SUNG KYUN KWAN UNIVERSITY(SKKU)

2021. 12. 27.

KIAS-겨울학교

양자컴퓨터 살펴보기

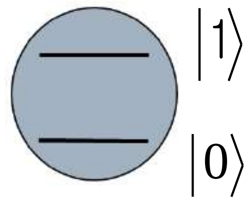
정연욱 성균관대학교

양자컴퓨터

양자컴퓨터에서 사용하는 양자역학 현상

큐비트 (Qubit)

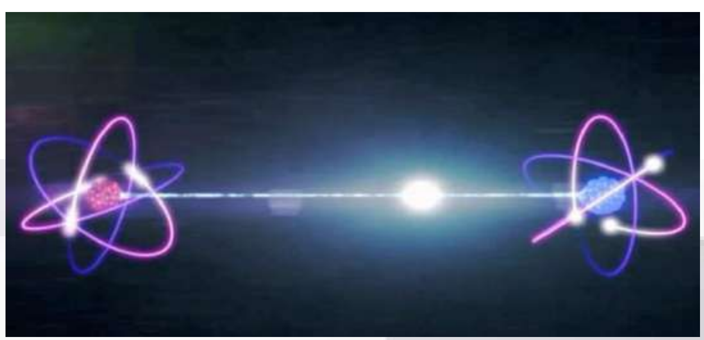
중첩 (superposition)

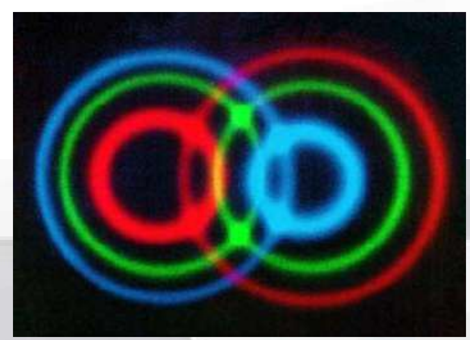


$$\alpha|0\rangle + \beta|1\rangle$$

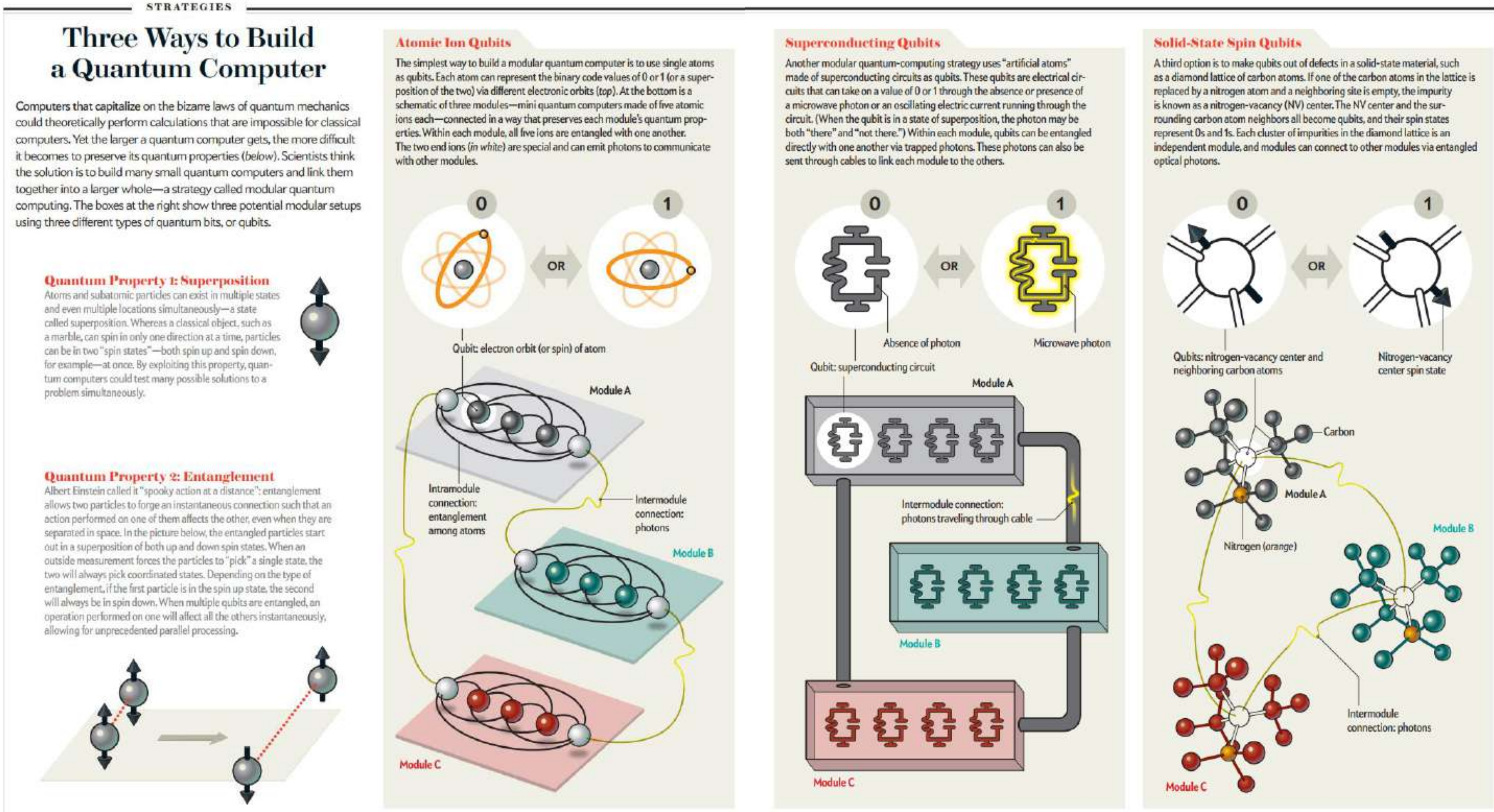
얽힘 (entanglement)

$$|00\rangle + |11\rangle$$





물리적으로 큐비트를 구현하는 방법들 (Qubit Candidates)



Three Ways to Build a Quantum Computer

Computers that capitalize on the bizarre laws of quantum mechanics could theoretically perform calculations that are impossible for classical computers. Yet the larger a quantum computer gets, the more difficult it becomes to preserve its quantum properties (*below*). Scientists think the solution is to build many small quantum computers and link them together into a larger whole—a strategy called modular quantum computing. The boxes at the right show three potential modular setups using three different types of quantum bits, or qubits.

Quantum Property 1: Superposition

Atoms and subatomic particles can exist in multiple states and even multiple locations simultaneously—a state called superposition. Whereas a classical object, such as a marble, can spin in only one direction at a time, particles can be in two "spin states"—both spin up and spin down, for example—at once. By exploiting this property, quantum computers could test many possible solutions to a problem simultaneously.

Quantum Property 2: Entanglement

Albert Einstein called it "spooky action at a distance": entanglement allows two particles to forge an instantaneous connection such that an action performed on one of them affects the other, even when they are separated in space. In the picture below, the entangled particles start out in a superposition of both up and down spin states. When an outside measurement forces the particles to "pick" a single state, the two will always pick coordinated states. Depending on the type of entanglement, if the first particle is in the spin up state, the second will always be in spin down. When multiple qubits are entangled, an operation performed on one will affect all the others instantaneously, allowing for unprecedented parallel processing.

Atomic Ion Qubits

The simplest way to build a modular quantum computer is to use single atoms as qubits. Each atom can represent the binary code values of 0 or 1 (or a superposition of the two) via different electronic orbits (*top*). At the bottom is a schematic of three modules—mini quantum computers made of five atomic ions each—connected in a way that preserves each module's quantum properties. Within each module, all five ions are entangled with one another. The two end ions (*in white*) are special and can emit photons to communicate with other modules.

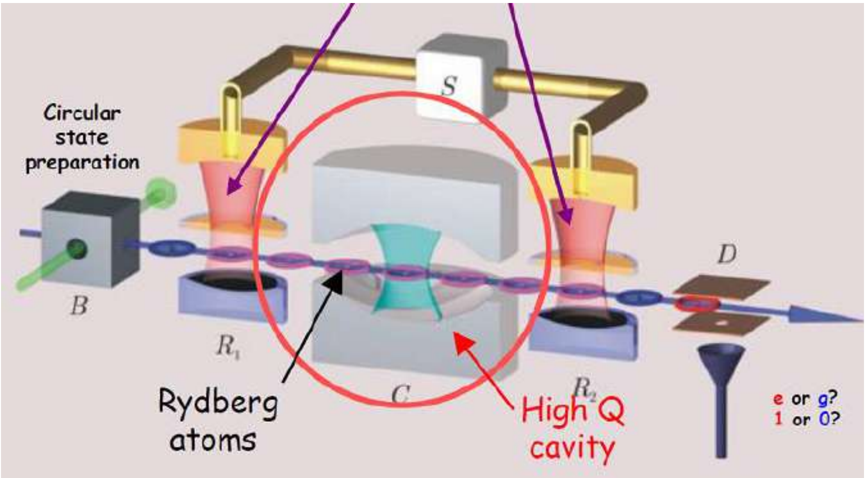
Superconducting Qubits

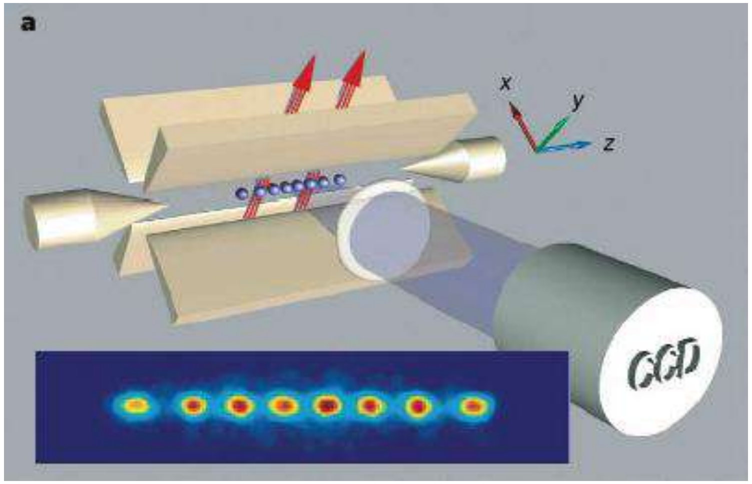
Another modular quantum-computing strategy uses "artificial atoms" made of superconducting circuits as qubits. These qubits are electrical circuits that can take on a value of 0 or 1 through the absence or presence of a microwave photon or an oscillating electric current running through the circuit. (When the qubit is in a state of superposition, the photon may be both "there" and "not there.") Within each module, qubits can be entangled directly with one another via trapped photons. These photons can also be sent through cables to link each module to the others.

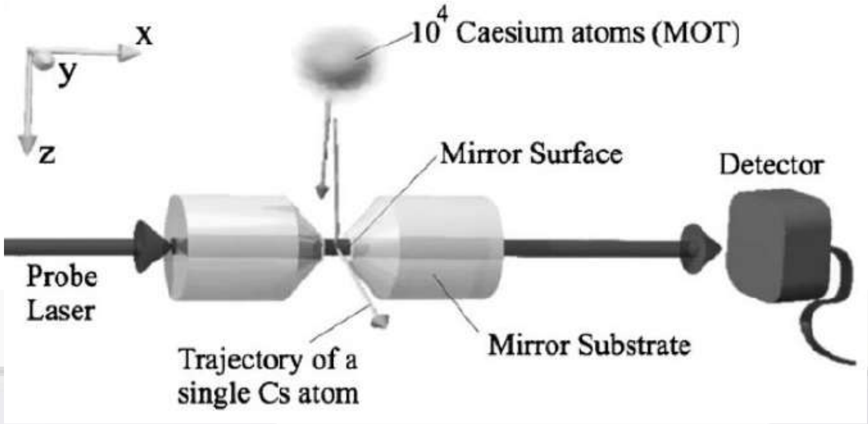
Solid-State Spin Qubits

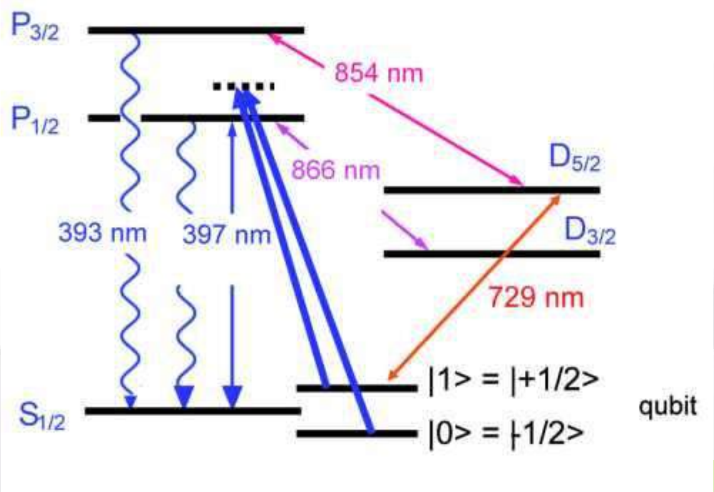
A third option is to make qubits out of defects in a solid-state material, such as a diamond lattice of carbon atoms. If one of the carbon atoms in the lattice is replaced by a nitrogen atom and a neighboring site is empty, the impurity is known as a nitrogen-vacancy (NV) center. The NV center and the surrounding carbon atom neighbors all become qubits, and their spin states represent 0s and 1s. Each cluster of impurities in the diamond lattice is an independent module, and modules can connect to other modules via entangled optical photons.

Natural Qubit : Atom(Ion) & Photon



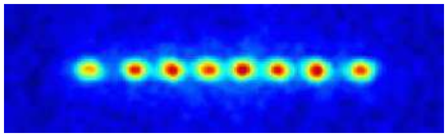




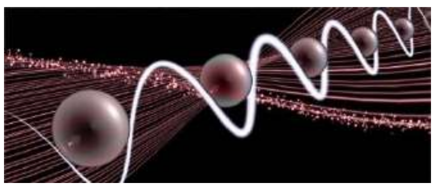


물리적으로 큐비트를 구현하는 방법들 (Qubit Candidates)

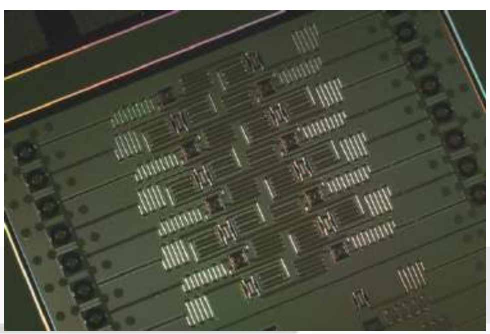
ion trap



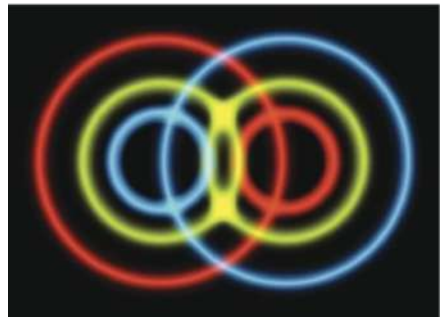
neutral atom



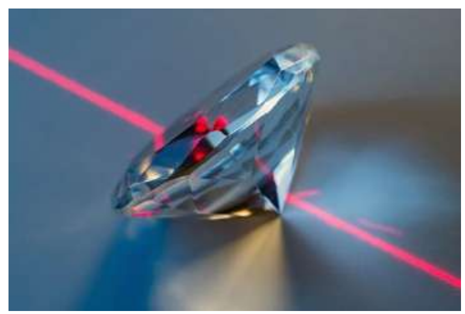
superconductor



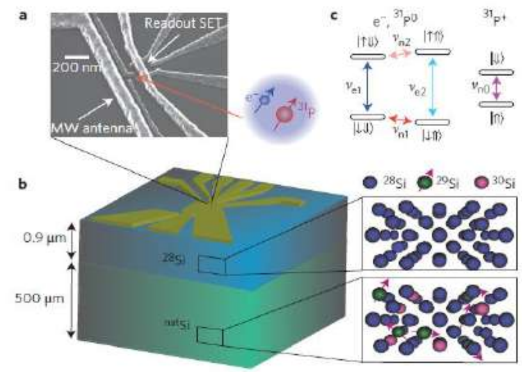
photon



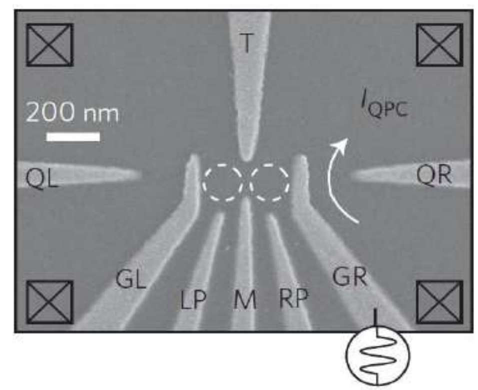
diamond defect (NV-center)



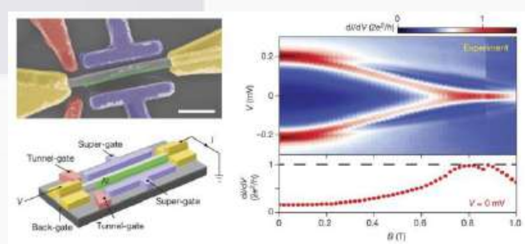
semiconductor defect



semiconductor quantum dot

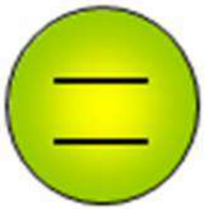


Majorana (Topological qubit)



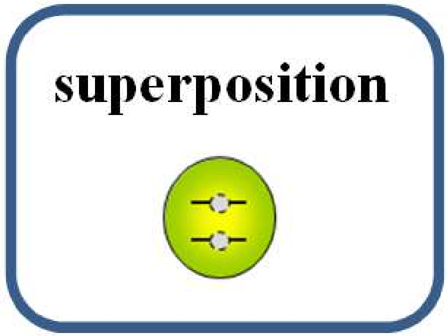
큐비트(Qubit = “Quantum Bit”)

Qubit : A quantum system with two states

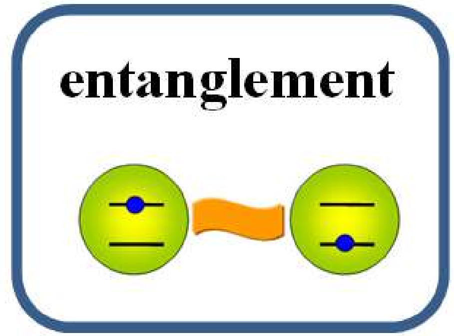


$|1\rangle$

$|0\rangle$



$$\alpha|0\rangle + \beta e^{i\phi}|1\rangle$$



$$|01\rangle - |10\rangle$$

DiVincenzo Criteria (2001)

1) A scalable physical system with well characterized qubits.
2) The ability to initialize the state of the qubits.
3) A coherence times much longer than the gate operation time.
4) A “universal” set of quantum gates
5) A qubit-specific measurement capability

양자컴퓨터의 계층구조

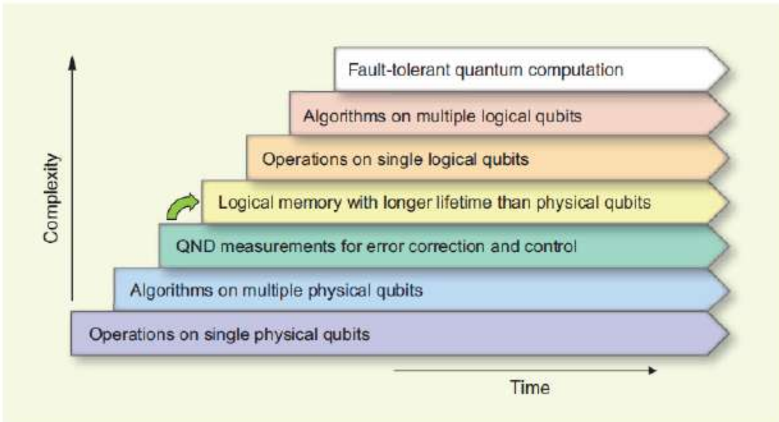


Fig. 1. Seven stages in the development of quantum information processing. Each advancement requires mastery of the preceding stages, but each also represents a continuing task that must be perfected in parallel with the others. Superconducting qubits are the only solid-state implementation at the third stage, and they now aim at reaching the fourth stage (green arrow). In the domain of atomic physics and quantum optics, the third stage had been previously attained by trapped ions and by Rydberg atoms. No implementation has yet reached the fourth stage, where a logical qubit can be stored, via error correction, for a time substantially longer than the decoherence time of its physical qubit components.

Devoret, Schoelkopf, Science 2013

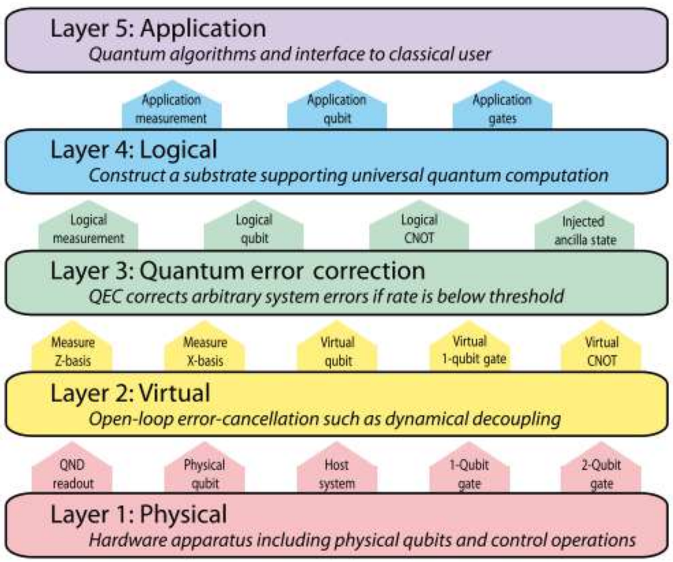
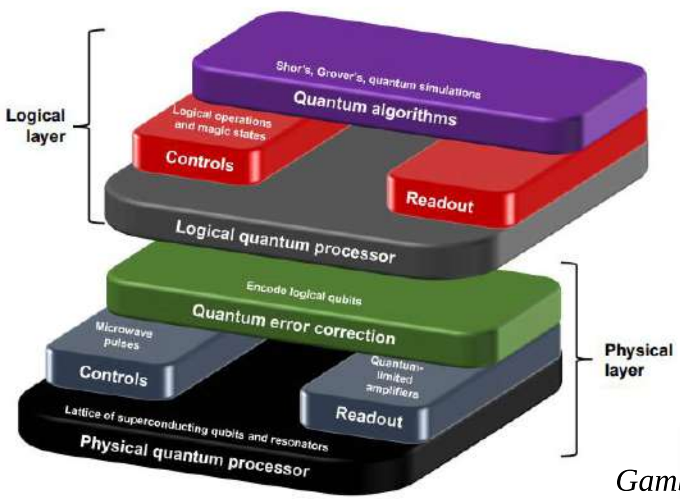


FIG. 1. Layered control stack that forms the framework of a quantum-computer architecture. Vertical arrows indicate services provided to a higher layer.

Jones, Yamamoto, PRX 2012



Gambetta, ArXiv 2015

Superconducting quantum computer system : schematic

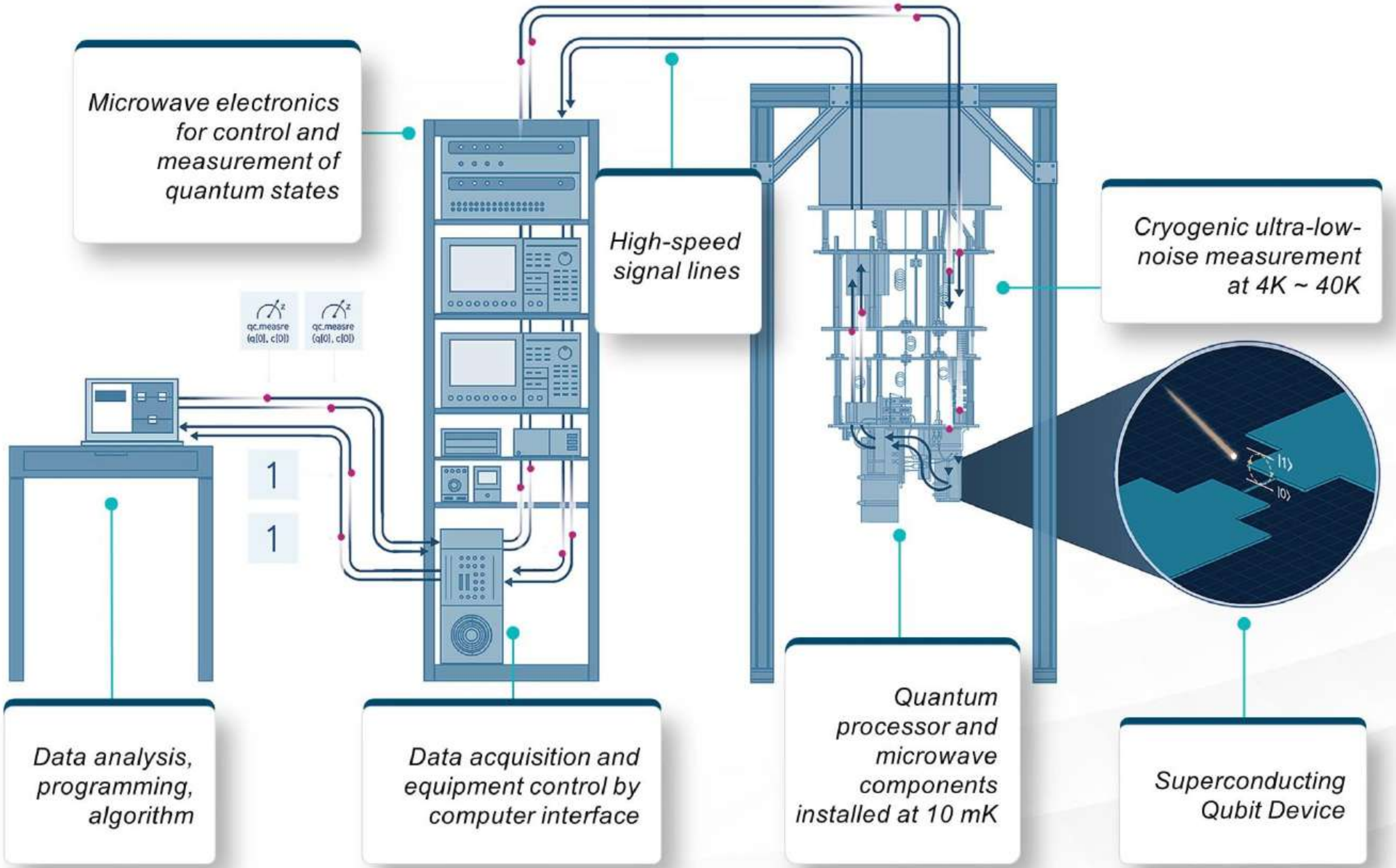
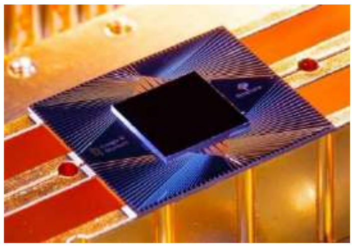


figure credit: IBM

8

양자컴퓨터는 더 이상 상상이 아니고 현실

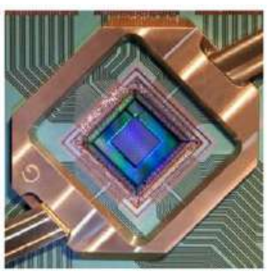
Google

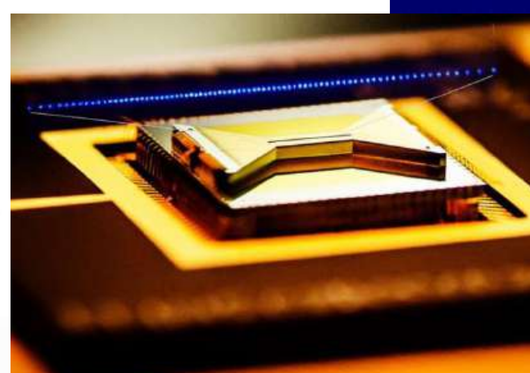


IBM

Rigetti

D-wave





IonQ

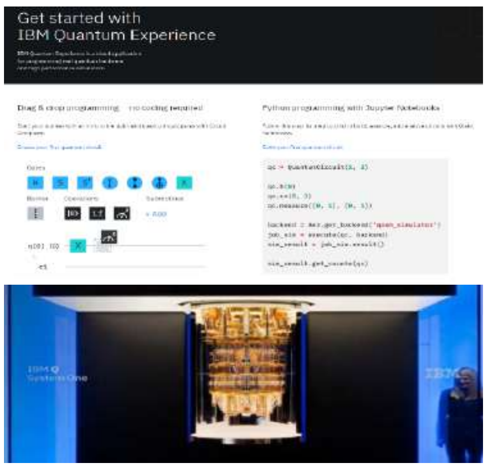
Microsoft Intel Amazon

PsiQ AQT Honeywell

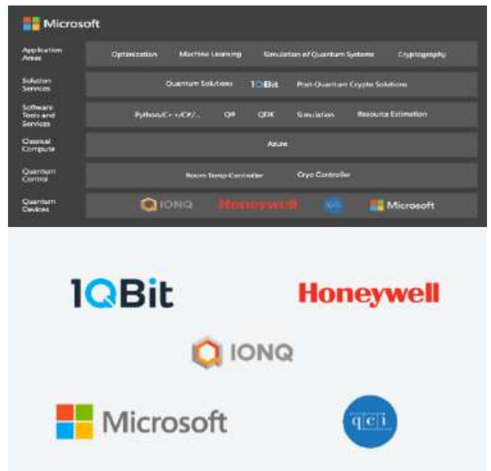
양자컴퓨터 클라우드(Quantum Cloud)

Quantum Cloud Candidates

IBM IBM Q Experience



Microsoft Azure Quantum



amazon Braket

Google

An open-source quantum framework for building and experimenting with noisy intermediate scale quantum (NISQ) algorithms on near-term quantum processors

Cirq

An open-source platform for translating problems in chemistry and materials science into quantum circuits that can be executed on existing platforms

OpenFermion

rigetti

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IONQ

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초전도 (superconducting) 큐비트의 눈부신 발전

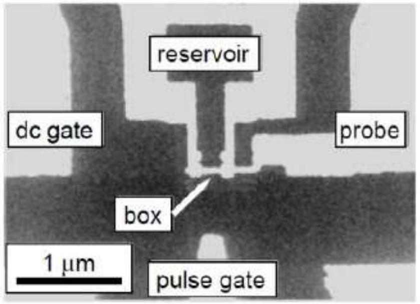
letters to nature

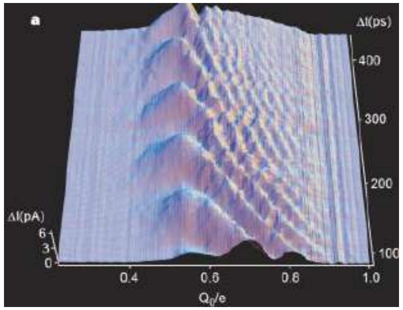
Coherent control of macroscopic quantum states in a single-Cooper-pair box

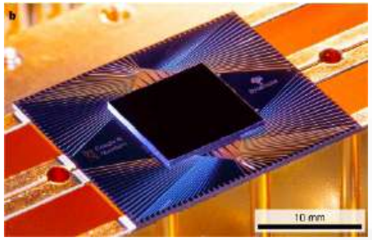
Y. Nakamura*, Yu. A. Pashkin† & J. S. Tsai*

** NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan

Nature 1999





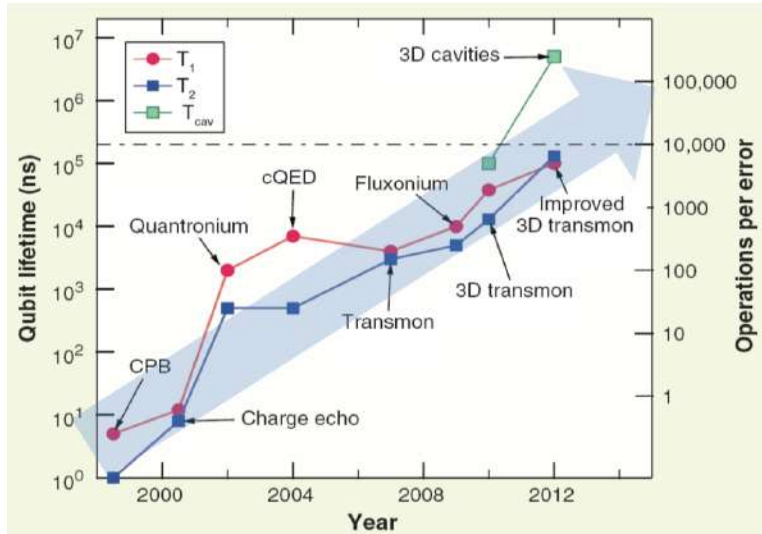


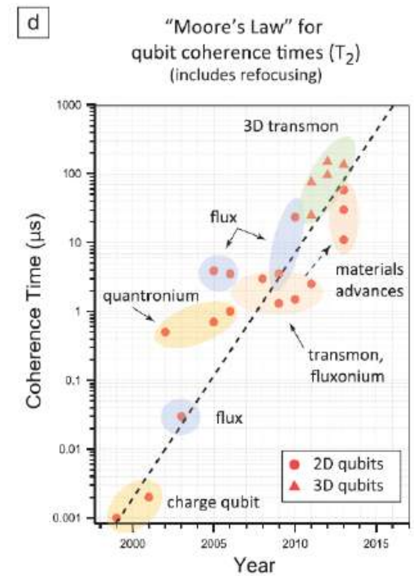
최초 1999년, NEC

2019년, Google, IBM

초전도 큐비트의 성능 향상

Schoelkopf Plot
초전도큐비트 결맞음시간
3년에 10 배씩 증가





Neven's Law
큐비트의 수는
이중지수적으로 증가


SCIENTIFIC AMERICAN.

Quantamagazine

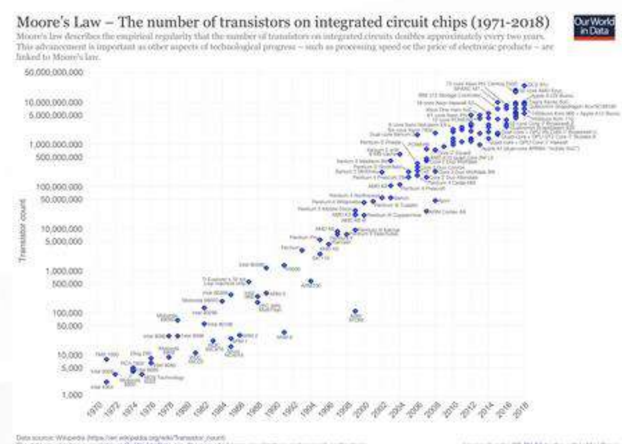
COMPUTING

A New "Law" Suggests Quantum Supremacy Could Happen This Year

Quantum computers are improving at a doubly exponential rate

$$2^{2^1}, 2^{2^2}, 2^{2^3}, 2^{2^4}$$

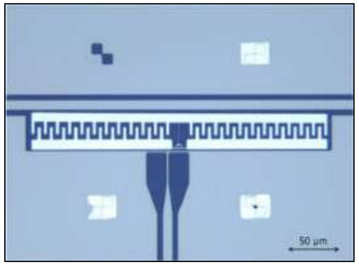
Moore's Law
반도체 집적도는
대략 2년마다
두 배씩 증가



What you need to know for superconducting qubit

↓ $k_B T << \hbar\omega$ ↑

Device Fab.



Superconducting Electronics (Josephson + Microwave)

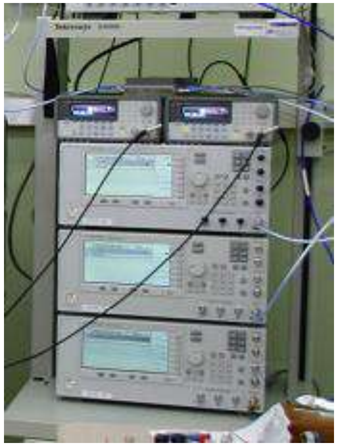
\+

Ultra-low T

Dilution Refrigerator (~10 mK)

\+

RF Meas.



Precision MW Measurement
< or @ single photon

Josephson Junction

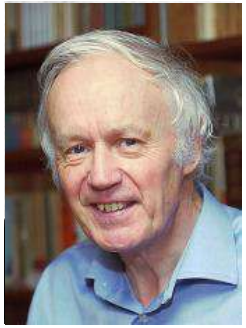
Are macroscopic degrees of freedom governed by quantum mechanics?

80 Supplement of the Progress of Theoretical Physics, No. 69, 1980

Macroscopic Quantum Systems and the Quantum Theory of Measurement

A. J. Leggett

School of Mathematical and Physical Sciences
University of Sussex, Brighton BN1 9QH



Nobel Prize 2003

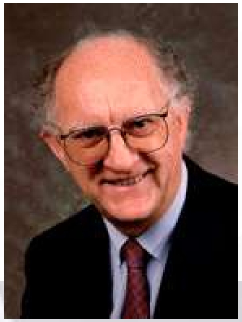
Quantum Mechanics of a Macroscopic Variable: The Phase Difference of a Josephson Junction

John Clarke, Andrew N. Cleland, Michel H. Devoret, Daniel Esteve, John M. Martinis

Experiments to investigate the quantum behavior of a macroscopic degree of freedom, namely the phase difference across a Josephson tunnel junction, are described. The experiments involve measurements of the escape rate of the junction from its zero voltage state. Low temperature measurements of the escape rate for junctions that are either nearly undamped or moderately damped agree very closely with predictions for macroscopic quantum tunneling, with no adjustable parameters. Microwave spectroscopy reveals quantized energy levels in the potential well of the junction in excellent agreement with quantum-mechanical calculations. The system can be regarded as a "macroscopic nucleus with wires."

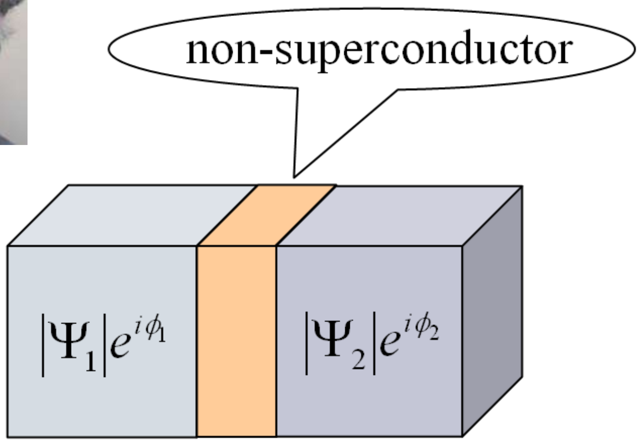
emphasized, one must distinguish carefully between macroscopic quantum phenomena originating in the superposition of a large number of microscopic variables and those displayed by a single macroscopic degree of freedom. It is the latter that we discuss in this article.

Our usual observations on a billiard ball or Brownian particle reveal classical behavior because Planck's constant $\hbar$ is so tiny. However, at least in principle there is nothing to prevent us from designing an experiment in which these objects are quantum mechanical. To do so we have to satisfy two criteria: (i) the thermal energy must be small compared with the separation of the quantized energy levels, and (ii) the macroscopic degree of freedom must be sufficiently decoupled from all other degrees of freedom if the lifetime of the quantum states is to be longer than the characteristic time scale of the system (*1*). To illustrate the application of these



Science 1988

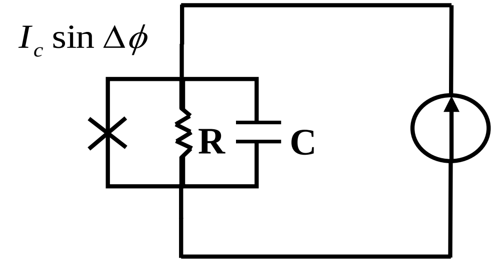
Josephson Junction



$\Rightarrow$ **Josephson Relations**

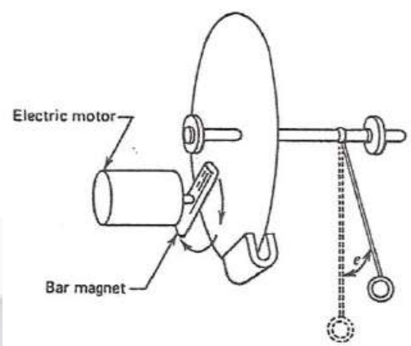
$$I = I_c \sin(\phi_1 - \phi_2)$$

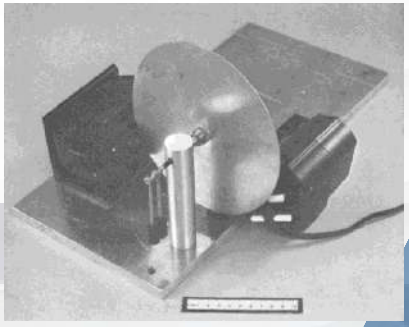
$$V(t) = \frac{\hbar}{2e}\frac{d}{dt}(\phi_1 - \phi_2)$$



$$I_{dc} = \frac{\hbar}{2e} C \frac{d^2\phi}{dt^2} + \frac{\hbar}{2e}\frac{1}{R}\frac{d\phi}{dt} + I_c \sin(\phi)$$

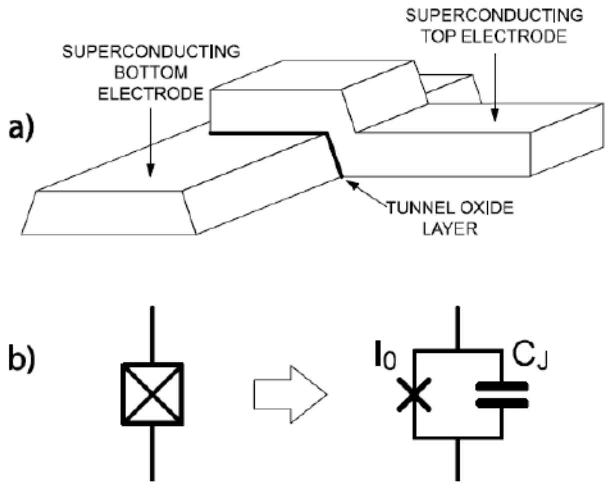
const. torque — **mass** — **damping** — **pendulum**

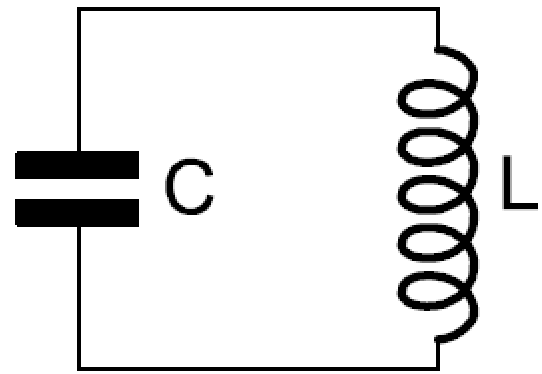




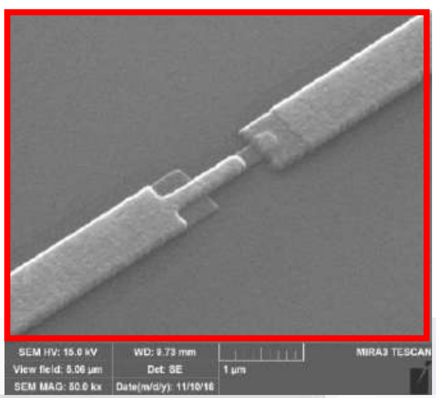
Sullivan and Zimmerman, Am. J. Phys. 39, 1504 (1971)

Josephson Junction

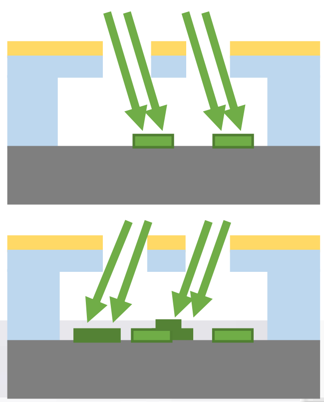




$$\omega_{LC} = \frac{1}{\sqrt{LC}}$$



Josephson junction



Two angle evaporation

Josephson Inductance

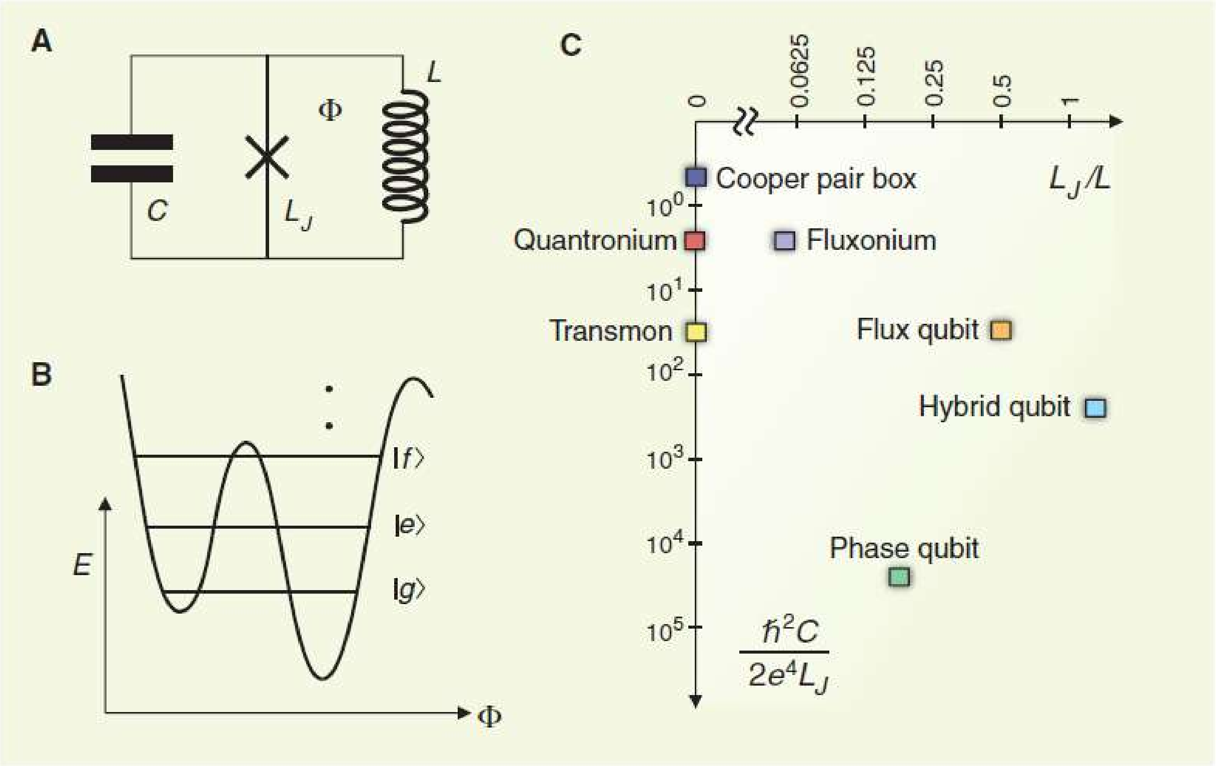
$$L_J(\delta) = \left(\frac{\partial I}{\partial \Phi}\right)^{-1} = \frac{L_{J0}}{\cos\delta}$$

Tuning of $I_c\,(E_J)$

$$E_J(\Phi_{ext}) = E_J \cos(\pi\Phi_{ext}/\Phi_0)$$

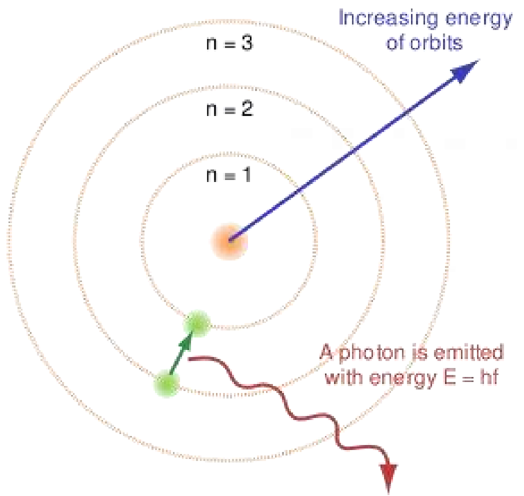
SC Qubit = "Electronic Circuit"

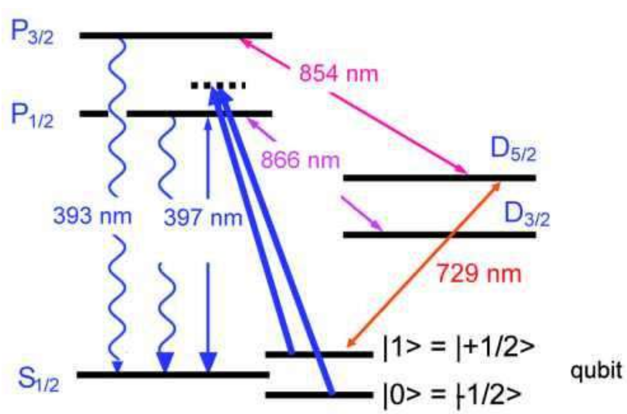
You design your Circuit = You design your Atom
= You design your Hamiltonian



Qubit with electrons? - "interact, but be isolated"

How to make an artificial Atom?



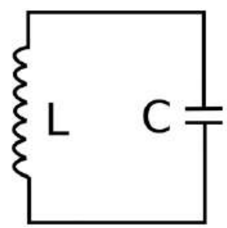


(Quantum) Harmonic Oscillator

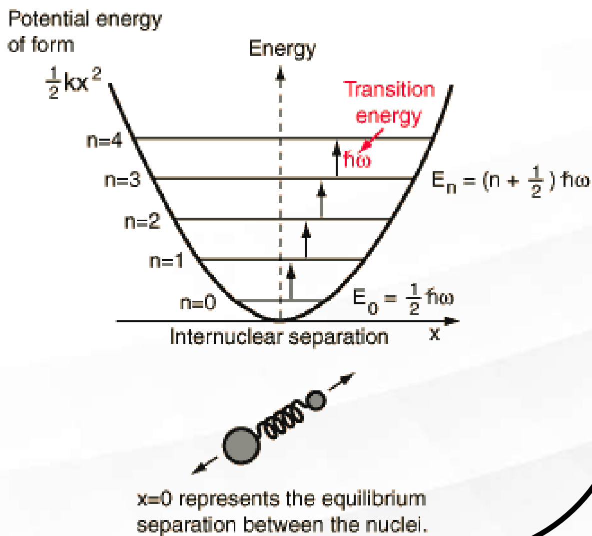
$$H = \frac{1}{2m}(\hat{p}^2) + \frac{1}{2}k(\hat{x}^2) \qquad [x, p] = i\hbar$$

$$E = \hbar\omega_{HO}(a^+ a + \frac{1}{2}) \qquad \omega_{HO} = \sqrt{\frac{k}{m}}$$

LC Oscillator



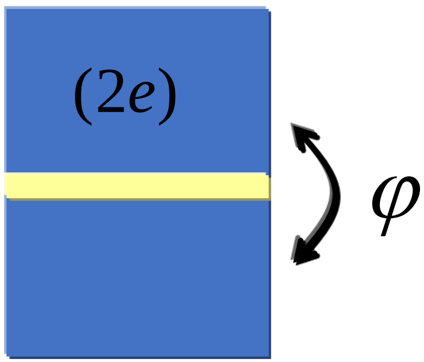
$$\omega_{LC} = \frac{1}{\sqrt{LC}}$$



→ Need Nonlinearity (Anharmonicity) for Qubit

Josephson Junction

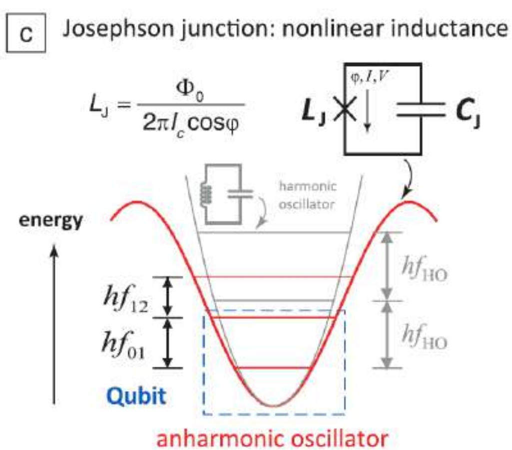
Josephson Qubit



$$E_{\text{Charge}}(n) = \frac{(2e)^2}{2C}(\hat{n})^2 = \frac{1}{2}(8E_C)(\hat{n})^2$$

$$E_{\text{Josephson}}(\varphi) = \frac{\hbar I}{2e}(1-\cos\varphi) \approx \frac{1}{2}E_J\varphi^2$$

$$E_C \equiv \frac{e^2}{2C} \qquad E_J \equiv \frac{\hbar I}{2e}$$



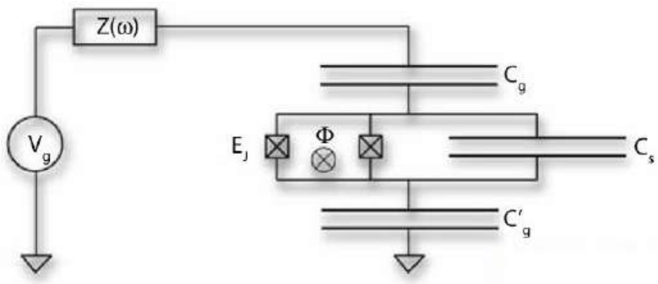
$$H = E_{\text{Charge}}(n) + E_{\text{Josephson}}(\varphi) \approx \frac{1}{2}(8E_C)(\hat{n})^2 + \frac{1}{2}E_J\varphi^2$$

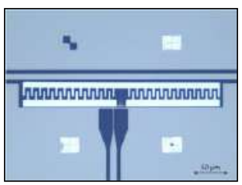
$$\Delta E \sim \sqrt{8E_C E_J} + anharmonicity$$

Low-loss Nonlinear Oscillator with 1 photon

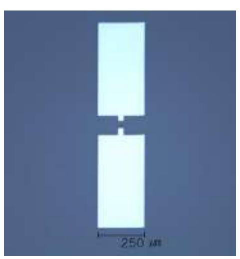
Transmon

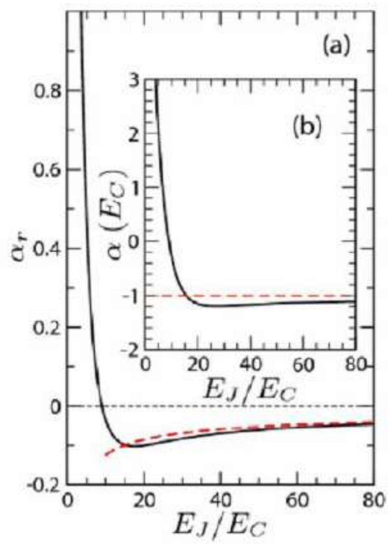
Shunted with a Capacitor

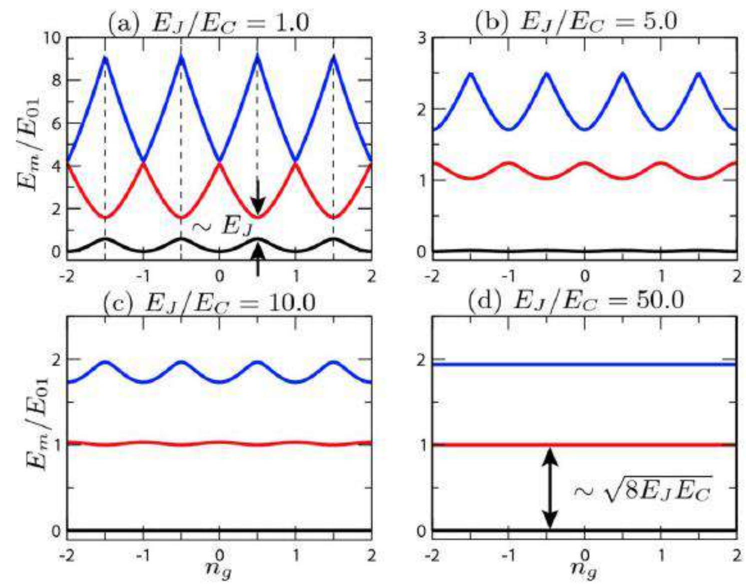




or







$$E_m \simeq -E_J + \sqrt{8E_CE_J}\left(m+\frac{1}{2}\right) - \frac{E_C}{12}(6m^2+6m+3)$$

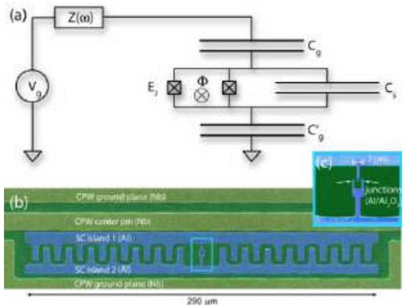
$$\alpha \equiv E_{12} - E_{01}, \quad \alpha_r \equiv \alpha/E_{01}$$

$$\alpha \simeq -E_C \qquad \alpha_r \simeq -(8E_J/E_C)^{-1/2}$$

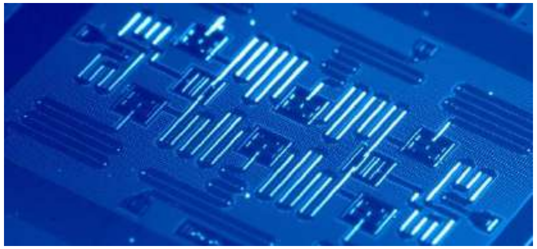
Sweet spot everywhere, by design

J. Koch, PRA 2007

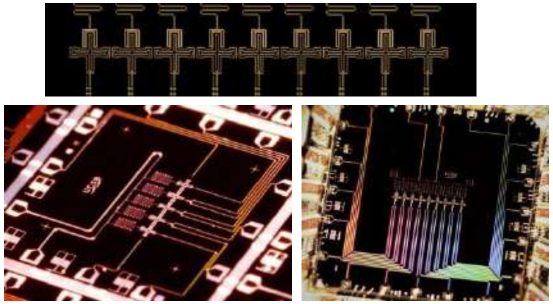
Transmon



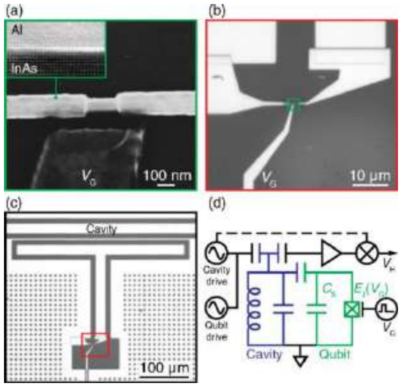
Transmon (Yale)



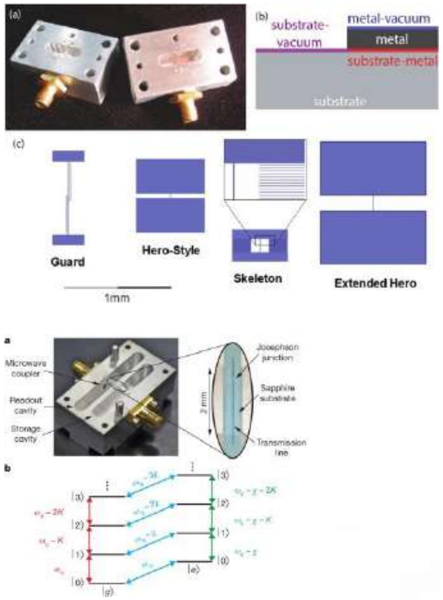
Transmon (IBM)



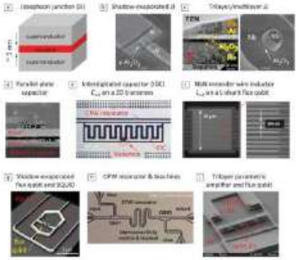
Xmon (Google-UCSB)



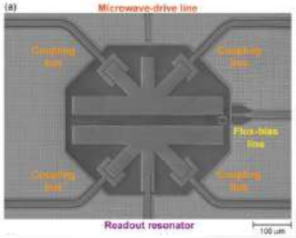
Gatemon (Niels Bohr Inst.)



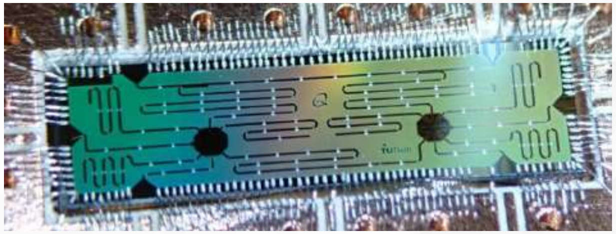
3D-transmon (Yale, IBM)

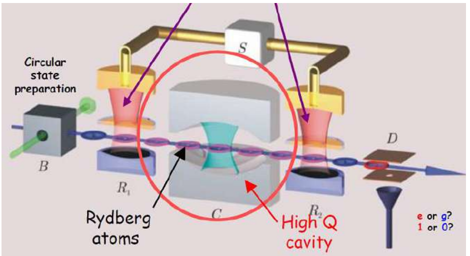


MIT-LL



Starmon (Delft-QUTech)



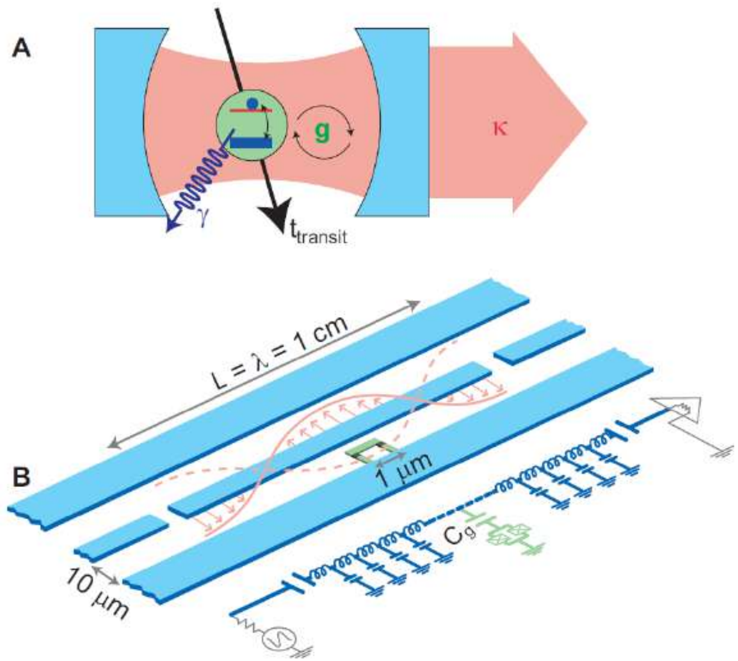


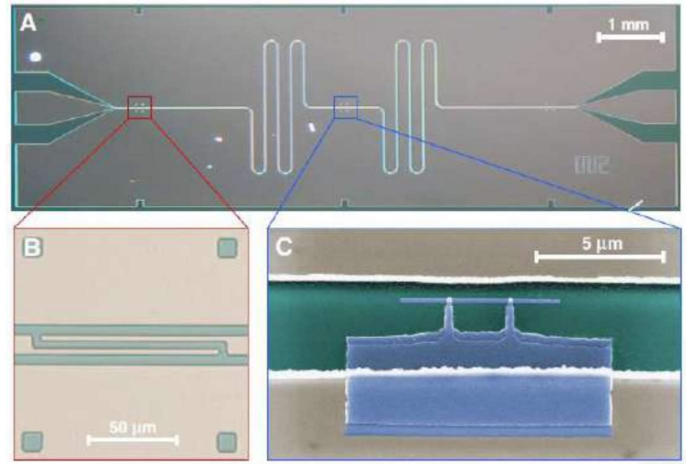
Nature 2004

Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics

A. Wallraff[1], D. I. Schuster[1], A. Blais[1], L. Frunzio[1], R.- S. Huang[1,2], J. Majer[1], S. Kumar[1], S. M. Girvin[1] & R. J. Schoelkopf[1]

[1]Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA
[2]Department of Physics, Indiana University, Bloomington, Indiana 47405, USA





***Jaynes-Cummings* Hamiltonian**

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g\left(a^\dagger\sigma^- + a\sigma^+\right) + H_\kappa + H_\gamma$$

Dispersive limit Jaynes-Cummings Hamiltonian

If qubit and cavity are well off resonance

$$\Delta \equiv \left|\omega_r - \omega_a\right| >> g \qquad \chi \equiv \frac{g^2}{\Delta} << g$$

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g\left(a^\dagger\sigma^- + a\sigma^+\right) + H_\kappa + H_\gamma$$

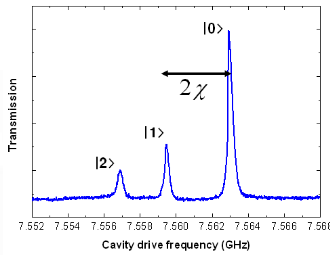
$$\Rightarrow H = \hbar\omega_r\left(a^+ a + \frac{1}{2}\right) + \hbar\omega_a\frac{\sigma_z}{2} + 2\hbar\chi\left(a^+ a + \frac{1}{2}\right)\frac{\sigma_z}{2}$$

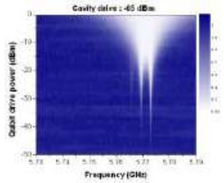
$$= \hbar\left(\omega_r + \chi\sigma_z\right)\left(a^+ a + \frac{1}{2}\right) + +\hbar\left(\omega_a + \chi\right)\frac{\sigma_z}{2}$$

qubit-state dependent cavity frequency shift

$$= \hbar\omega_r\left(a^+ a + \frac{1}{2}\right) + \hbar\left(\omega_a + 2\chi\left(a^+ a + \frac{1}{2}\right)\right)\frac{\sigma_z}{2}$$

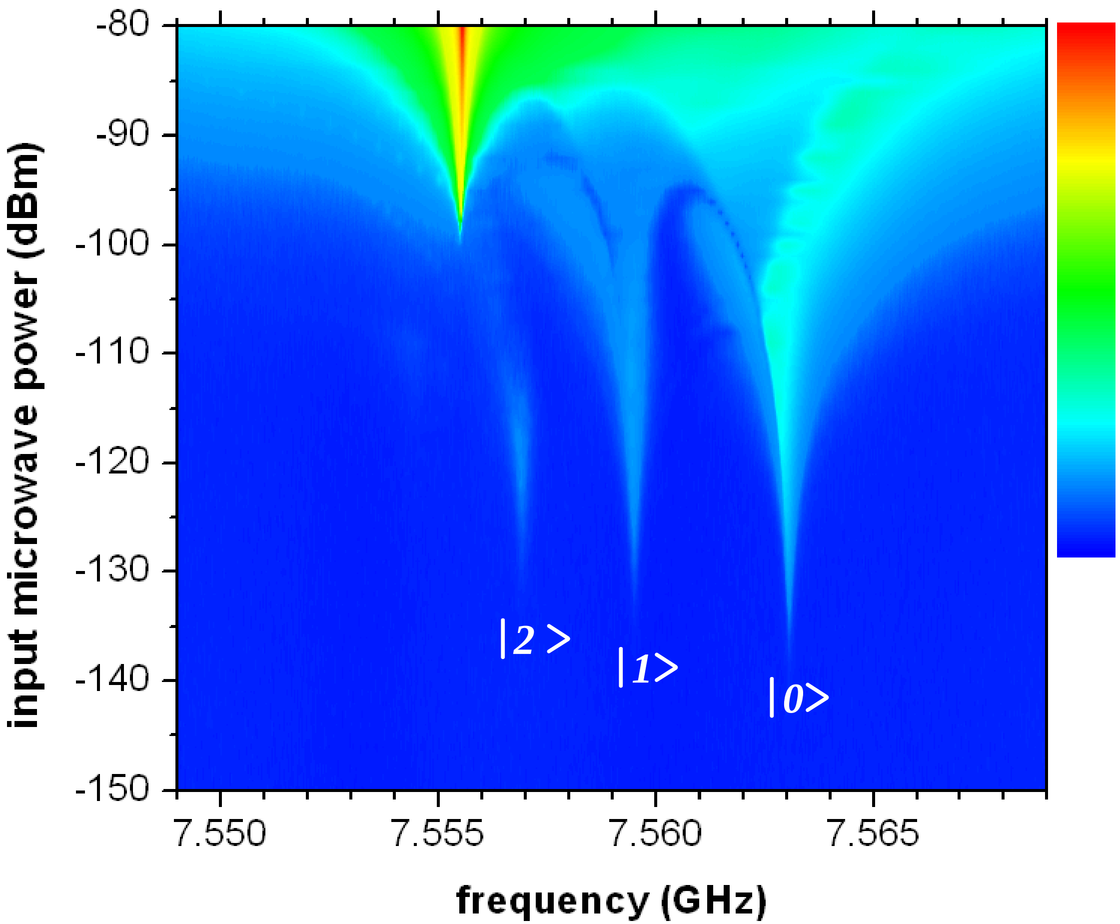
cavity photon-number dependent qubit energy shift

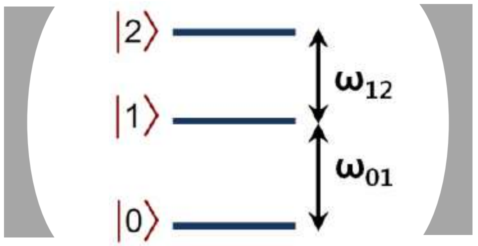


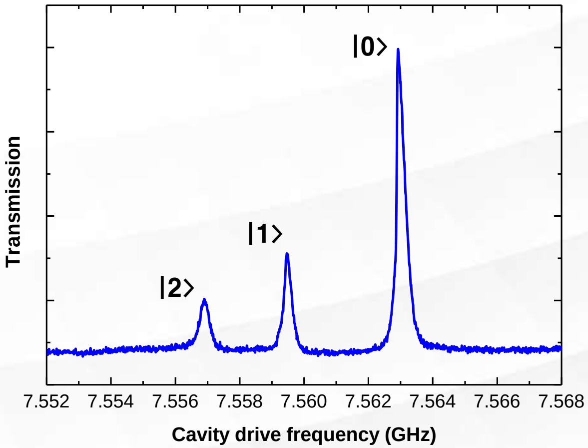


Cavity Spectroscopy

Cavity Transmission

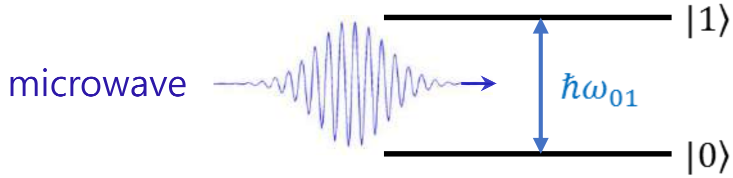




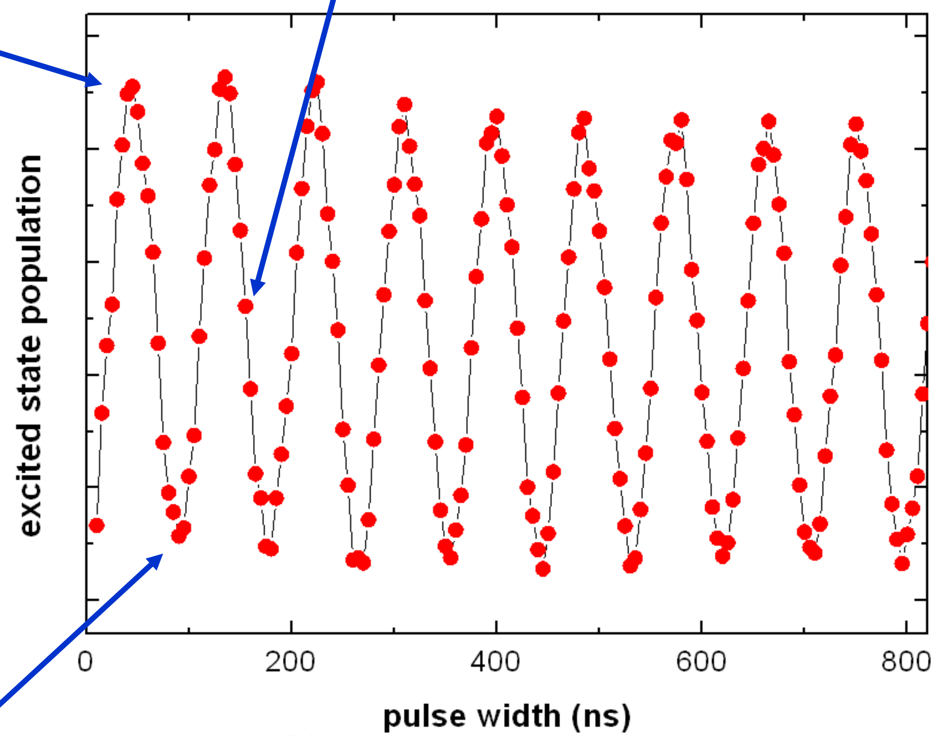


Single Qubit Control : Rabi Oscillation

$$\frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$



$|1\rangle$

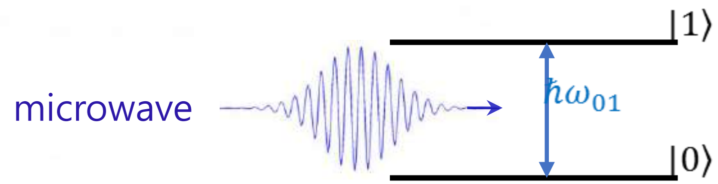


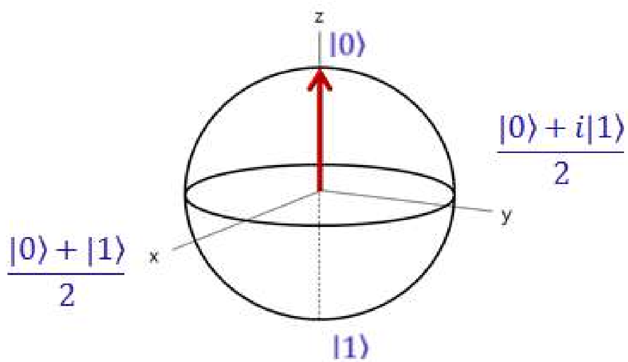
$$\alpha|0\rangle + \beta|1\rangle$$

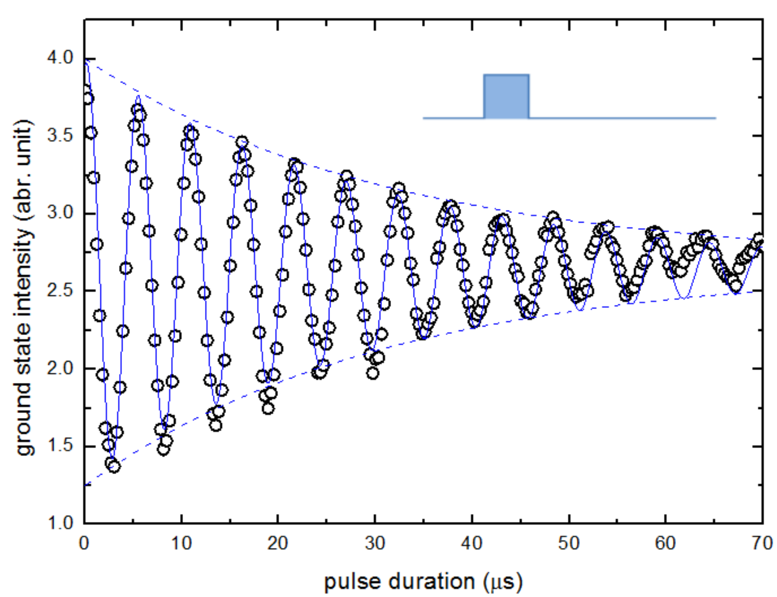
$|0\rangle$

큐비트 제어 및 결맞음

Coherent rotation of qubit states is controlled by microwave pulses







$$R_x(\theta) \equiv e^{-i\frac{\theta}{2}X} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}X = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$R_y(\theta) \equiv e^{-i\frac{\theta}{2}Y} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Y = \begin{bmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$R_z(\theta) \equiv e^{-i\frac{\theta}{2}Z} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Z = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$

Universal Quantum Gate Set

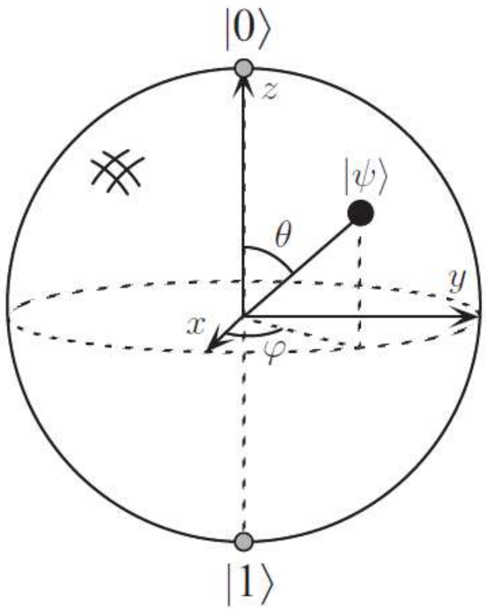


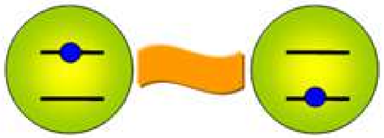
Figure 1.3. Bloch sphere representation of a qubit.

Gate	Symbol	Matrix
Hadamard	H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Pauli-X	X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y	Y	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z	Z	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Phase	S	$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$	T	$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$

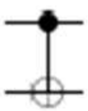
single-qubit gates

+

two-qubit (entangling) gate



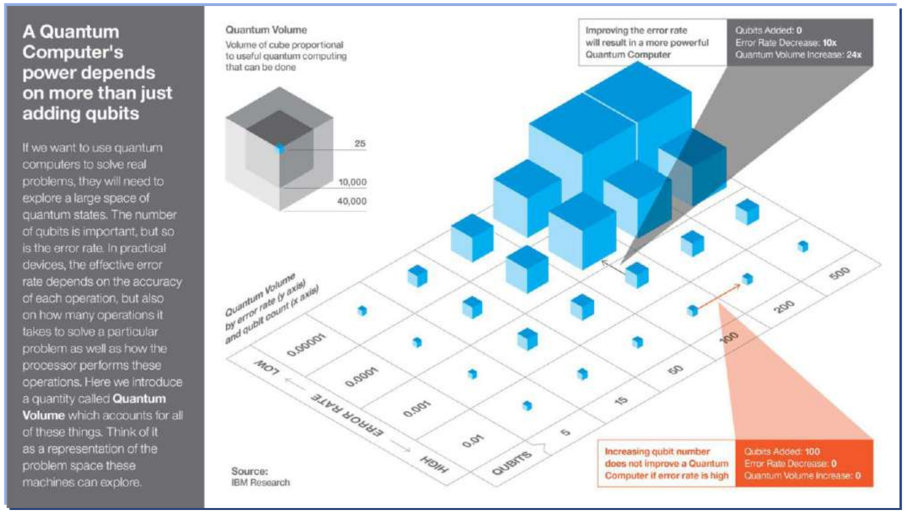
controlled-NOT



$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

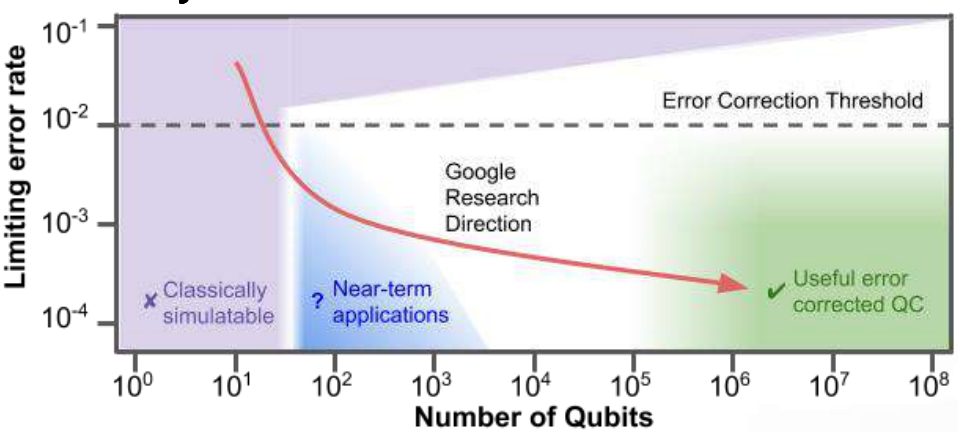
양자컴퓨터의 성능은 무엇이 결정하는가?

Quantum Volume



Slide credit: IBM

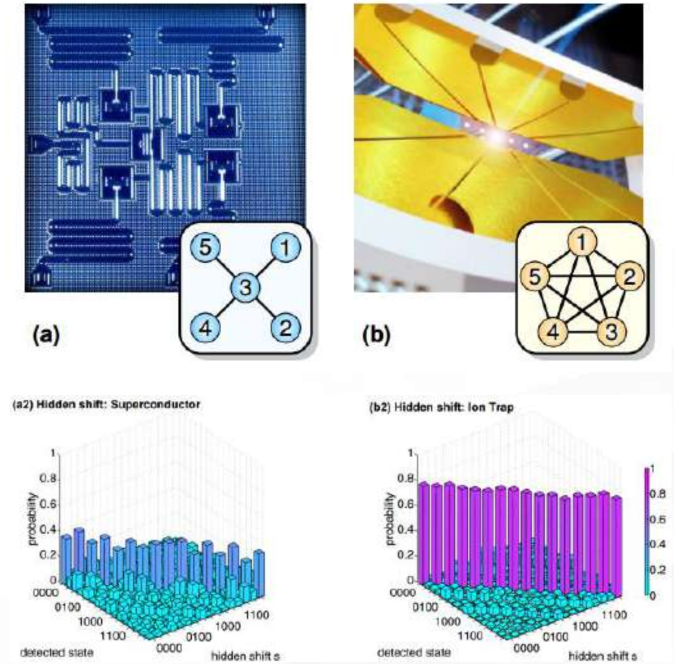
Fidelity



Slide credit: Google

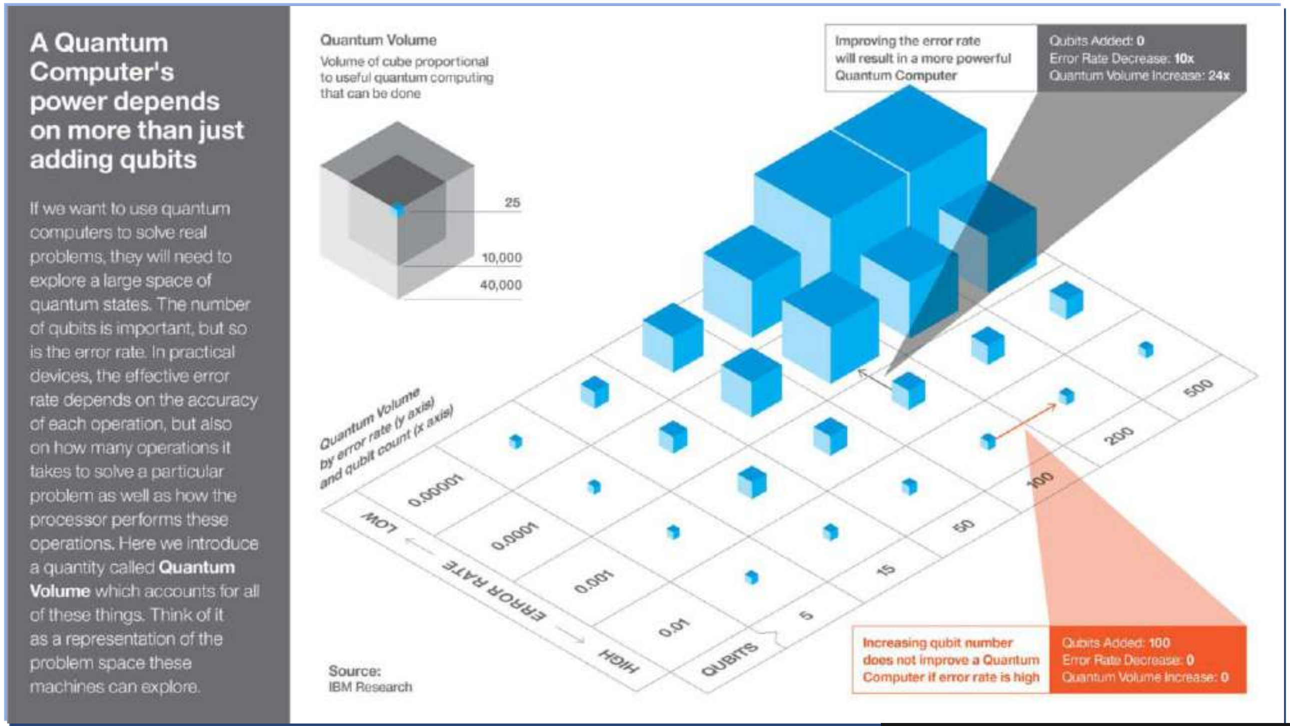
큐비트의 개수만이 성능을 결정하지 않으며 여러가지 성능지수를 복합적으로 고려해야 함.

Qubit Connectivity

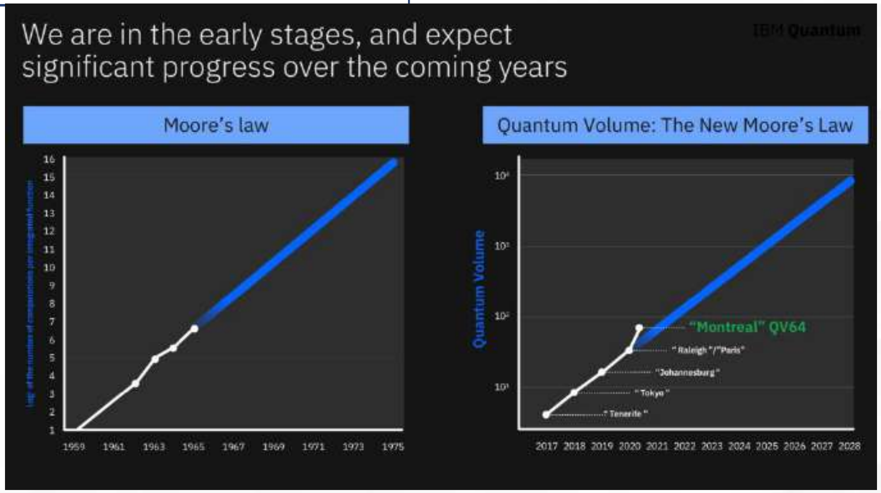


Credit: IonQ

성능지표: Quantum Volume (IBM)



다른 성능지표도 있음
예) Algorithmic Qubit (IonQ)



양자우월성 (Quantum Supremacy)

단 하나의 문제에서라도 양자컴퓨터가 기존 컴퓨터를 능가할 수 있는가?

Article

Quantum supremacy using a programmable superconducting processor

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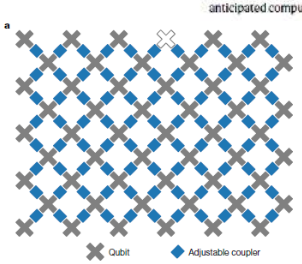
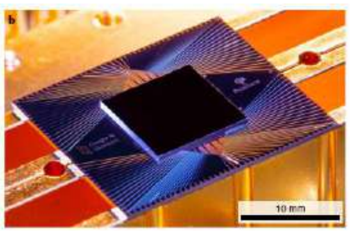
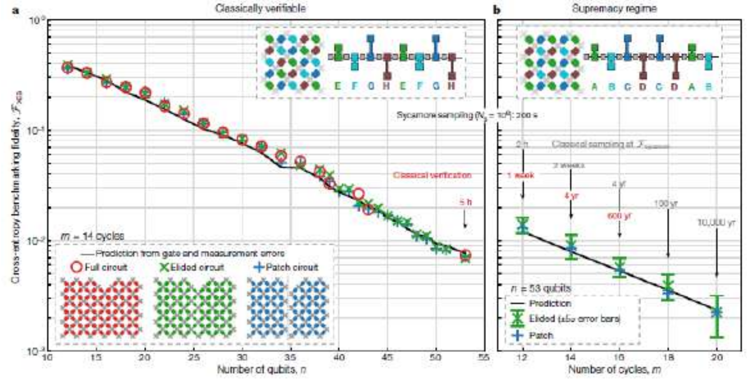
Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[3], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[3], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5]*

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2-7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8-14] for this specific computational task, heralding a much-anticipated computing paradigm.





Google은 초전도 양자컴퓨터를 이용하여 기존 슈퍼컴퓨터가 하기 어려운 계산을 훨씬 빨리 할 수 있음을 시연함

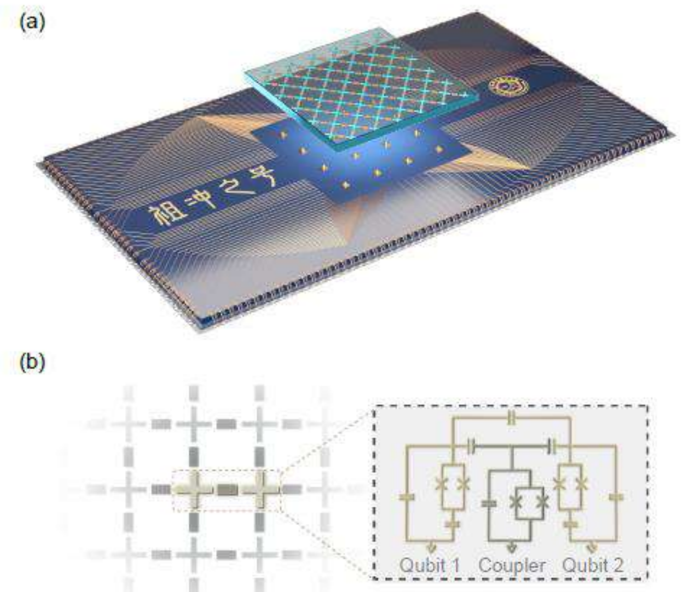


Quantum Advantage from Hefei

Strong quantum computational advantage using a superconducting quantum processor

Yulin Wu,[1,2,3] Wan-Su Bao,[4] Sirui Cao,[1,2,3] Fusheng Chen,[1,2,3] Ming-Cheng Chen,[1,2,3] Xiawei Chen,[2] Tung-Hsun Chung,[1,2,3] Hui Deng,[1,2,3] Yajie Du,[2] Daojin Fan,[1,2,3] Ming Gong,[1,2,3] Cheng Guo,[1,2,3] Chu Guo,[1,2,3] Shaojun Guo,[1,2,3] Lianchen Han,[1,2,3] Linyin Hong,[5] He-Liang Huang,[1,2,3,4] Yong-Heng Huo,[1,2,3] Liping Li,[2] Na Li,[1,2,3] Shaowei Li,[1,2,3] Yuan Li,[1,2,3] Futian Liang,[1,2,3] Chun Lin,[6] Jin Lin,[1,2,3] Haoran Qian,[1,2,3] Dan Qiao,[2] Hao Rong,[1,2,3] Hong Su,[1,2,3] Lihua Sun,[1,2,3] Liangyuan Wang,[2] Shiyu Wang,[1,2,3] Dachao Wu,[1,2,3] Yu Xu,[1,2,3] Kai Yan,[2] Weifeng Yang,[5] Yang Yang,[2] Yangsen Ye,[1,2,3] Jianghan Yin,[2] Chong Ying,[1,2,3] Jiale Yu,[1,2,3] Chen Zha,[1,2,3] Cha Zhang,[1,2,3] Haibin Zhang,[2] Kaili Zhang,[1,2,3] Yiming Zhang,[1,2,3] Han Zhao,[2] Youwei Zhao,[1,2,3] Liang Zhou,[5] Qingling Zhu,[1,2,3] Chao-Yang Lu,[1,2,3] Cheng-Zhi Peng,[1,2,3] Xiaobo Zhu,[1,2,3] and Jian-Wei Pan[1,2,3]

[1]*Hefei National Laboratory for Physical Sciences at the Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*
[2]*Shanghai Branch, CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Shanghai 201315, China*
[3]*Shanghai Research Center for Quantum Sciences, Shanghai 201315, China*
[4]*Henan Key Laboratory of Quantum Information and Cryptography, Zhengzhou 450000, China*
[5]*QuantumCTek Co., Ltd., Hefei 230026, China*
[6]*Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China*
(Dated: June 29, 2021)



ArXiv:2106.14734

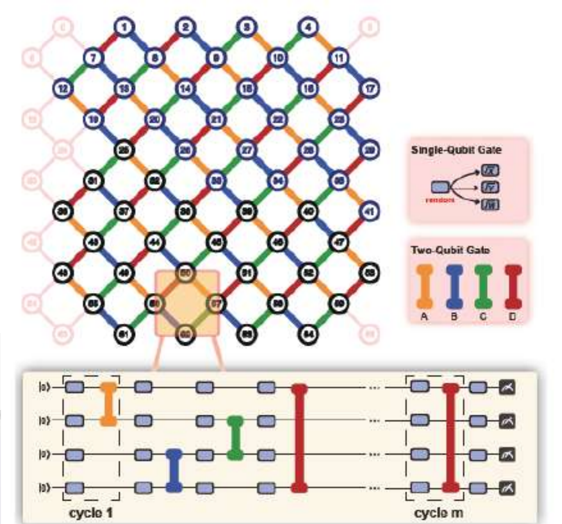
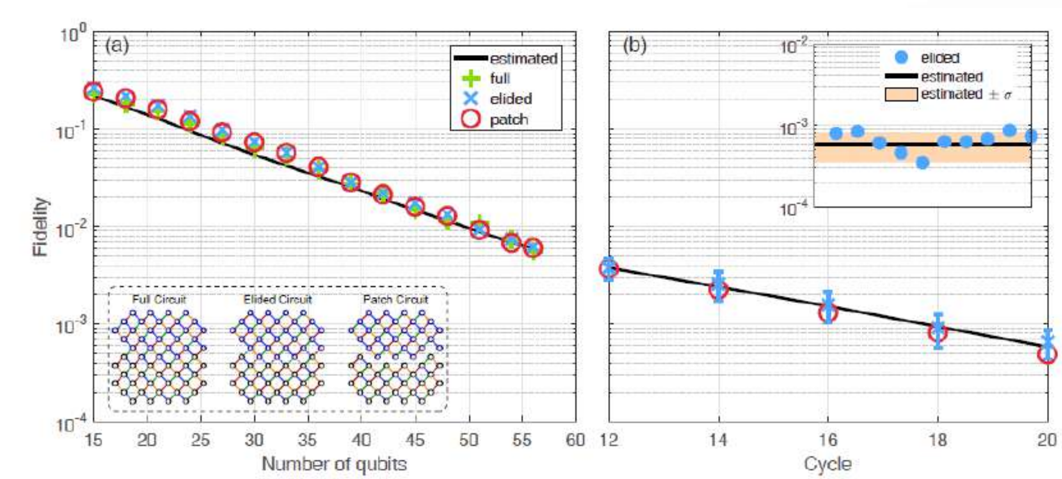


FIG. 3. **56-qubit random quantum circuit operations.** The cir-



QEC on Sycamore

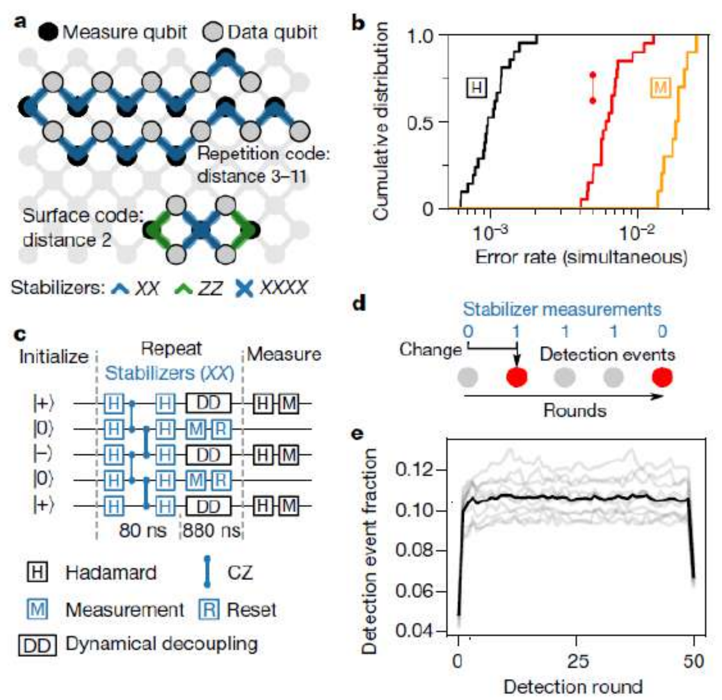
Article

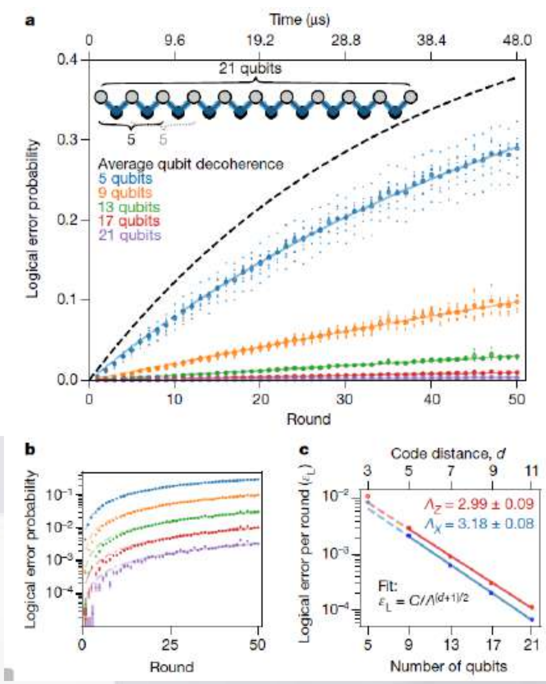
Exponential suppression of bit or phase errors with cyclic error correction

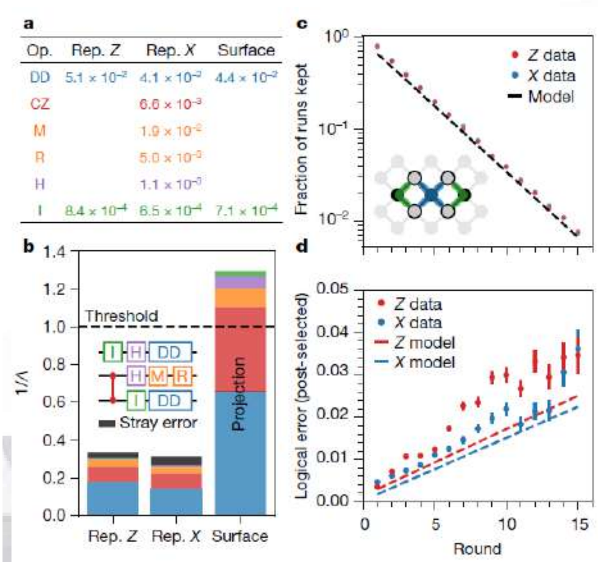
https://doi.org/10.1038/s41586-021-03588-y
Received: 11 January 2021
Accepted: 28 April 2021
Published online: 14 July 2021
Open access

Google Quantum AI*

Realizing the potential of quantum computing requires sufficiently low logical error rates[1]. Many applications call for error rates as low as 10^{-15} (refs. [2–9]), but state-of-the-art quantum platforms typically have physical error rates near 10^{-3} (refs. [10–14]). Quantum error correction[15–17] promises to bridge this divide by distributing quantum logical







Good Review on superconducting qubit

Applied Physics Reviews

A quantum engineer's guide to superconducting qubits

Cite as: Appl. Phys. Rev. **6**, 021318 (2019); https://doi.org/10.1063/1.5089550
Submitted: 20 January 2019 . Accepted: 03 May 2019 . Published Online: 17 June 2019

P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver

COLLECTIONS

Note: This paper is part of the Special Topic on Quantum Computing.

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LETTER

https://doi.org/10.1038/s41586-019-1040-7

Error mitigation extends the computational reach of a noisy quantum processor

Abhinav Kandala[1]*, Kristan Temme[1], Antonio D. Córcoles[1], Antonio Mezzacapo[1], Jerry M. Chow[1] & Jay M. Gambetta[1]

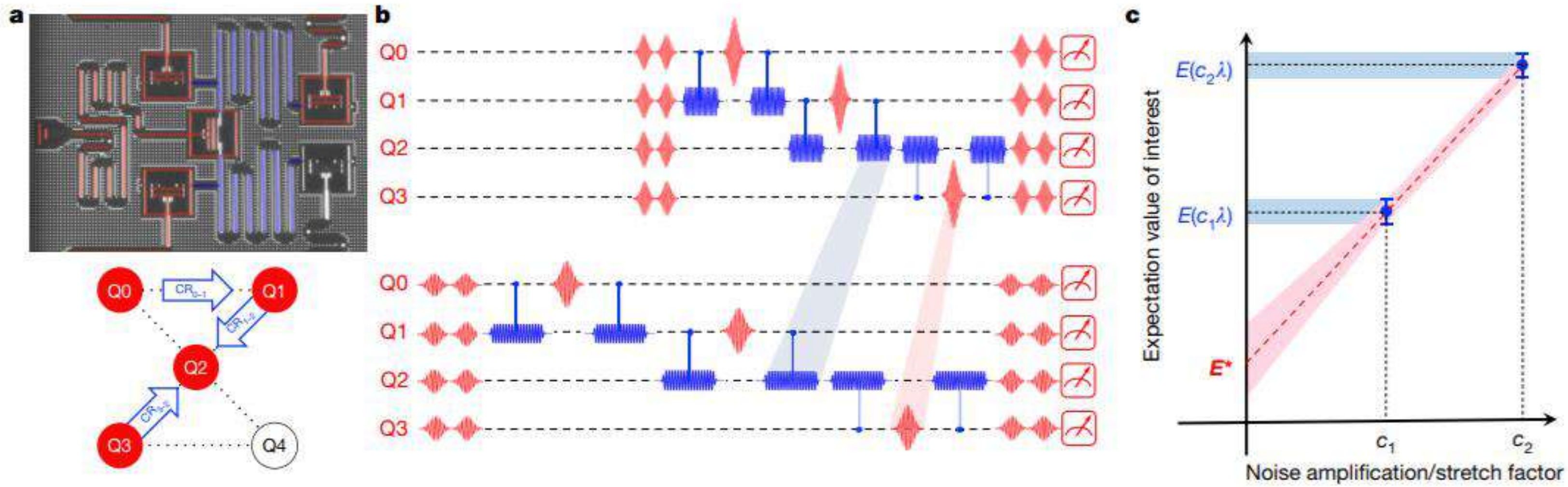


Fig. 1 | Device and experimental protocol. a, False-coloured optical micrograph (top) of the superconducting quantum processor and schematic (bottom) of the qubits (Q0, Q1, Q2, Q3) and gates ($CR_{0\text{-}1}$, $CR_{1\text{-}2}$, $CR_{3\text{-}2}$) used in the experiment. The device is composed of five transmon qubits, with the coupling provided by two superconducting co-planar waveguide resonators, in blue. **b**, A measurement of the expectation value after rescaled state preparation is equivalent to a measurement under an amplified noise strength, if the noise is time invariant. **c**, An illustration of the error mitigation method, shown here for a first-order Richardson extrapolation to the zero-noise limit, highlights that the variance of the mitigated estimate E^* is crucially dependent on the variance of the unmitigated measurements and the stretch factors c_i.

양자컴퓨터로 무엇을 할 것인가? – 양자 알고리듬

Quantum Algorithm Zoo

This is a comprehensive catalog of quantum algorithms. If you notice any errors or omissions, please email me at **stephen.jordan@nist.gov**. Your help is appreciated and will be acknowledged.

Algebraic and Number Theoretic Algorithms

Algorithm: Factoring
Speedup: Superpolynomial
Description: Given an *n*-bit integer, find the prime factorization. The quantum algorithm of Peter Shor solves this in $\widetilde{O}(n^3)$ time [82,125]. The fastest known classical algorithm for integer factorization is the general number field sieve, which is believed to run in time $2^{\widetilde{O}(n^{1/3})}$. The best rigorously proven upper bound on the classical complexity of factoring is $O(2^{n/3+o(1)})$ [252]. 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. A quantum algorithm even faster than Shor's for the special case of factoring "semiprimes", which are

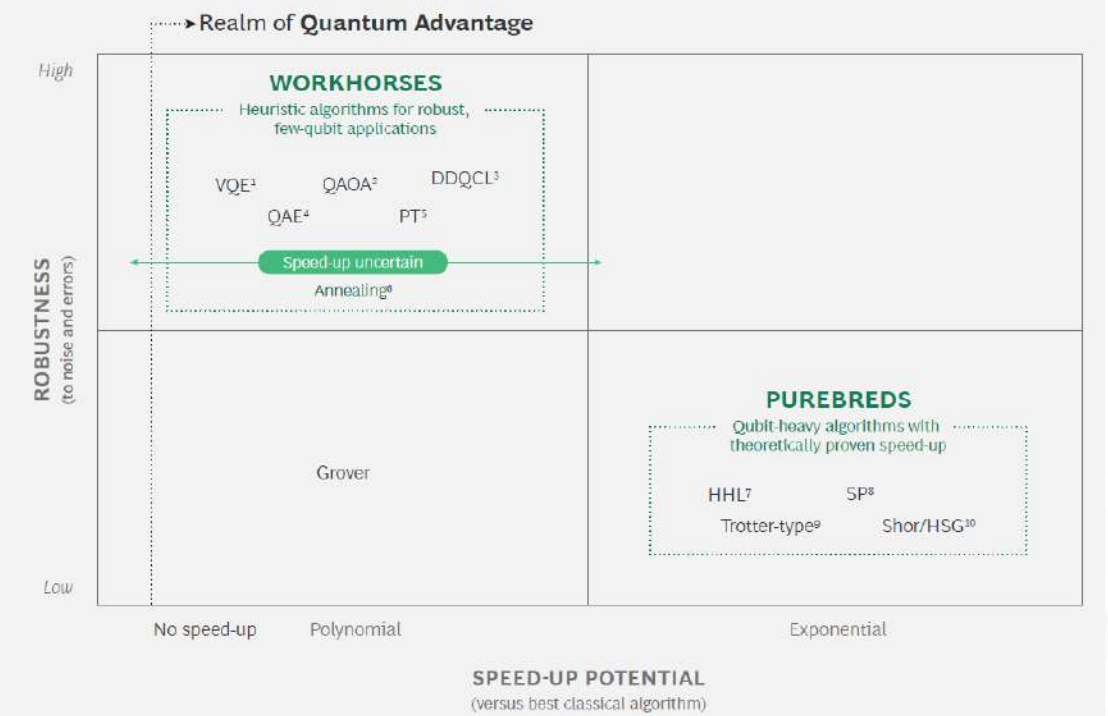
Oracular Algorithms

Algorithm: Searching
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 $O(\sqrt{N})$ queries [48], which is optimal [216]. This has algorithm has subsequently been generalized to search in the presence of multiple "winners" [15], evaluate the sum of an arbitrary function [15,16,73], find the global minimum of an arbitrary function [35,75, 255], take advantage of alternative initial states [100] or nonuniform probabilistic priors [123], work with oracles whose runtime varies between inputs [138], approximate definite integrals [77], and converge to a fixed-point [208, 209]. The generalization of Grover's algorithm known as amplitude estimation [17] is now an important primitive in quantum algorithms. Amplitude estimation forms the core of most known quantum algorithms related to collision finding and graph properties. One of the natural applications for Grover search is speeding up the solution to NP-complete problems such as 3-SAT. Doing so is nontrivial, because the best classical algorithm for 3-SAT is not quite a brute force search. Nevertheless, amplitude amplification enables a quadratic quantum speedup over the best classical 3-SAT algorithm, as shown in [133]. Quadratic speedups for other constraint satisfaction problems are obtained in [134]. For further examples of application of Grover search and amplitude amplification see [261, 262]. A problem closely related to, but harder than, Grover search, is spatial search, in

Approximation and Simulation Algorithms

Algorithm: Quantum Simulation
Speedup: Superpolynomial
Description: It is believed that for any physically realistic Hamiltonian *H* on *n* degrees of freedom, the corresponding time evolution operator e^{-iHt} can be implemented using poly(*n,t*) gates. Unless BPP=BQP, this problem is not solvable in general on a classical computer in polynomial time. Many techniques for quantum simulation have been developed for general classes of Hamiltonians [25,95,92,5,12,170,205,211,244,245,278,293,294,295], chemical dynamics [63,68,227,310], condensed matter physics [1,99, 145], and quantum field theory [107,166,228,229,230]. The exponential complexity of classically simulating quantum systems led Feynman to first propose that

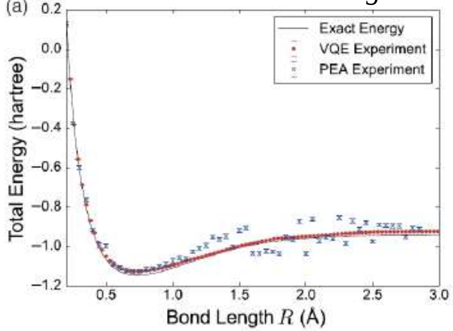
EXHIBIT 8 | Workhorse Algorithms Will Dominate During the NISQ Era

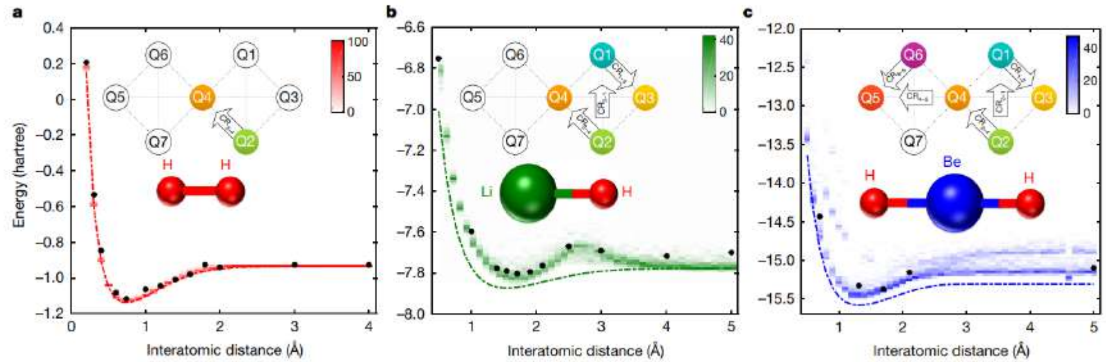


Sources: BCG analysis; expert interviews.
[1] Variational quantum eigensolver.
[2] Quantum approximate optimization algorithm.
[3] Data-driven quantum circuit learning for generative modeling in machine learning tasks.
[4] Quantum auto encoder, a compression algorithm for quantum data.
[5] Population transfer between computational states with similar energies for search and reverse annealing optimization.
[6] Optimization by quantum annealing as an alternative to circuit-based algorithms.
[7] Linear-system-solving algorithm devised by Harrow, Hassidim, and Lloyd.
[8] Semidefinite programming.
[9] Trotter-based algorithms for molecular simulation and adiabatic state preparation.
[10] Algorithms exploiting hidden-subgroup symmetries such as Shor's algorithm.

소재물성, 화학반응 등

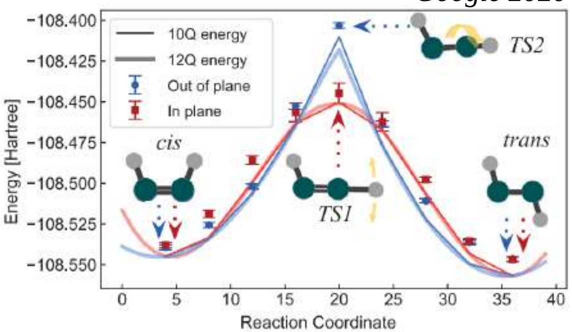
Google 2016

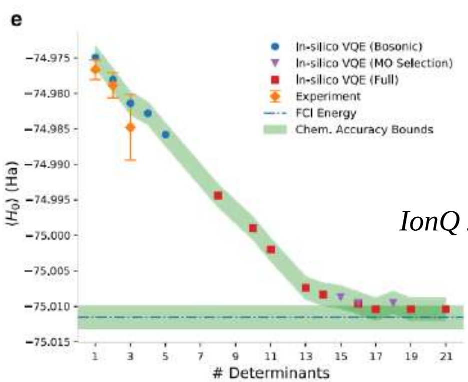




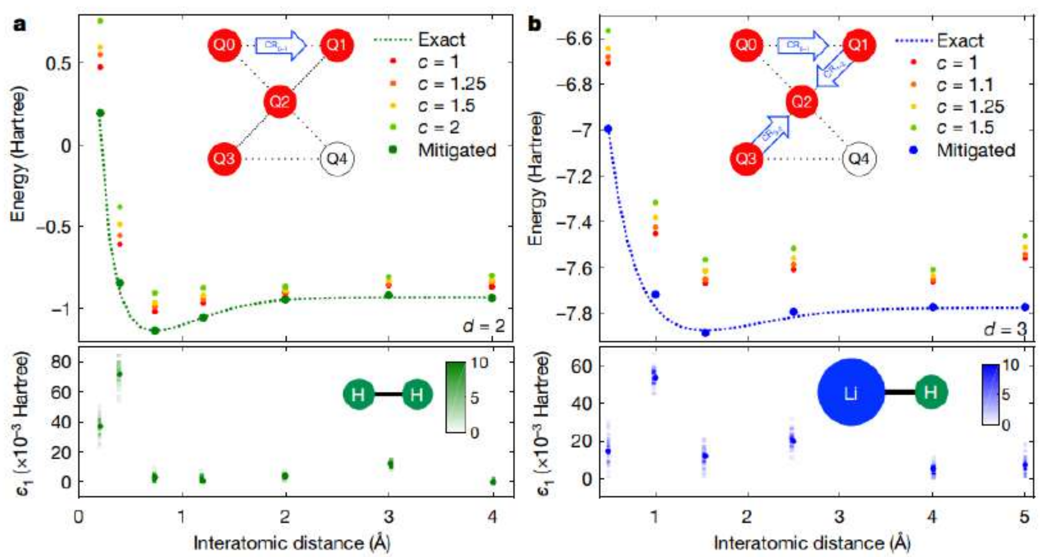
IBM 2017

Google 2020





IonQ 2020



IBM 2019

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PsiQuantum expects commercial quantum computer by 2025 · Cambridge quantum computing start-up targets global expansion · Bitcoin has ambitions for gold's role

Quantum technologies

IBM to build Europe's first quantum computer in Germany

Researchers keen to use the technology without sending data to the US

The Q System One computer will be operational at a site near Stuttgart from early next year © IBM

Joe Miller in Frankfurt MARCH 13 2020

Bloomberg

Technology

Israel Allocates $60 Million to Build First Quantum Computer

By Yaacov Benmeleh

2021년 3월 3일 오후 9:07 GMT+9

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GeQCoS Project to Develop German Quantum Computer Based on Superconducting Qubits

February 1, 2021

JÜLICH, Germany, Feb. 1 2021 — Building a quantum processor with novel properties based on superconducting qubits – this is the aim of the four year project GeQCoS ('German Quantum Computer based on Superconducting Qubits') funded by the German Federal Ministry of Education and Research (BMBF).

JÜLICH Forschungszentrum

In this joint project, Germany's leading scientists in the field of superconducting quantum circuits have teamed up to develop innovative concepts for the construction of an improved quantum processor. They aim to realize a quantum processor with improved quality based on new materials and manufacturing methods by the Karlsruhe Institute of Technology (KIT), tailor-made theoretical concepts of the Friedrich-Alexander University Erlangen Nürnberg (FAU), optimized control methods of the Forschungszentrum Jülichs (FZJ) and concepts for new architectures with higher connectivity at the Walther-Meißner-Institute (WMI – Bavarian Academy of Sciences and Technical University of Munich). In order to achieve this goal, semiconductor manufacturer Infineon will develop scalable manufacturing processes, while the Fraunhofer Institute for Applied Solid State Physics (IAF) in Freiburg is promoting the development of optimized chip packages. The processor performance will eventually be demonstrated using a specifically developed quantum algorithm at the WMI.

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French President Details €1.8b Quantum Plan

January 22, 2021 Anne-Françoise Pelé

Two years after unveiling France's roadmap in artificial intelligence, French President Emmanuel Macron presented this week a national strategy for quantum technologies. The five-year €1.8 billion plan aims to finance research in quantum computing, communications and sensing.

"Quantum strategy is of paramount importance," said Macron during a speech on January 21st at the Center for Nanoscience and Nanotechnologies (C2N) in Paris-Saclay, France. "Like artificial intelligence, microelectronics, health, energy and space technologies, quantum technologies are among the few keys to the future that France absolutely must have in hand."

The French government will invest €200 million per year over the next five years, or €1 billion in total. The remaining €800 million will come from commitments made by industrial players (€500 million), European funding (€200 million), and investors revolving around the French startup ecosystem (€100 million).

"By tripling our annual financial effort, we are already joining the leading trio of quantum nations [after the United States and China]," claimed Macron.

France's quantum strategy is based on two main axes. "The first is global and integrated technological development, from fundamental research to industrialization," said Macron. "The second is the strengthening of the French innovation ecosystem in its European environment, in particular by developing human capital and by recruiting, training and attracting the best both in public research and in industry."

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Press release

Government backs UK's first quantum computer

The UK's first quantum computer to be commercially available to businesses will be located in Abingdon in Oxfordshire

From: Department for Business, Energy & Industrial Strategy, UK Research and Innovation, and Amanda Solloway MP

Published: 2 September 2020

- The UK's first commercially available quantum computer to be hosted in Abingdon, backed by £10 million government and industry investment
- quantum computers could help solve issues including accelerating new drug treatments and improving traffic flow in cities and towns
- Science Minister sets out bold new vision for the UK to become the world's first quantum-ready economy and launches the new National Quantum Computer Centre in Oxfordshire

QC40

https://www.youtube.com/watch?v=GR6ANm6Z0yk

QC40: Physics of Computation Conference 40th Anniversary

QC40 is a one-day virtual event that will celebrate the 40th anniversary of the Physics of Computation Conference which was jointly organized by MIT and IBM, and held at the MIT Endicott House in 1981.

The conference was a defining moment in the history of quantum computation. At QC40, we will take a close look at the changes in quantum computing over the past 40 years, with a panel discussion and keynote addresses by attendees from the original conference and pioneers in the field of quantum computing.

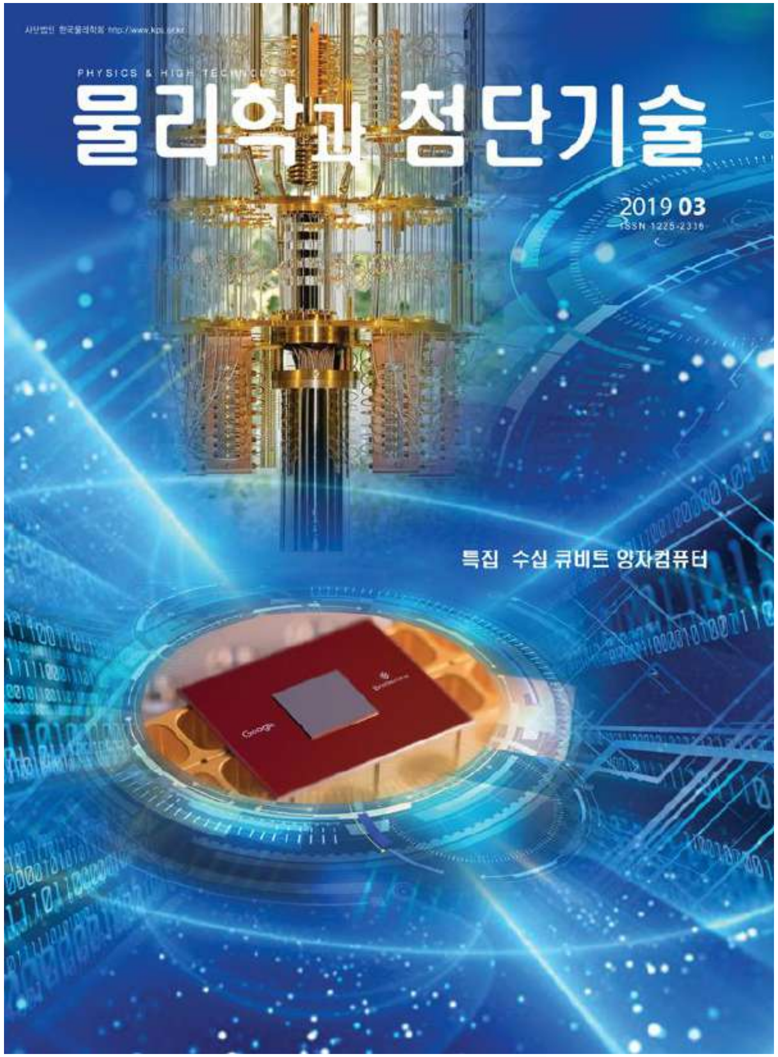
The day will also feature academic talks highlighting recent work in quantum information science (more details under "What is QC40?"). The top outstanding talk submissions will be recognized with up to $5,000 grants as a way to contribute to future research.

Celebrate 40 years of quantum

Keynotes, contributed talks, and more bridging the 1981 Physics of Computation conference with current research.

Physics of Computation Conference Endicott House MIT May 6-8, 1981

(테크니컬) 읽을거리: 수십 큐비트 양자컴퓨터



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김기환·김정상·김태현

Trapped Ion Quantum Computer

Kihwan KIM, Jungsang KIM and Taehyun KIM

tially with the number of qubits. Thus, competition is underway to develop a quantum computer capable of computing with 50 or more physical qubits coherently without the need for an error correction. In the last couple of years,

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정연욱·주재우

Superconducting Quantum Computer

Yonuk CHONG and Jaewoo JOO

스템의 수준과 그 활용 연구들이 어떤 과정을 거쳐 여기까지 왔으며 어떤 의미인지, 지금은 무슨 일들이 진행되고, 앞으로는 어떻게 발전할 것인지 등에 대해서 개략적으로 이야기하고자 한다.

특집 Feature articles　　수십 큐비트 양자컴퓨터 특집

광학기반 양자컴퓨터를 향하여

DOI: 10.3938/PhiT.28.009

김용수·신희득·허준석

Towards the Photonic Quantum Computer

Yong-Su KIM, Heedeuk SHIN and Joonsuk HUH

곳남이 적어 양자통신, 양자시뮬레이션 등 연구에 널리 이용된다. 광자를 이용한 양자정보처리를 구현하기 위해서는 많은 수의 광자기반 큐비트를 생성하고, 이들의 상태를 원하는 대로 제어한 후, 그 결과를 측정할 수 있어야 한다.

SUNG KYUN KWAN UNIVERSITY(SKKU)

THANK YOU

Yonuk Chong SungKyunKwan University (SKKU)