Grover algorithm implementation on IBM quantum computer

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Quantum Computing for High Energy Physics workshop

5 Nov 2018, 08:30 → 6 Nov 2018, 18:50 Europe/Zurich

500-1-001 - Main Auditorium (CERN)

Federico Carminati (CERN)

Description

Motivations and Objectives

The ambitious upgrade programme for CERN's Large Hadron Collider (LHC) will result in significant challenges related to information and communications technologies (ICTs) over the next decade and beyond. It is therefore vital that we — members of the high-energy physics (HEP) research community and beyond — keep looking for innovative technologies, so as to ensure that we can continue to maximise the discovery potential of the world-leading research infrastructures at our disposal. Technologies related to quantum computing hold the promise of substantially speeding up computationally expensive tasks.

While significant developments are being made in the field of quantum computing, today's hardware has not yet reached the level at which it could be put into production within our community. Both established computing vendors and start-up companies are carrying out important activity in this field. Nevertheless, it remains difficult to foresee when more stable hardware — capable of providing concrete benefits for the HEP community — will be available.

Given both the potential and the uncertainty surrounding quantum computing, it is important to explore what these new technologies could bring to our field. It is also incumbent upon us to improve our understanding of which of our activities could most benefit from quantum-computing algorithms, as well as working to understand what the overall impact on the computing models used within HEP are likely to be. A large part of this work can be carried out today using on quantum simulators.

To ensure this activity is a success, it is vital that that we bring the whole community together, fostering common activities and knowledge sharing. CERN openlab is therefore capitalising on its deep connections with the HEP community and its well-established links across many of the world's leading ICT companies to set up this kick-off workshop. As well as providing a forum for sharing knowledge and ideas, the event will serve to provide an overview of the current state of quantum-computing technologies and will help us all to understand which activities within the HEP community most well suited to the application of such technologies.

Webcast

There is a live webcast for this event Watch

Videoconference Rooms

Quantum_Computing_for_High_Energy_Physics Join

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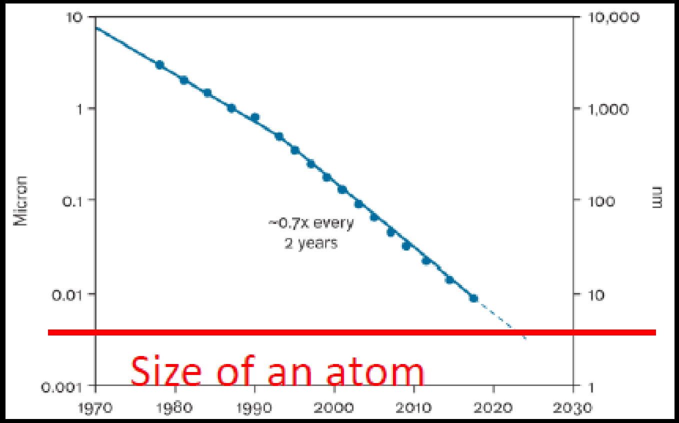
Quantum Computing ?

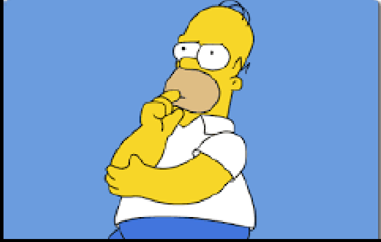


"Nature is quantum, goddamn it! So if we want to simulate it, we need a quantum computer."
R.Feynman, 1981, Endicott House, MIT

Is Quantum Computing a natural consequence of Moore's law?

- Short distance -> High Energy Physics
- Long distance -> Cosmology
- Entanglement (i.e. complexity) -> Quantum Information Technology
- QC makes the "hardness" of a problem dependent on the physical apparatus used

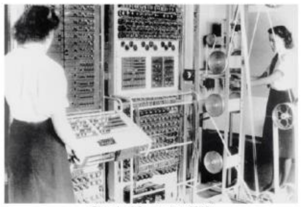
Just for the skeptical



- I think there can be a world market for maybe five computers. (Thomas Watson, CEO of IBM, 1943)
- There is no reason for an individual to have a computer at home . (Ken Olsen , president, director and founder of Digital Equipment Corp., 1977)
- I think that this thing that Tim (Berners-Lee) has shown me has no future (F.Carminati, 1989)

Basics of Quantum Computing

The Quantum World



Classical Computer, 1940s

Quantum Computer, 2010s

classical computer

is in a **deterministic state** at any time
defined by all bits of the computer

n bits → 2^n possible states, one at a time

quantum computer

uses **qubits** to take advantage of quantum speedup
superposition of states possible
„all states at the same time"

50 qubits → 10^{15} states simultaneously available

e.g. $|\psi\rangle = a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + \cdots$

qubits

$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

superposition

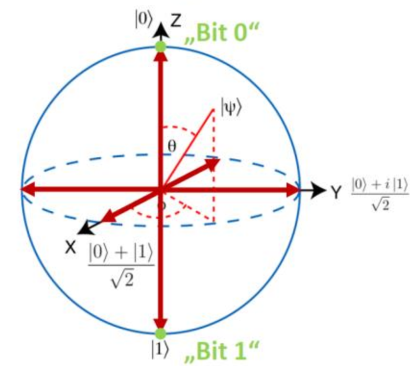
$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ $|\alpha|^2 + |\beta|^2 = 1$

z.B.

$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$

$|\circlearrowright\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)$ $|\circlearrowleft\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$

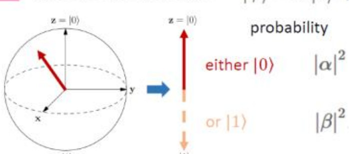
Bloch sphere



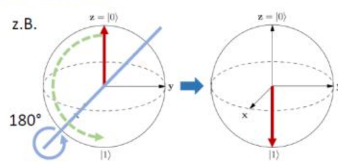
IBM Quantum Experience - quantumexperience.ng.bluemix.net/

measurement and quantum gates

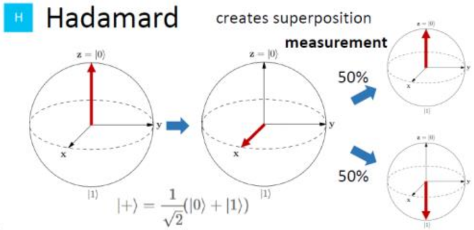
measurement $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



X Z Y rotations

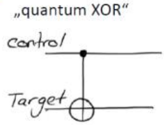


H Hadamard creates superposition



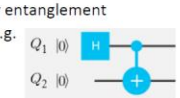
controlled-NOT

„quantum XOR"



for entanglement

e.g.



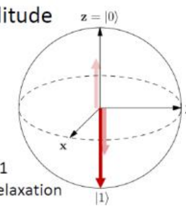
$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

→ no classical equivalent exists

decoherence

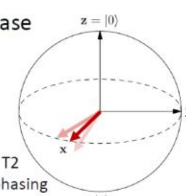
loss of quantum information

amplitude

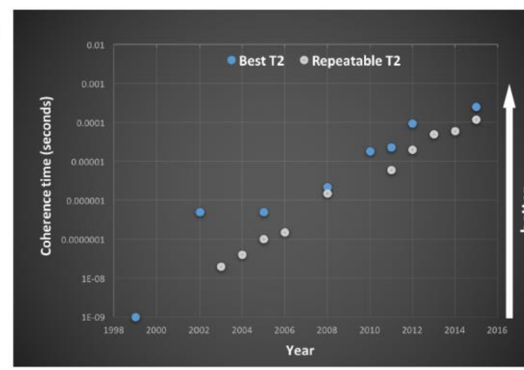


T1
energy relaxation

phase



T2
dephasing



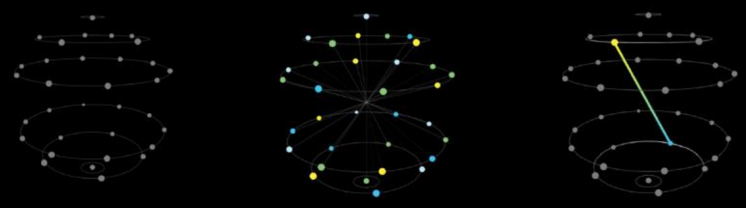
longer coherence times mean lower error rates
which allows more time to compute

IBM Quantum Experience – http://quantumexperience.ng.bluemix.net/

Quantum Algorithms

a quantum algorithm

IBM



The spread

First part of the algorithm is to make an equal superposition of all 2^n states by applying H gates

The problem

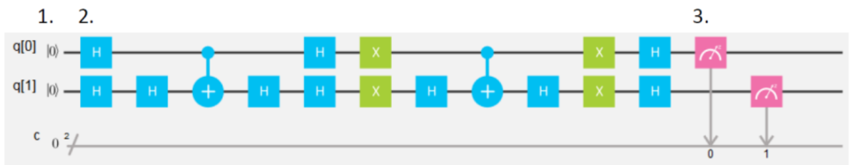
The second part is to encode the problem into this states; put phases on all 2^n states

The magic

The magic of quantum algorithms is to interfere all these states back to a few outcomes containing the solution

quantum algorithm

IBM

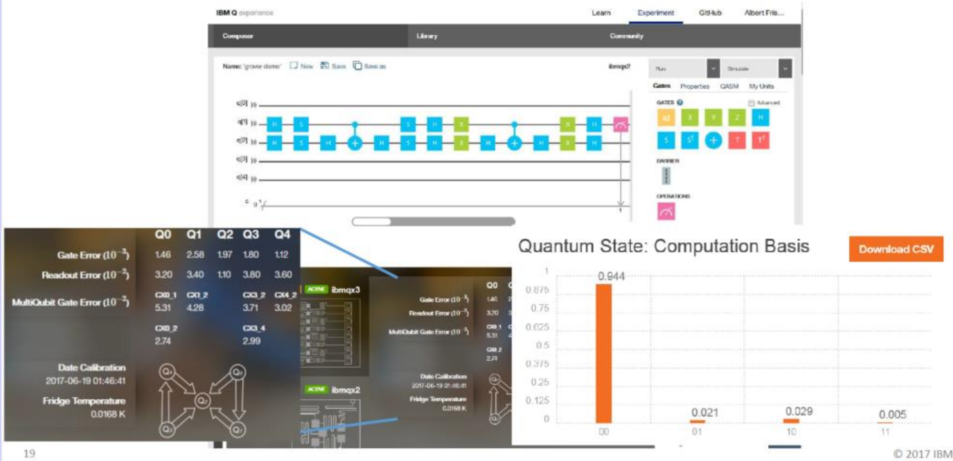


1. **initialization** of all qubits in $|0\rangle$
2. sequence of **operations** on single or multiple qubits
3. **measurement** (read-out) concludes algorithm

multiple repetitions for **statistical claims** necessary

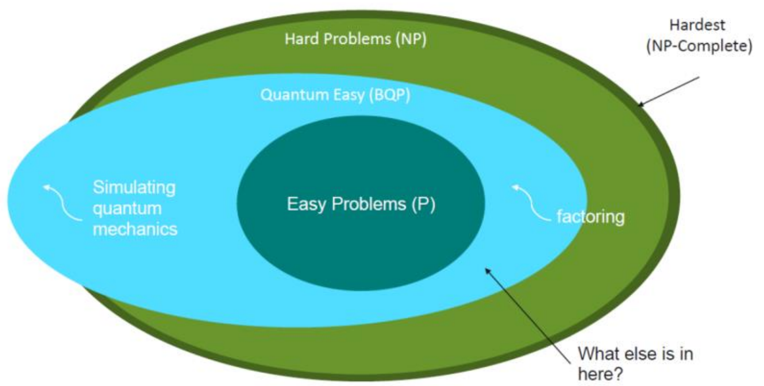
live demo 2-qubit Grover algorithm

IBM



motivation

IBM



Lev S. Bishop - https://developer.ibm.com/open/events/dw-open-tech-talk-qiskit-and-quantum-computing/

Some practical quantum algorithms

Algorithm: Factoring (1994)
Speedup: Superpolynomial
Description: Given an n-bit integer, find the prime factorization.
The quantum algorithm of Peter Shor solves this in $O(n^3)$ time. The fastest known classical algorithm for integer factorization is the general number field sieve, which runs in time $\exp(O(n^{1/3}))$
Shor's factoring algorithm breaks RSA public-key encryption and the closely related quantum algorithms for discrete logarithms break the DSA and ECDSA digital signature schemes and the Diffie-Hellman key-exchange protocol.

Peter Shor, MIT

Algorithm: Searching (1996)
Speedup: Polynomial
Description: We are given an oracle with N allowed inputs. For one input w ("the winner") the corresponding output is **1**, and for all other inputs the corresponding output is **0**. The task is to find w.
On a classical computer this requires $\Omega(N)$ queries. The quantum algorithm of Lov Grover achieves this using $O(N^{1/2})$ queries, which is **optimal**.

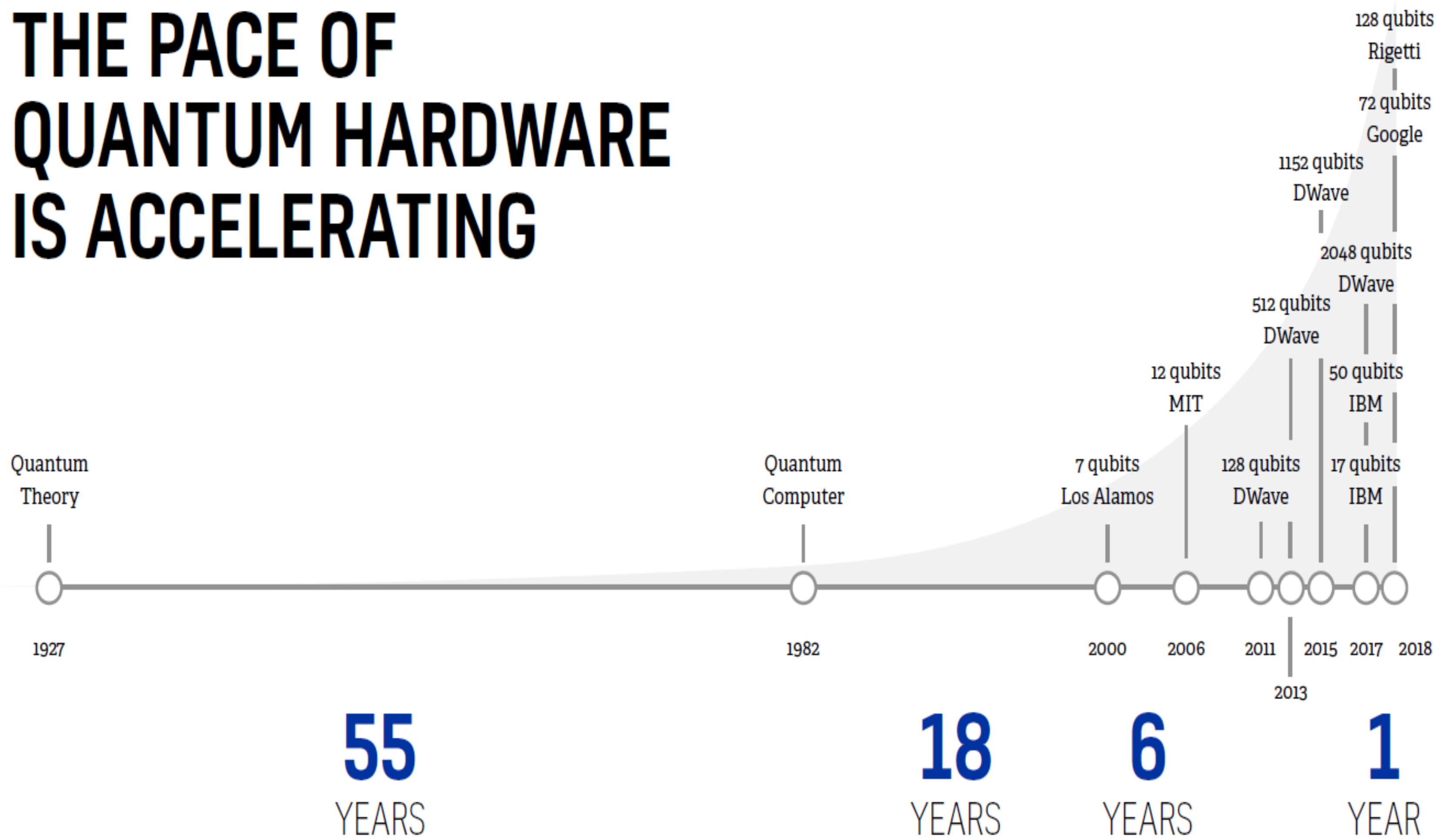
Lov Grover, Bell Labs

Algorithm: Linear Systems (2008)
Speedup: Superpolynomial
Description: We are given oracle access to an $n \times n$ matrix A and some description of a vector b. We wish to find some property of $f(A)b$ for some efficiently computable function f. Suppose A is a Hermitian matrix with $O(\text{polylog } n)$ nonzero entries in each row and condition number k. As it was shown, a quantum computer can in $O(k^2 \log n)$ time compute to polynomial precision various expectation values of operators with respect to the vector $f(A)b$ (provided that a quantum state proportional to b is efficiently constructable). For certain functions, such as $f(x)=1/x$, this procedure can be extended to non-Hermitian and even non-square A. The runtime of this algorithm was subsequently improved to $O(k \log^3 k \log n)$.

Seth LLoyd, MIT

https://math.nist.gov/quantum/zoo/

THE PACE OF QUANTUM HARDWARE IS ACCELERATING



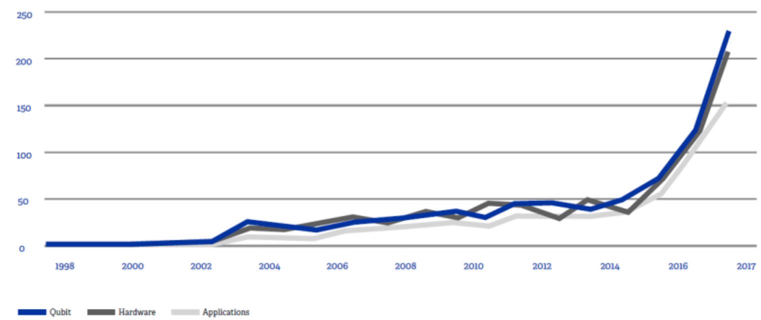
A.Ochoa (Strangeworks)

NO SMALL EFFORT 2015, €m

1,500	WORLD
550	EUROPEAN UNION*
360	UNITED STATES
220	CHINA
120	GERMANY
105	BRITAIN
100	CANADA
75	AUSTRALIA
67	SWITZERLAND
63	JAPAN
52	FRANCE
44	SINGAPORE
36	ITALY
35	AUSTRIA
30	RUSSIA
27	NETHERLANDS
25	SPAIN
22	DENMARK
15	SWEDEN
13	SOUTH KOREA
12	FINLAND
12	POLAND

*Combined estimated budget for EU countries. Source: McKinsey

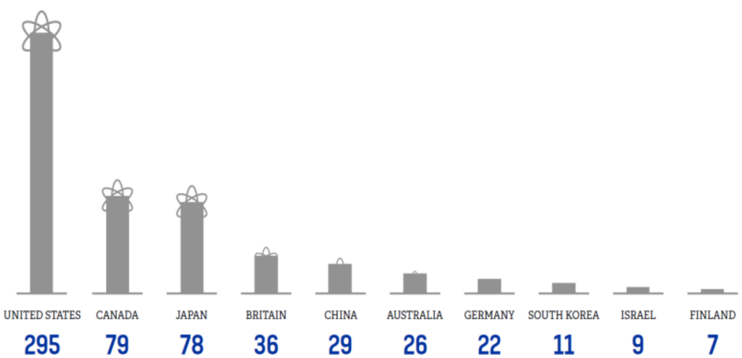
QUANTUM COMPUTING PATENT FAMILIES BY CATEGORY AND PUBLICATION YEAR



Based on 1,951 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based of DWPI with US as primary country; documents can appear in more than one category; currently 293 documents for 2017.

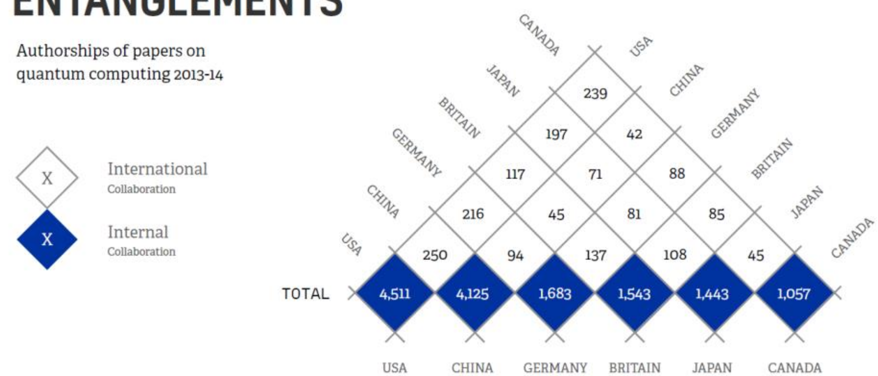
EXCITED STATES

Patent applications to 2015, in



FOREIGN ENTANGLEMENTS

Authorships of papers on quantum computing 2013-14



Source: Digital. Science; Clarivate. *Collaboration between more than two countries may be counted multiple times.

A.Ochoa (Strangeworks)

Quantum Technology – “qubit” Building Blocks

Quest for qubits

Gabriel Popkin*

Science 02 Dec 2016:
Vol. 354, Issue 6316, pp. 1090-1093
DOI: 10.1126/science.354.6316.1090

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	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	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.

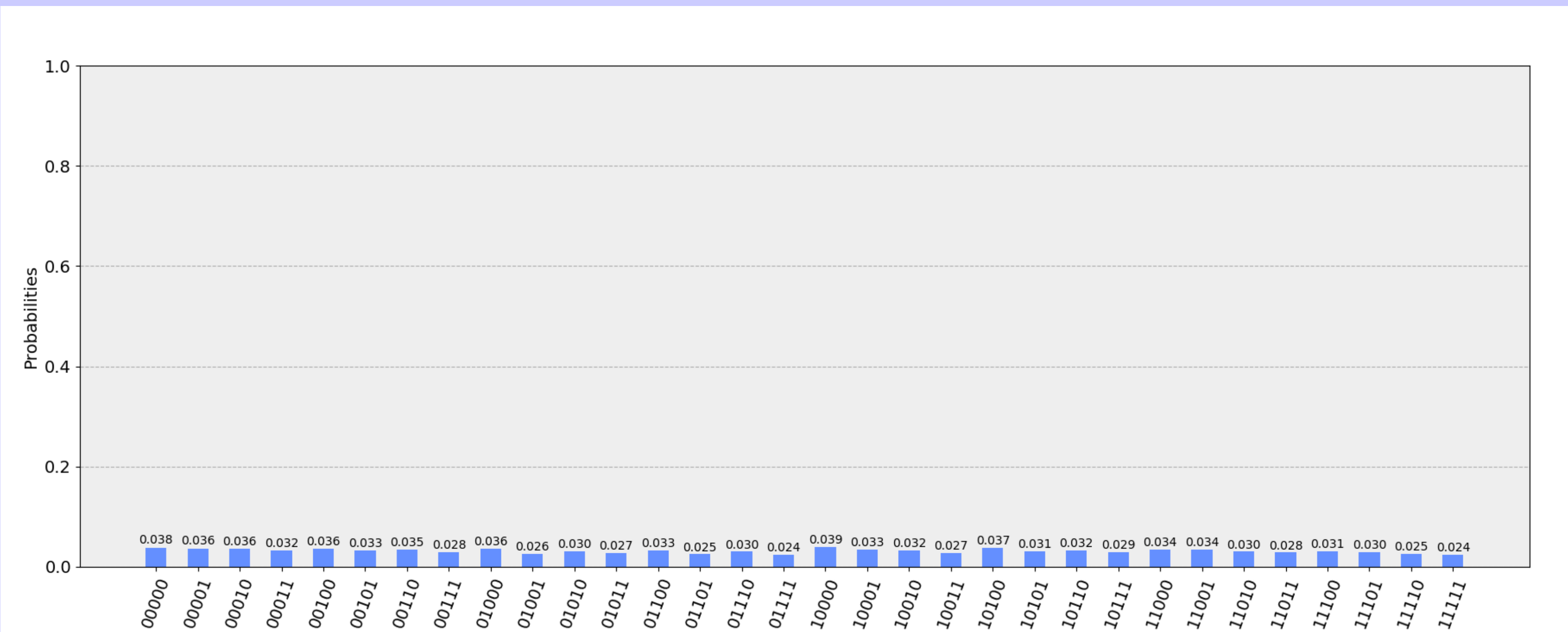
CREDITS: (GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) GABRIEL POPKIN

D-Wave The Quantum Computing Company™

Bo Ewald (D-Wave)

Equal superposition of 5-qubit states on quantum computer of IBM

$$\sum_{i_1=0}^{1}\sum_{i_2=0}^{1}\sum_{i_3=0}^{1}\sum_{i_4=0}^{1}\sum_{i_5=0}^{1}\frac{1}{4\sqrt{2}}\left|i_1\right\rangle\otimes\left|i_2\right\rangle\otimes\left|i_3\right\rangle\otimes\left|i_4\right\rangle\otimes\left|i_5\right\rangle$$



Circuit structure for Grover's algorithm

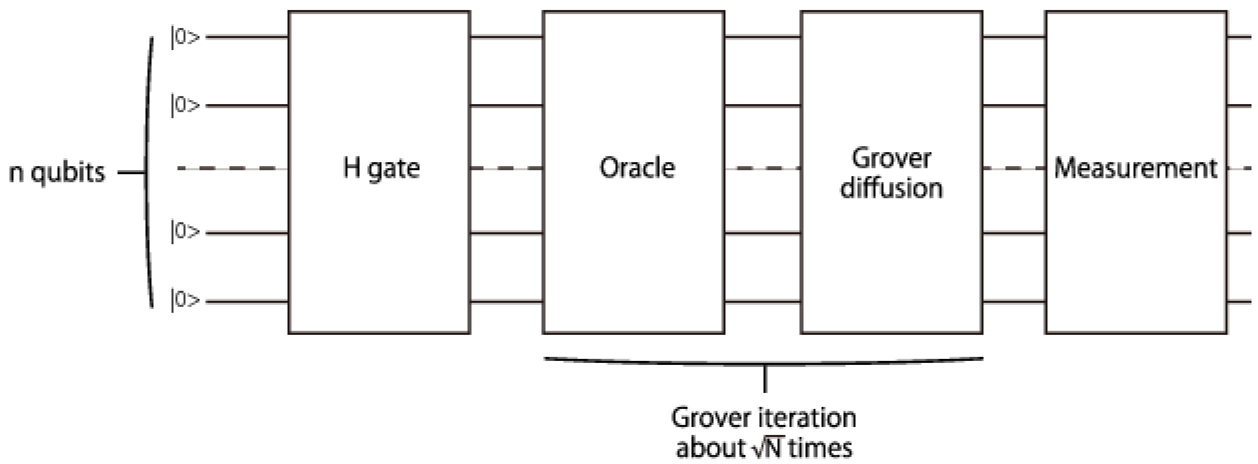
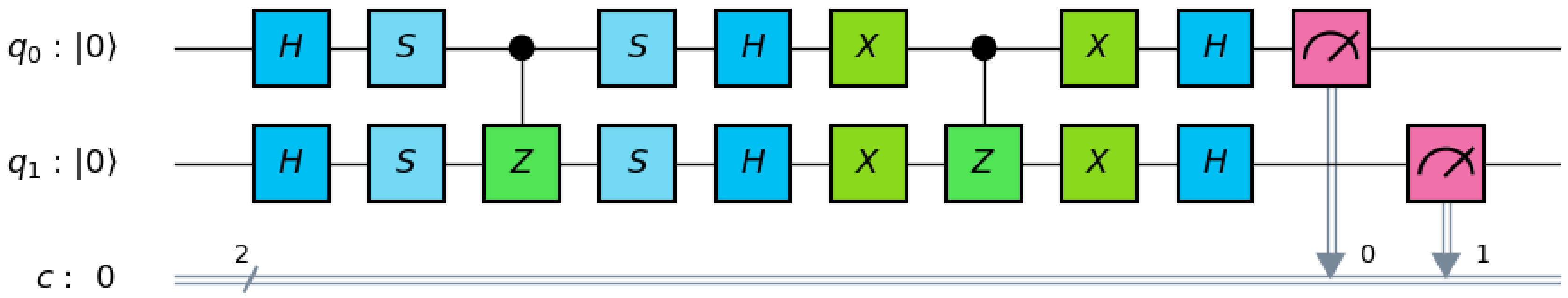


Fig. 1: Schematic circuit for the Grover's algorithm.

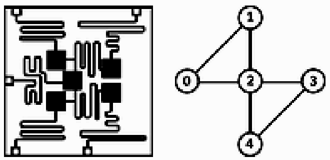
Circuit for Grover's algorithm for N=2



5-qubit quantum processors

IBM Q 5 Tenerife [ibmqx4]

[redacted]

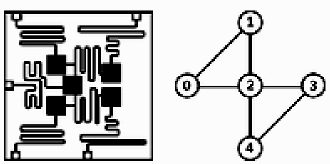


Last Calibration: 2019-04-18 12:58:33

	Q0	Q1	Q2	Q3	Q4
Frequency (GHz)	5.25	5.30	5.34	5.43	5.17
T1 (μs)	41.60	44.20	42.40	46.90	54.60
T2 (μs)	15.00	18.50	25.40	24.30	6.50
Gate error (10^{-3})	0.69	0.86	1.46	1.55	1.29
Readout error (10^{-2})	7.60	6.50	2.30	5.30	4.20
MultiQubit gate error (10^{-2})		**CX1_0** 2.35	**CX2_0** 2.89	**CX3_2** 6.43	**CX4_2** 6.73
			CX2_1 4.47	**CX3_4** 3.98	

IBM Q 5 Yorktown [ibmqx2]

[redacted]



Last Calibration: 2019-04-18 14:01:08

	Q0	Q1	Q2	Q3	Q4
Frequency (GHz)	5.29	5.24	5.03	5.30	5.08
T1 (μs)	52.30	50.80	54.50	48.50	48.30
T2 (μs)	57.80	33.60	44.40	37.50	36.80
Gate error (10^{-3})	4.81	2.40	4.12	4.72	3.26
Readout error (10^{-2})	6.30	1.80	3.20	2.30	4.10
MultiQubit gate error (10^{-2})	**CX0_1** 7.12	**CX1_2** 4.75		**CX3_2** 6.43	**CX4_2** 4.43
	CX0_2 6.70			**CX3_4** 5.26	

2-qubit Grover search