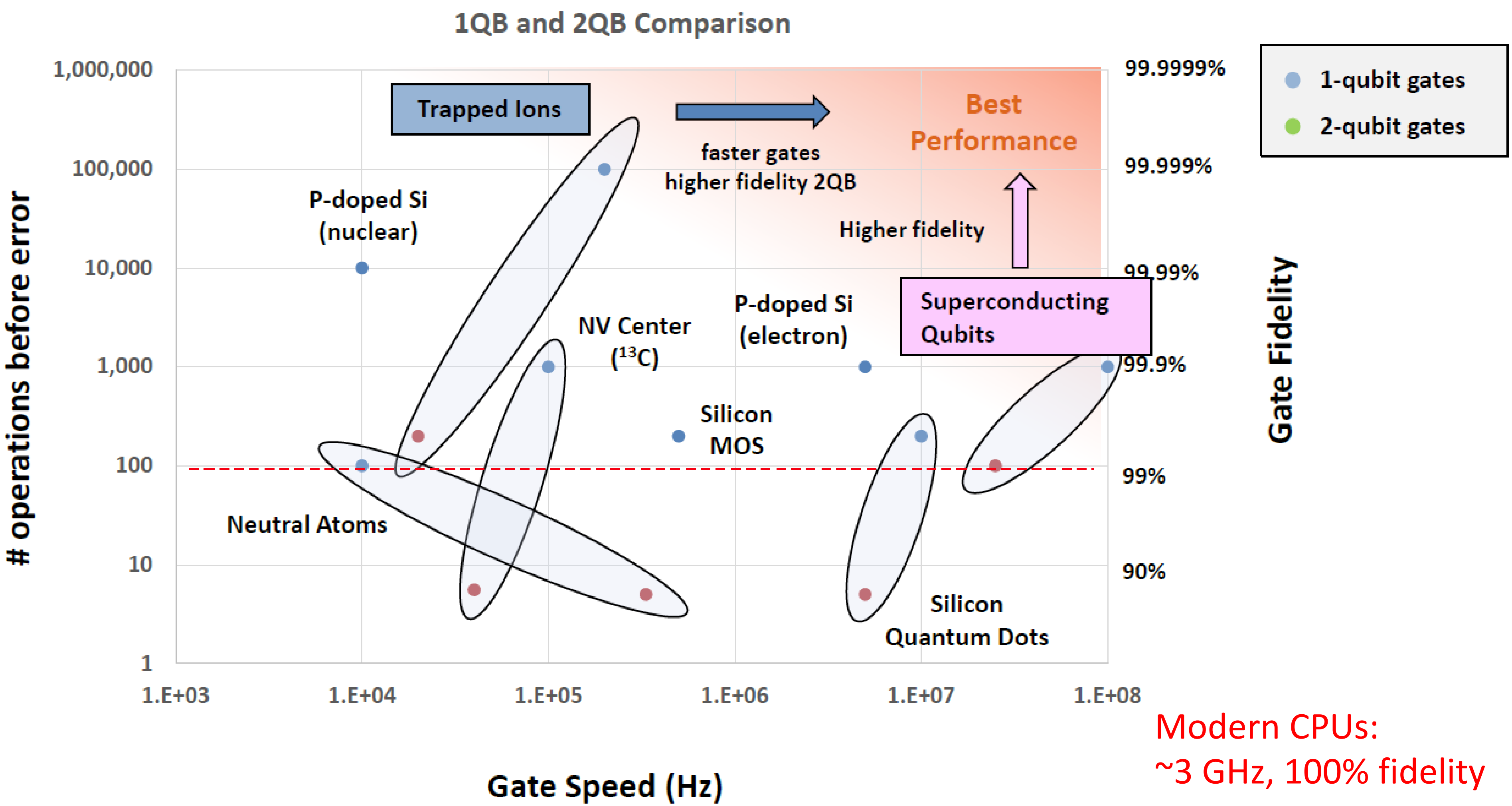
- I gratefully acknowledge the computing resources provided and operated by the Joint Laboratory for System Evaluation (JLSE) at Argonne National Laboratory

Fidelity of Quantum Computers



IBM Tokyo 20 qubit device
Credit: Martin Suchara

Qubit fidelity and speed



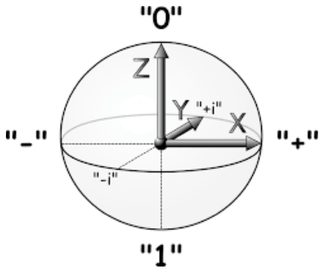
Modern CPUs:
~3 GHz, 100% fidelity

Credit: P. Cappallaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage

Quantum parallelism

- Apply NOT gate on first qubit

Initial state: $\Psi = \mathbf{c_1}|00\rangle + \mathbf{c_2}|01\rangle + \mathbf{c_3}|10\rangle + \mathbf{c_4}|11\rangle$
after NOT gate: $\Psi = \mathbf{c_1}|10\rangle + \mathbf{c_2}|11\rangle + \mathbf{c_3}|00\rangle + \mathbf{c_4}|01\rangle$



- Another way to present it:

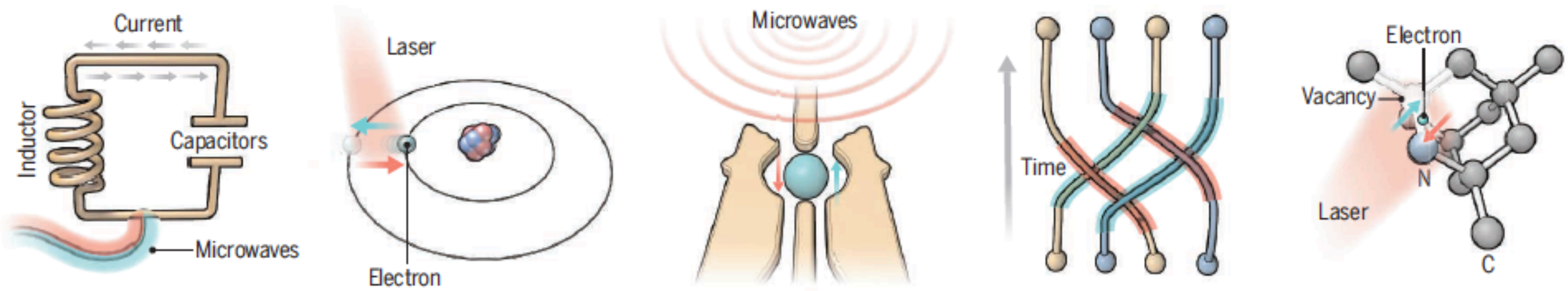
Coefficient	State	NOT on q1	Coefficient	State
c_1	$\|00\rangle$		c_3	$\|00\rangle$
c_2	$\|01\rangle$		c_4	$\|01\rangle$
c_3	$\|10\rangle$		c_1	$\|10\rangle$
c_4	$\|11\rangle$		c_2	$\|11\rangle$

- One gate operation on one qubit swaps all coefficients in state function Ψ simultaneously i.e. any quantum gate is a SIMD operation
- It is an example of quantum parallelism

Modern Quantum Computers

A bit of the action

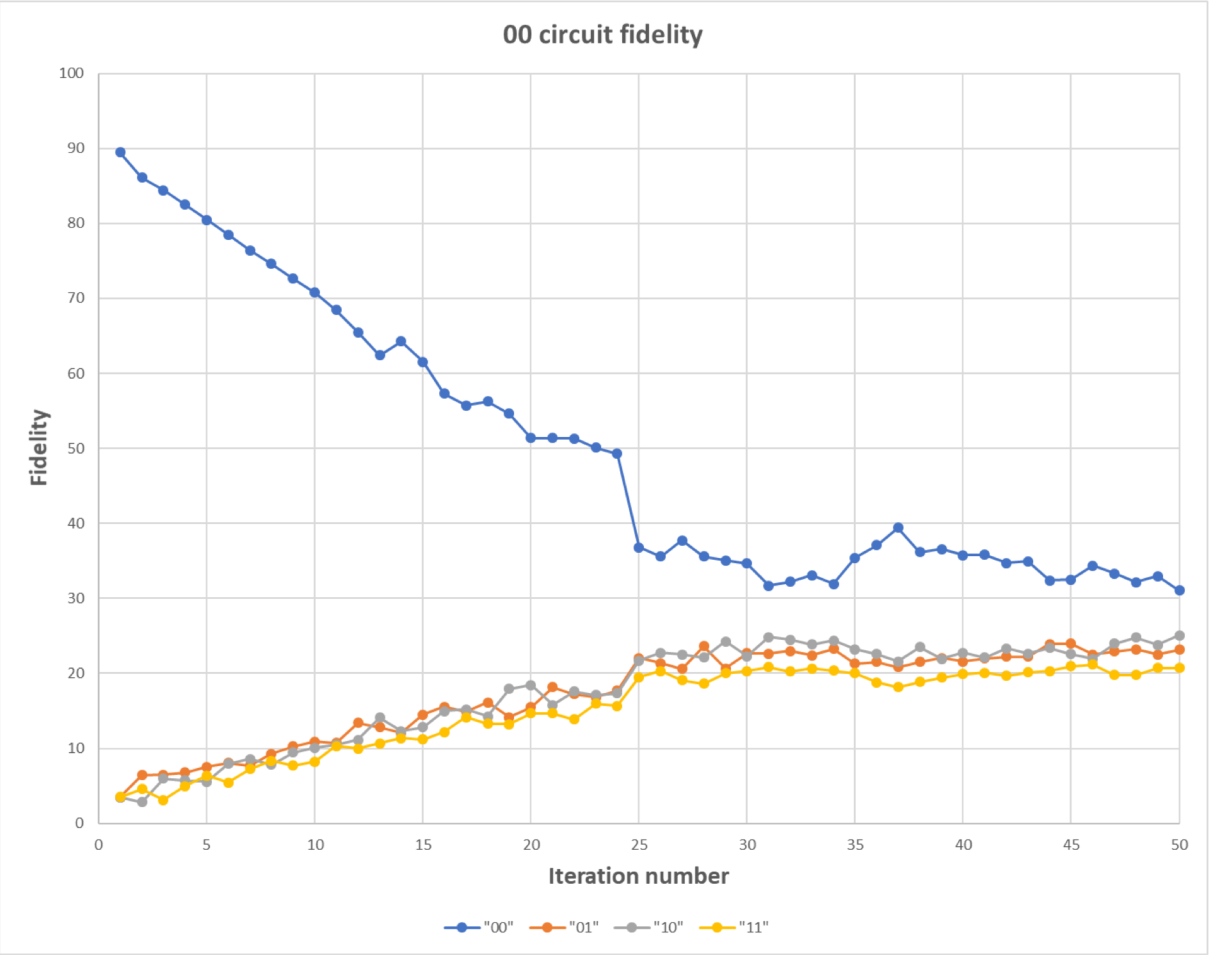
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

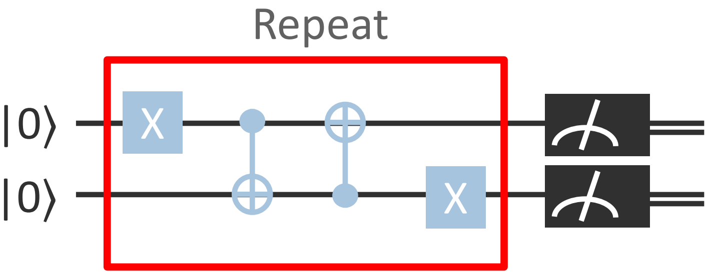


	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	72 Bristlecone, 50 IBM	20 Innsbruck	2	N/A	6
Company support	Google, IBM, Rigetti	ionQ, Innsbruck	Intel, Delft	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Circuit fidelity



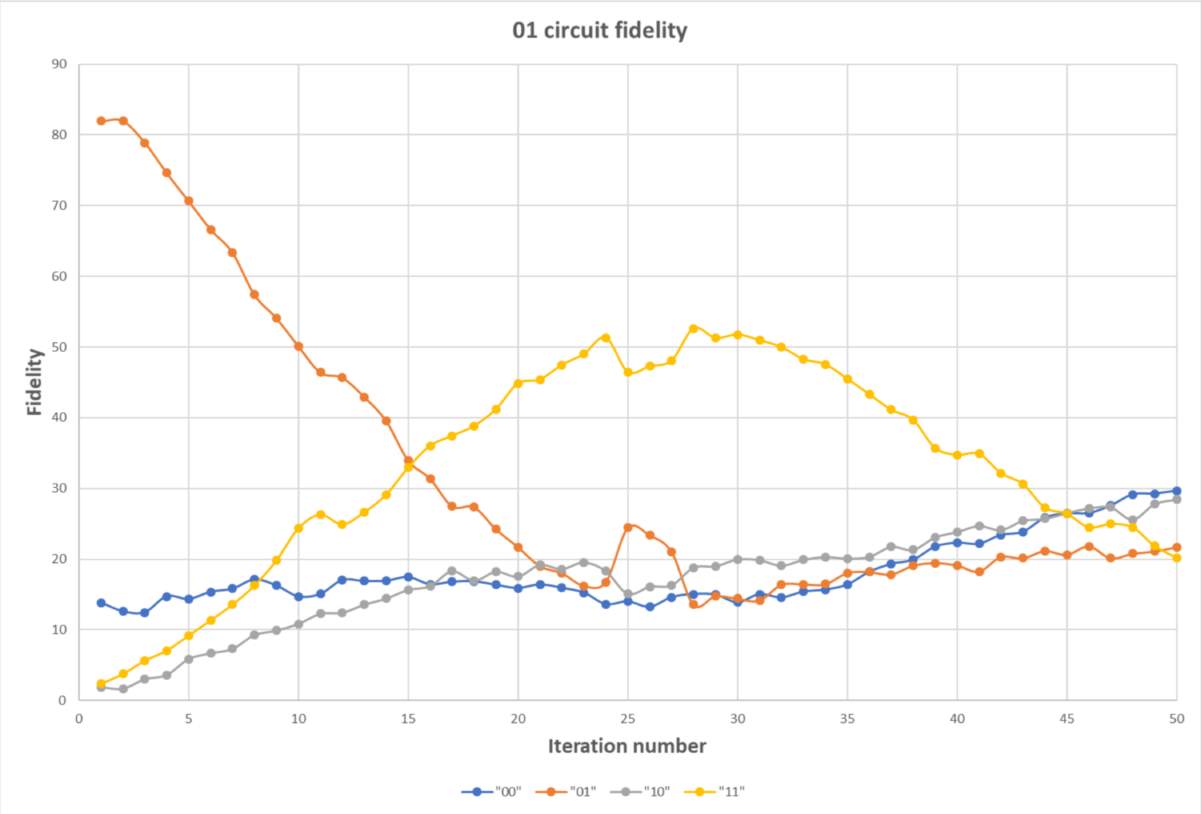


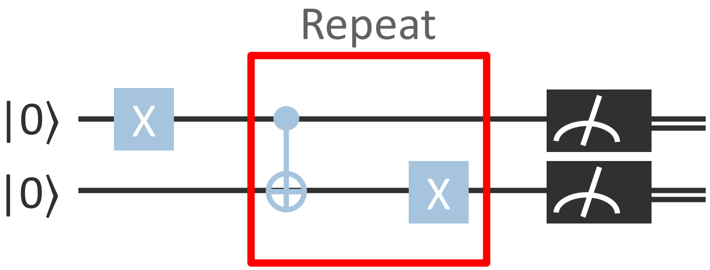
Device: ibmqx5
Shots: 5,000

Input |00> and Output |00>
4 gates per iteration
Correct answer after 200 gate operations

Symmetric		Rep X(q1)	Rep CNOT(q1,q2)	Rep CNOT(q2,q1)	Rep X(q2)
q1	0	1	1	0	0
q2	0	0	1	1	0

Circuit fidelity





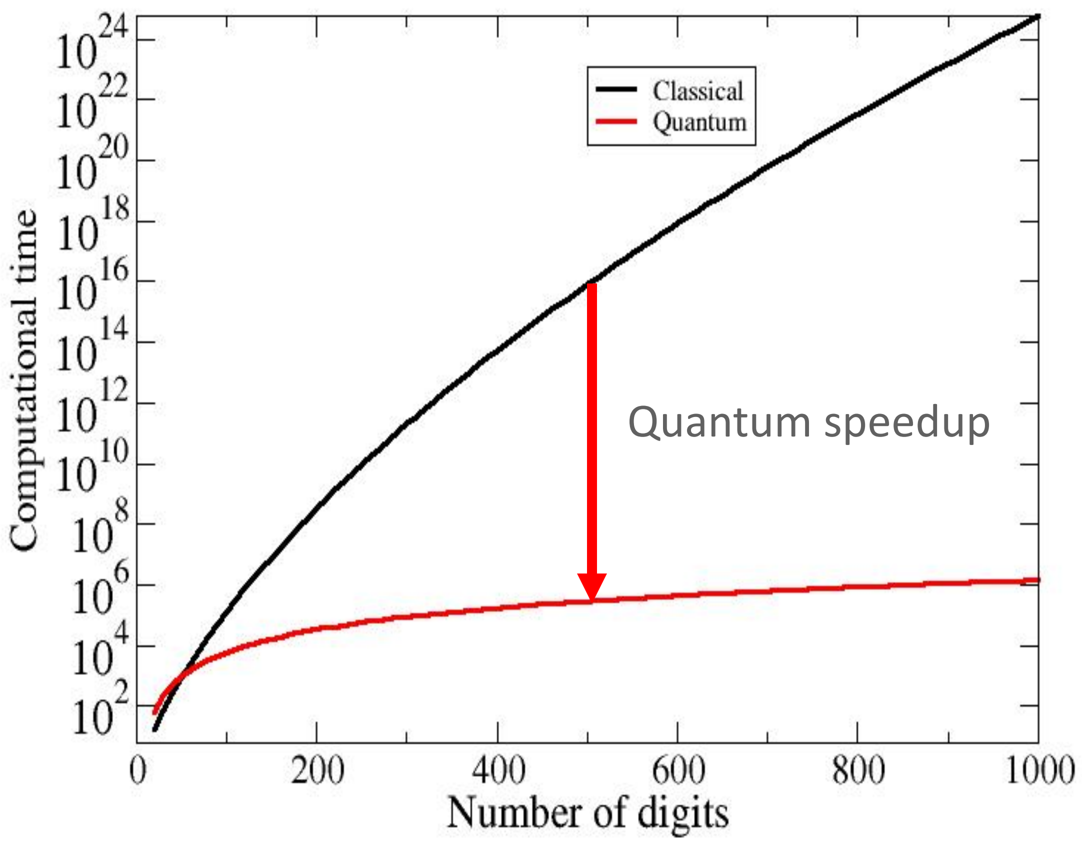
Device: ibmqx5
Shots: 5,000

Input |10> and Output |10>
2 gates per iteration
Wrong answer after 30 gate operations

Assymetric		X(q1)	Rep CNOT(q1,q2)	Rep X(q2)
q1	0	1	1	1
q2	0	0	1	0

Integer factorization

Shor's factorization algorithm: given an integer N, find its prime factors
Implications: public-key cryptography or asymmetric cryptography (RSA encryption)



Classical:

$O(e^{1.9\,(\log N)^{1/3}\,(\log \log N)^{2/3}})$

Quantum:

$O((\log N)^2(\log \log N)(\log \log \log N))$

10^4 gates for N=100

Shor, Peter W. in *Foundations of Computer Science, 1994 Proceedings., 35th Annual Symposium*, pp. 124-134. IEEE, 1994.

Largest Factored Numbers

Table 5: *Quantum factorization records*

Number	# of factors	# of qubits needed	Algorithm	Year implemented	Implemented without prior knowledge of solution
15	2	8	Shor	2001 [2]	×
	2	8	Shor	2007 [3]	×
	2	8	Shor	2007 [3]	×
	2	8	Shor	2009 [5]	×
	2	8	Shor	2012 [6]	×
21	2	10	Shor	2012 [7]	×
143	2	4	minimization	2012 [1]	✓
56153	2	4	minimization	2012 [1]	✓
291311	2	6	minimization	not yet	✓
175	3	3	minimization	not yet	✓

To break RSA 2048 bit key you need 4,096 logic qubits
The largest number to have been factorized on a conventional computer was
a 768-bit number, and it took more than two years of many hundreds of CPUs to do so

Database search

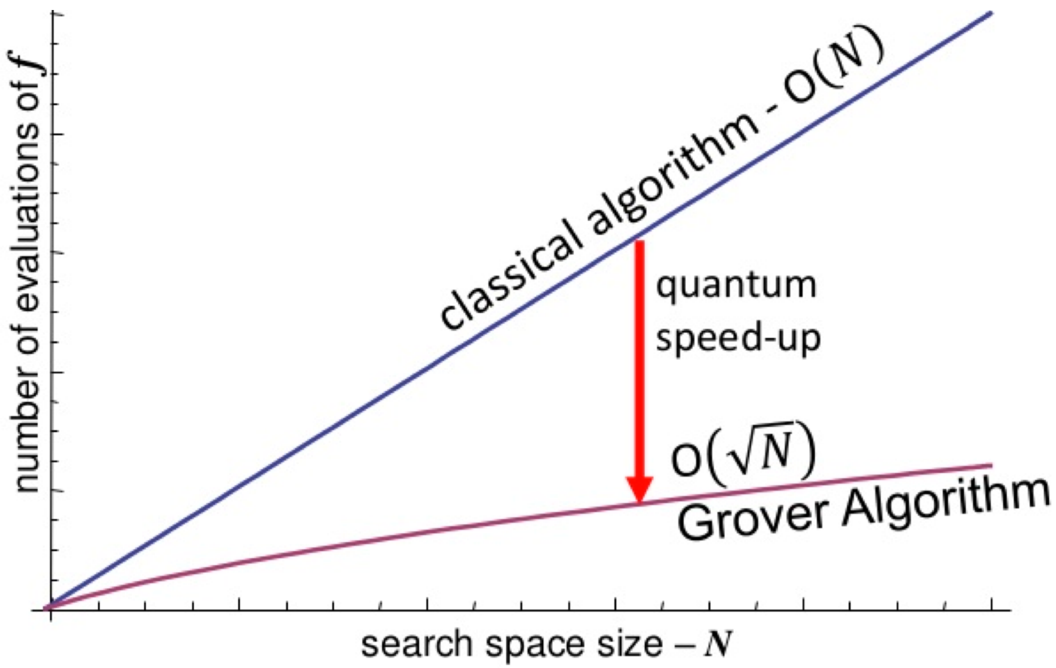
Grover's algorithm: searches in an unsorted database with N entries for a specified entry
Implications: cryptographic hashing
Requirements: millions of qubits

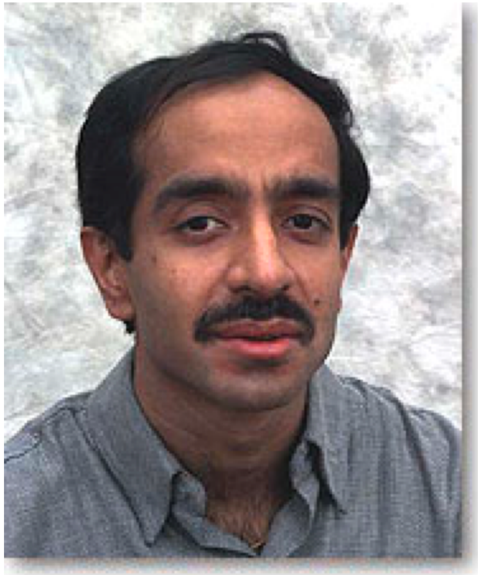
Classical:

$O(N)$

Quantum:

$O(\sqrt{N})$





Grover L.K. Proceedings, 28th Annual ACM Symposium on the Theory of Computing, (May 1996) p. 212

Solving linear systems of equations

- Solve linear systems Ax=b in log(N) time
  Harrow, Aram W., Avinatan Hassidim, and Seth Lloyd,
  PRL, 103, no. 15 (2009): 150502
- The algorithm estimates the result of a scalar measurement on the solution vector to a given linear system of equations
- Classical: $O(N_k)$
- Quantum: $O(\log(N)k^2)$
- Time evolution using the matrix A need to be implemented efficiently

$$e^{-iAt}|b>$$

- Exponential speedup for certain problems, but requires millions of qubits and 10^{29} gate operations (trillions of years)