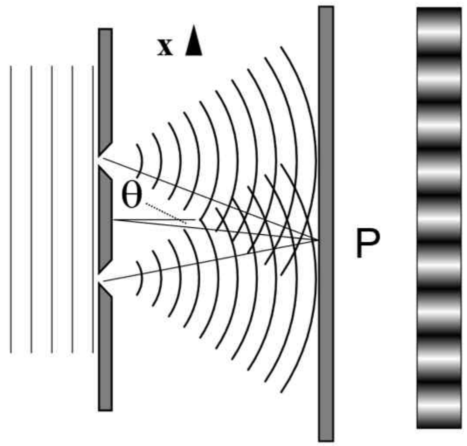
# 양자컴퓨터 개발 최신 동향

백경현
연세대학교
융합과학기술원

(2025.7.16. KpqC 연구단 워크숍)

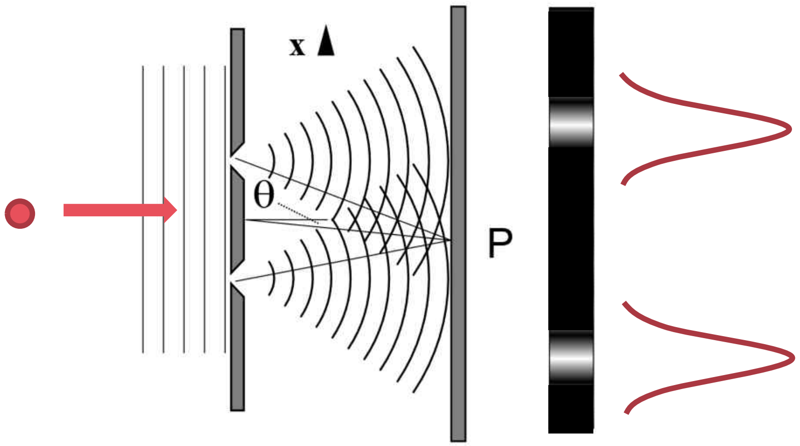
# Quantum superposition

- Quantum mechanics (양자역학)
  - Quantization (양자화)
  - Superposition principle (중첩원리)



# Quantum superposition

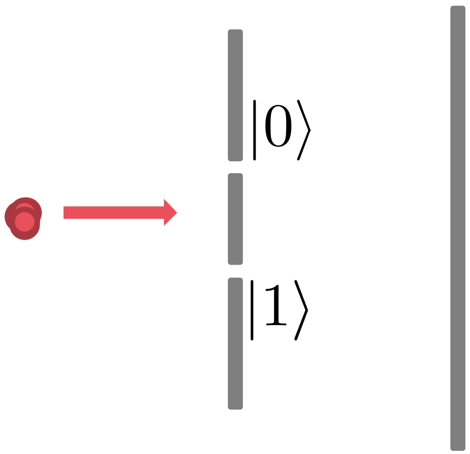
- Quantum mechanics (양자역학)
  - Quantization (양자화)
  - Superposition principle (중첩원리)

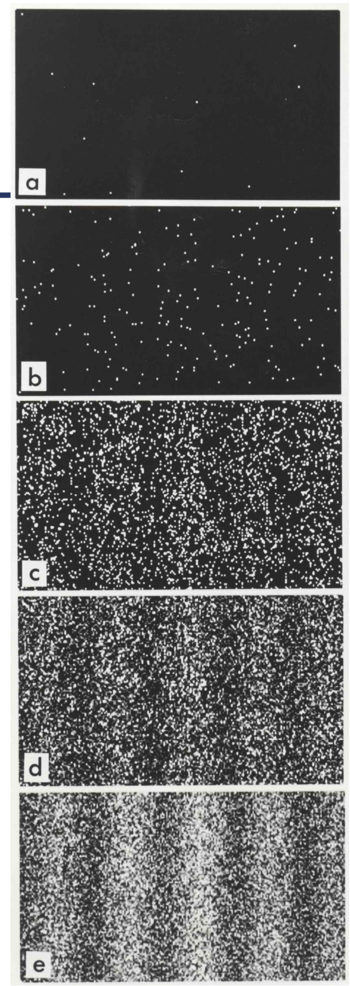


# Quantum superposition

- Quantum mechanics (양자역학)
  - Quantization (양자화)
  - Superposition principle (중첩원리)

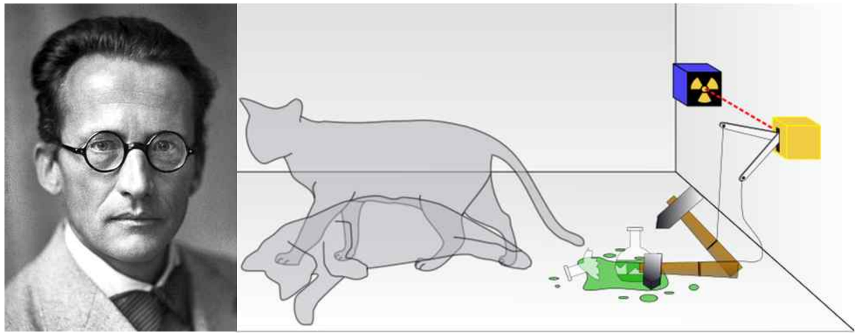
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



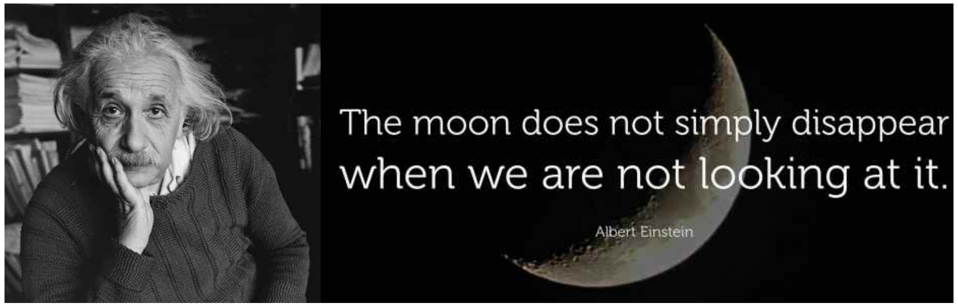



# Quantum superposition

- 슈뢰딩거의 고양이



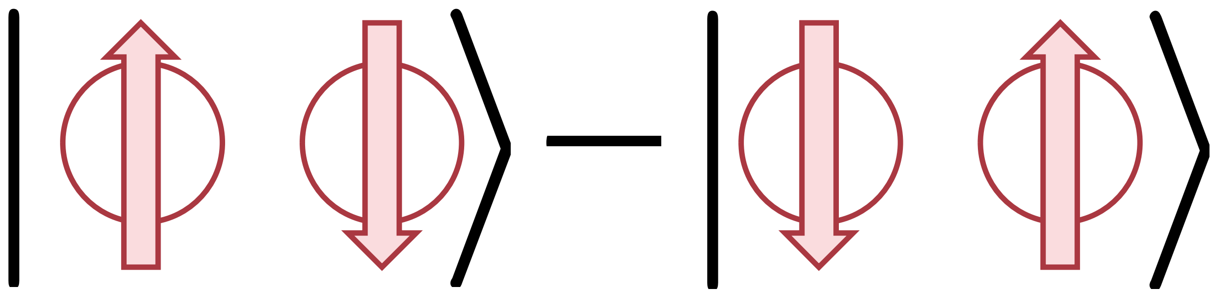
- 아인슈타인



# Introduction: Bell's theorem

- Quantum theory
  - Quantum superposition(양자 중첩)
  - Entanglement(얽힘)

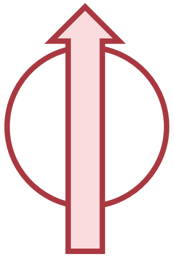
$$\frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

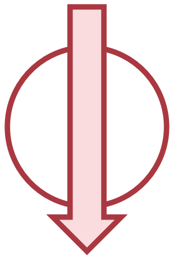


# Introduction: Bell's theorem

- Quantum theory
  - Quantum superposition(양자 중첩)
  - Entanglement(얽힘)

$$\frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

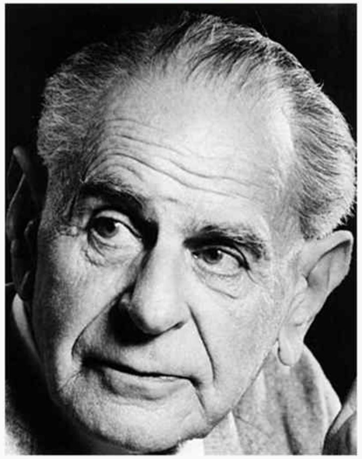




# Introduction: Bell’s theorem

- Quantum theory
  - Quantum superposition(양자 중
  - Entanglement(얽힘)
- Classical theory
  - Realism (실재론)
  - Locality (국소성)

Sir
**Karl Popper**
CH FBA FRS



| | |
|---|---|
| **Born** | Karl Raimund Popper<br>28 July 1902<br>Vienna, Austria-Hungary |
| **Died** | 17 September 1994 (aged 92)<br>London, England, United Kingdom |

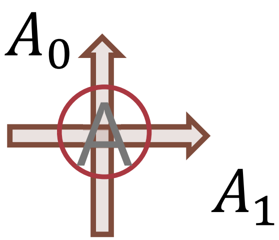
- Falsifiability(반증가능성)
- ***The Logic of Scientific Discovery (과학적 발견의 논리)*** (1959)

  \- 1934년에 독일어로 출판된 *Logic of Research: On the Epistemology of Modern Natural Science* (탐구의 논리) 영어번역(후속작)

# Introduction: Bell's theorem

- Bell's theorem (벨의 정리)
  (*On the Einstein Podolsky Rosen Paradox*, 1964)
  (*Speakable and Unspeakable in Quantum Mechanics, 1987)*

- Scenario
  Alice and Bob share a bipartite quantum state and measure it by their local measurements randomly.





**John Stewart Bell**

John Stewart Bell, CERN, 1973

| | |
|---|---|
| **Born** | John Stewart Bell<br>28 July 1928<br>Belfast, Northern Ireland, UK |
| **Died** | 1 October 1990 (aged 62)<br>Geneva, Switzerland |

# Introduction: Bell's theorem

- CHSH inequality (J. Clauser, M. Horne, A. Shimony and R.A. Holt inequality)
  - Joint probability obeying local hidden variable model should satisfy

$$\langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle \leq 2$$

- However, quantum theory violates the CHSH inequality

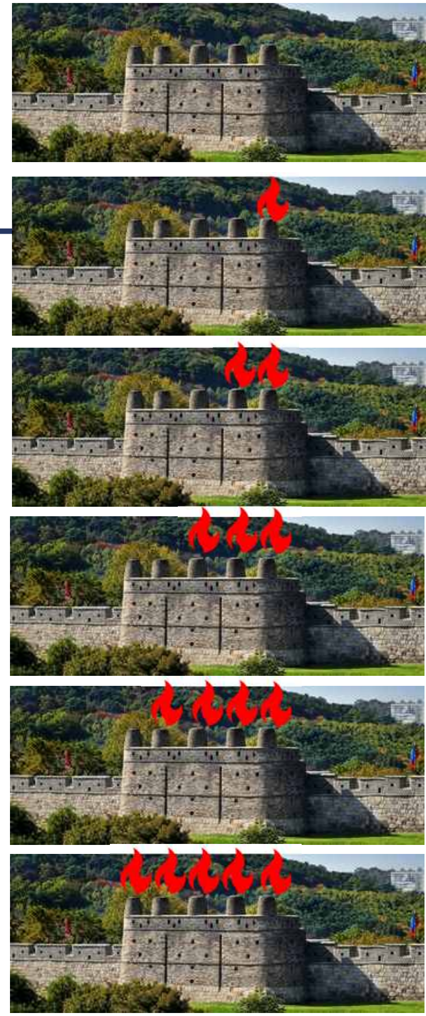
$$\langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle = 2\sqrt{2} > 2$$

→ It implies that quantum theory does not obey locality and realism at the same time.

# 비트에서 큐비트로

# Bit (Binary digit)

- 정보 저장 및 전달
  - 봉화대

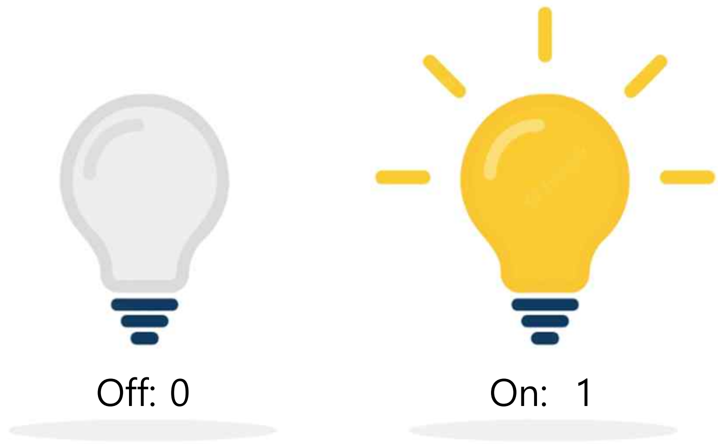


# Bit (Binary digit)

- 정보 저장 및 전달
  - 봉화대

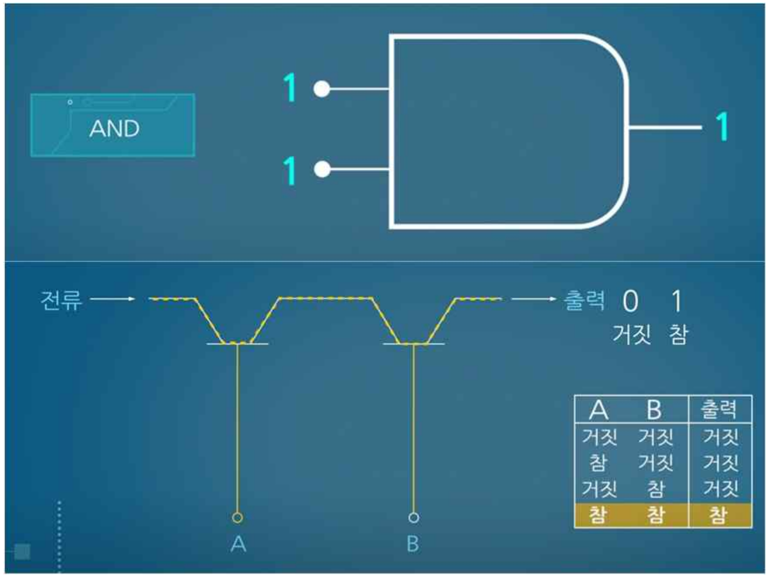
# Bit (Binary digit)

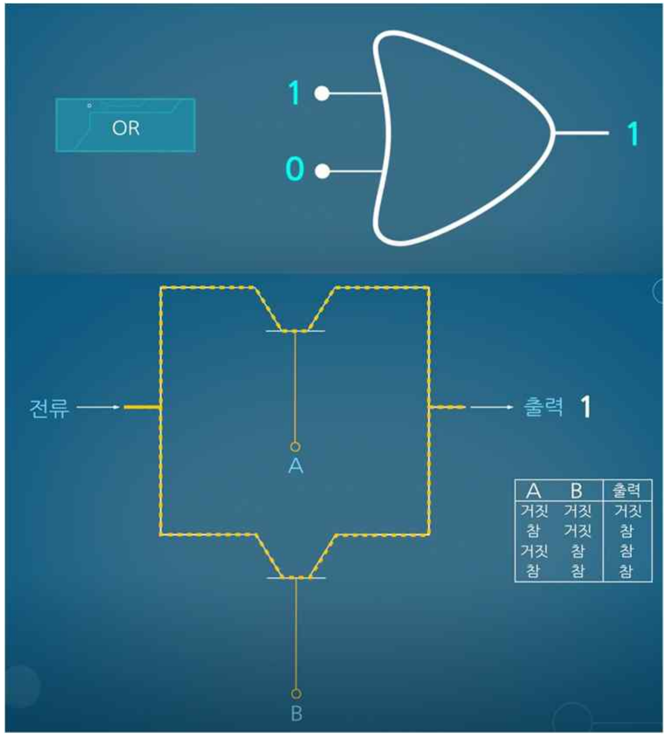
- Classical bit : 0 or 1



# Bit (Binary digit)

- Classical bit :  0 or 1



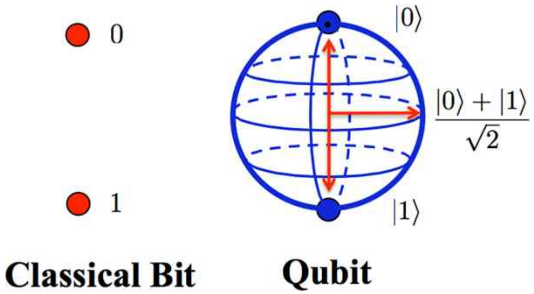




출처: https://www.youtube.com/watch?v=Fg00LN30Ezg&t=607s&ab_channel=bRd3I

# Qubit

- Classical bit : 0 or 1
- Qubit (Quantum bit, 큐비트)

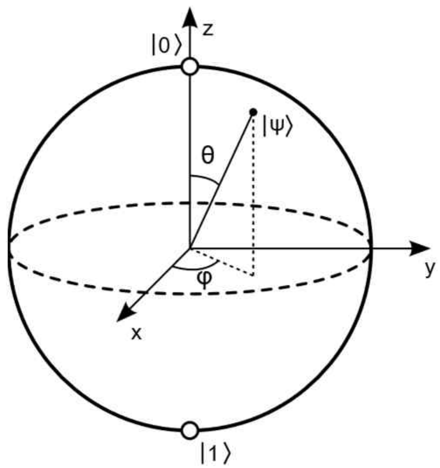
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$



# Qubit

- Classical bit : 0 or 1
- Qubit (Quantum bit, 큐비트)

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$



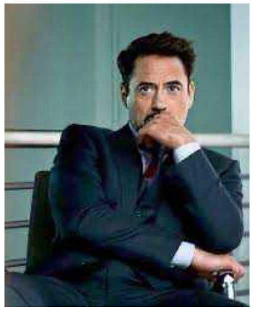

Bloch sphere
블로흐 구면

# Qubit

- Qubit 특성

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

  - Quantum superposition (양자 중첩)



양자중첩 무엇인가?

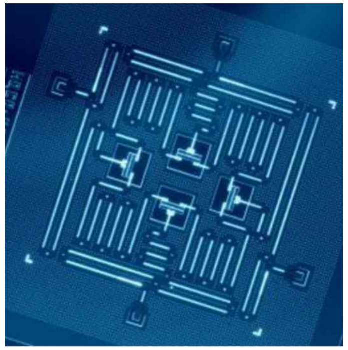
양자중첩을 어디에 쓸까?

# Qubit

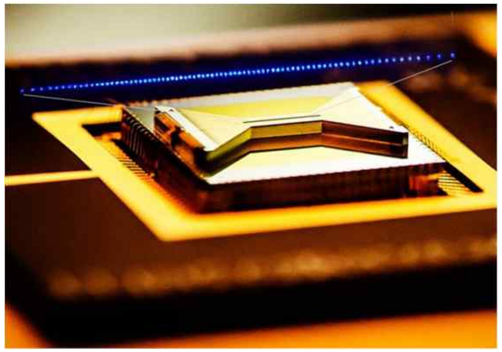
- Qubit (Quantum bit, 큐빗)

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

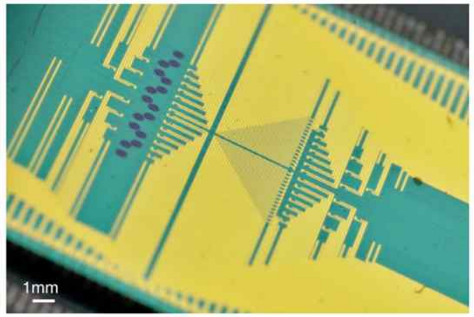
- Physical systems



Superconductor
IBM, npj quantum information, 2017



Trapped ion
Univ. of Maryland, 2018




Photonic quantum computer
Univ. of Bristol, Science, 2018

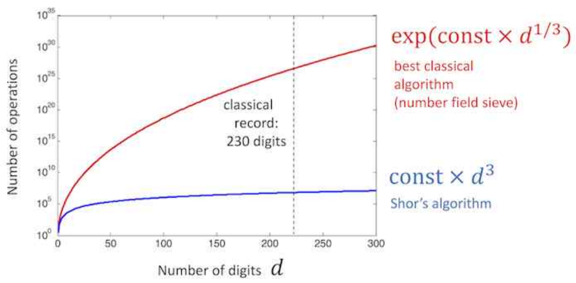
# 컴퓨팅에 대한 이해

## 고전컴퓨팅의 한계와
## 양자컴퓨터로부터 얻는 이득

# Quantum algorithm

## • 쇼어 알고리즘 (1994)

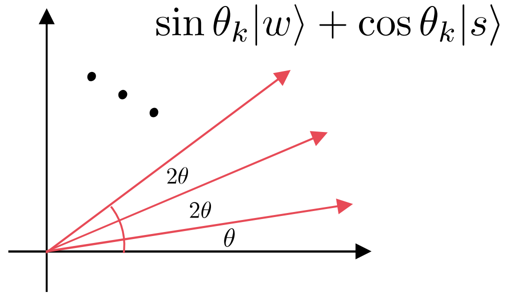
- 소인수분해 문제 공략
- 문제 크기 N에 대해 polylogarithmic 시간이 걸림
- 현존하는 가장 효율적인 고전 알고리즘은 sub-exponential 시간이 걸림




그래프 출처: IBM Quantum

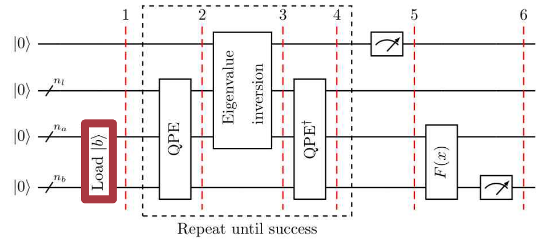
## • 그로버 알고리즘 (1996)

- 검색 문제 공략
- Search space N에 대해 Query complexity의 square root 속도 향상, 즉, $O(\sqrt{N})$.
- 고전 알고리즘은 N에 대해 비례 $O(N)$




## • HHL 알고리즘 (2009)

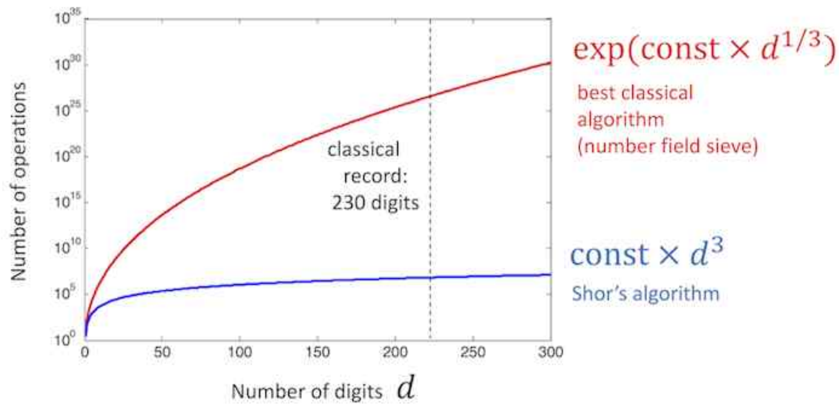
- $N$ by $N$ sparse matrix $A$ (sparsity << $N$)
- A unit vector $\vec{b}$
- $A\vec{x} = \vec{b}$을 만족하는 $\vec{x}$ 대하여 주어진 임의의 행렬 $M$에 대한 평균값을 구하는 알고리즘
- HHL 알고리즘을 이용하면 $O(\log N)$의 시간 안에 풀 수 있다.
(고전 알고리즘으로 푸는데 걸리는 시간은 $O(N)$에 비례함)




HHL algorithm (From Qiskit website)

# Quantum algorithm

- Shor's algorithm (1994)
  - RSA 키의 길이
    - 2019년 고전컴퓨터로 795비트를 소인수분해 했다는 기록이 있음.
    - 일반적으로 2048 비트가 사용되고 있음.
    - Shor's algorithm을 이용하면 $O(bg\ N)$ 횟수의 양자 게이트 시행으로 해를 구할 수 있다.



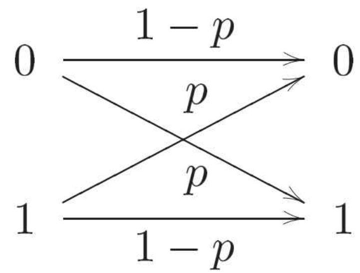
# 양자 에러 보정
# (Quantum Error Correction)

# Fault tolerant quantum computing

- 이상적인 양자컴퓨터는 유망한가?
  - 풀어야 할 많은 문제들이 남아있다.
  - Decoherence or Quantum noise
    - **Error correction**
      –효과적으로 에러를 발견하고 보정하는 수학적인 연구가 필요.
      e.g.) Hamming code in classical computing
    - **Quantum threshold**
      –에러 보정을 위해서는 99%의 정확성이 필요
    - **Logical qubits**
      –1개의 큐비트를 보호하기 위해 약 1000~10000개의 큐비트 필요

# 에러 보정 (Error-correction)

- 고전 에러 보정
  - 에러의 종류 : 비트 플립
    에러의 확률 : $p$



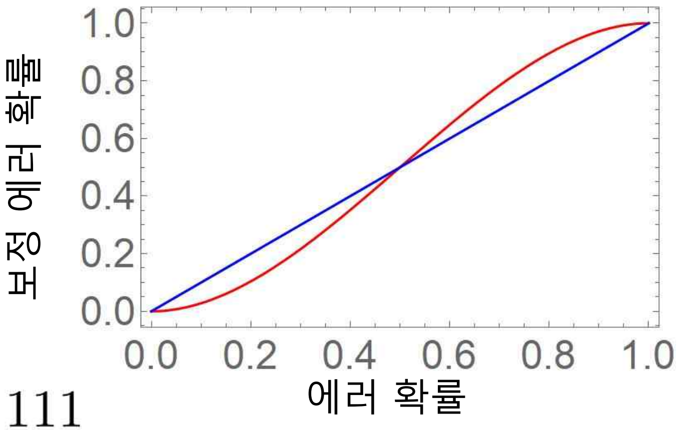

  - 논리 비트

$$0_L = 000 \qquad\qquad 1_L = 111$$

  - 만약 001 이란 값을 얻는다면 이를 000으로 보정해준다.
    마찬가지로 110을 얻는다면 이를 111로 보정해준다.

# 에러 보정 (Error Correction)

- 고전 에러 보정
  - 에러의 종류 : 비트 플립
    에러의 확률 : $p$




  - 논리 비트

$$0_L = 000 \qquad 1_L = 111$$

  - 이와 같은 방식으로 에러를 보정할 경우 논리 비트에 에러가 일어날 확률은

$$3p^2 - 2p^3$$

# 양자 에러 보정 (Quantum Error Correction)

- 양자 에러 보정의 어려움
  - **복사 불가(No-cloning theorem)**
    양자 상태는 원칙적으로(in principle) 복사가 불가능하다.
  - **에러의 연속성**
    양자 상태를 결정하는 연속 변수들에 에러가 일어난다.
  - 측정이 양자 상태를 **파괴(destroy) 혹은 교란(disturb)**한다.
    양자역학의 특성상 측정 후 양자 상태는 교란되며 그 결과 본래의 정보를 잃어버린다.

# 양자 에러 보정 (Quantum Error correction)

- 3 큐빗 비트플립 보정 (Three qubit bit-flip code)
  - 논리 큐비트(Logical qubit)

$$|0_L\rangle = |000\rangle \qquad |1_L\rangle = |111\rangle$$

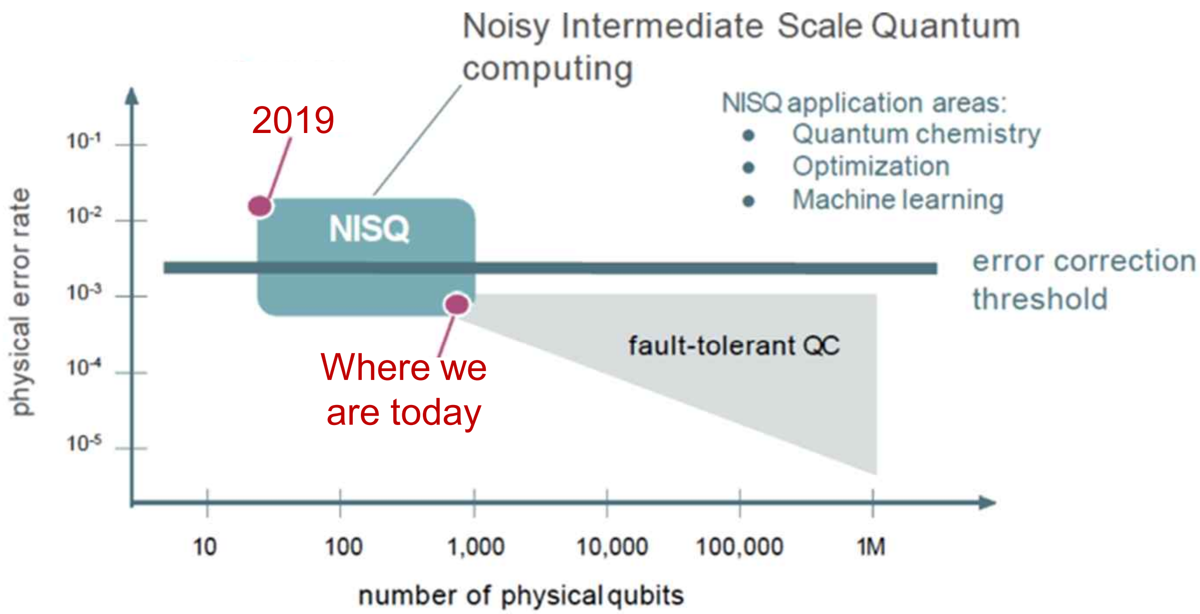
일반적인 논리 큐빗

$$|\psi_L\rangle = c_0|000\rangle + c_1|111\rangle$$

  - 보정 가능한 에러
    - 최대 한 번의 비트플립이 3 큐빗 중 하나에 일어나는 에러

$$(I, X_1, X_2, X_3)$$

# NISQ (Noisy Intermediate-Scale Quantum)




"Quantum computing in the NISQ era and beyond" Preskill, 2018 https://arxiv.org/abs/1801.00862

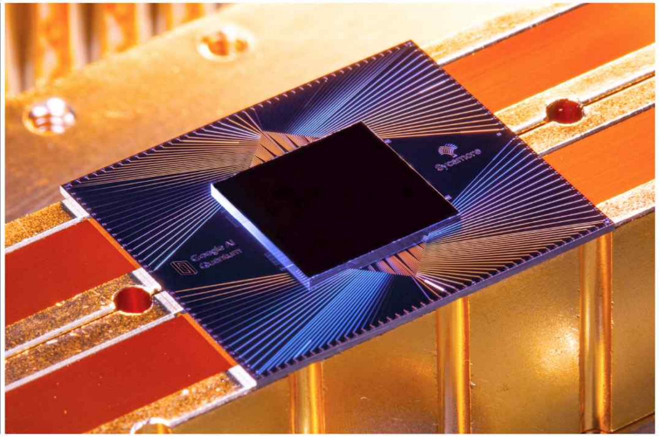
# 양자컴퓨터 개발 동향

# Quantum computer

- Google AI lab (2014)

- Superconducting qubit (초전도 큐비트)

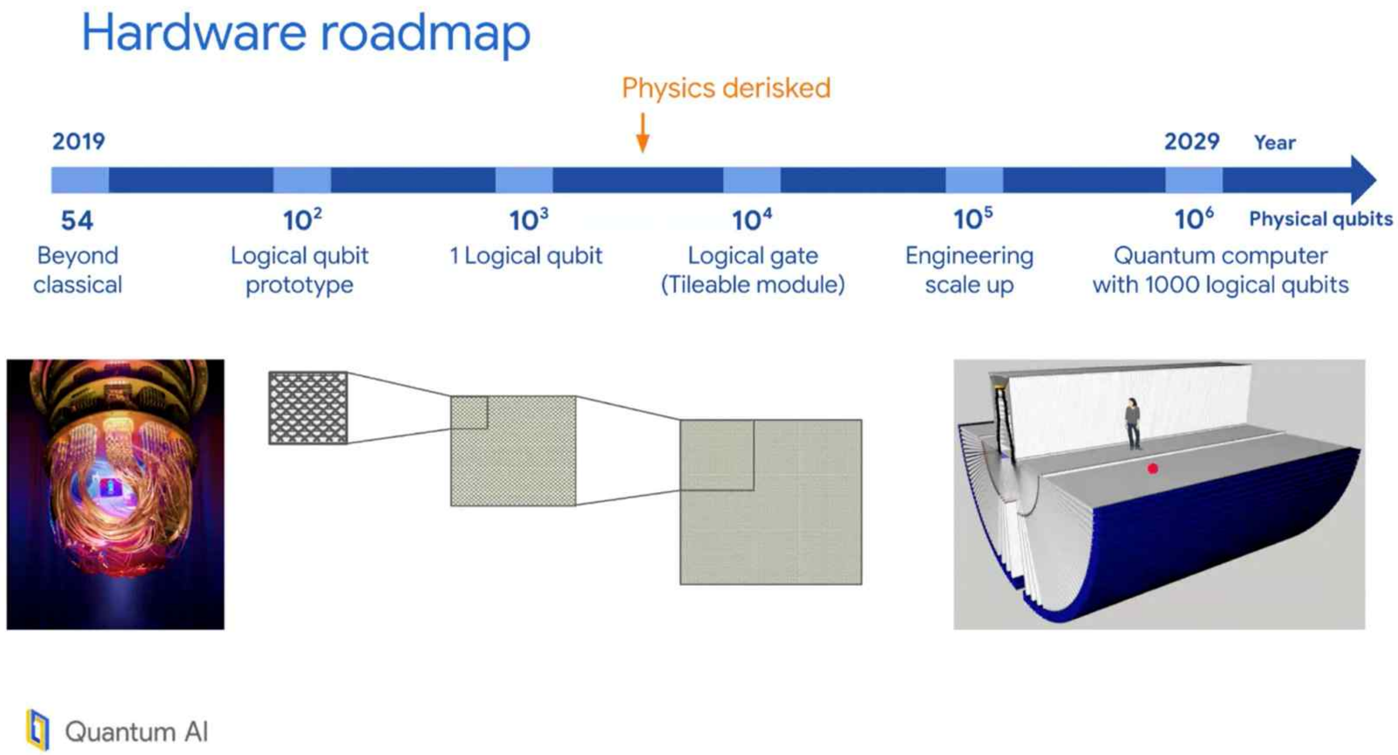
- Demonstrate quantum supremacy with 53 qubits (양자우월성)



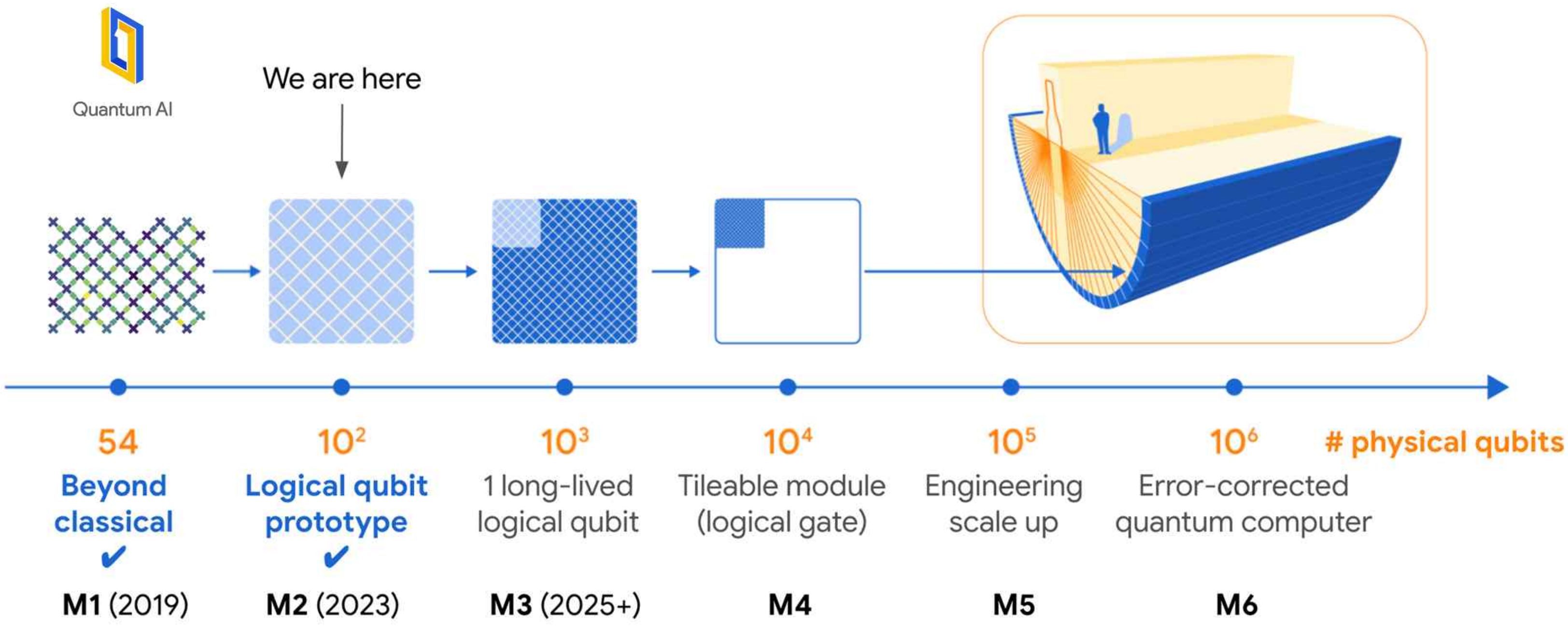
John Martins

https://ai.googleblog.com/2019/10/quantum-supremacy-using-programmable.html

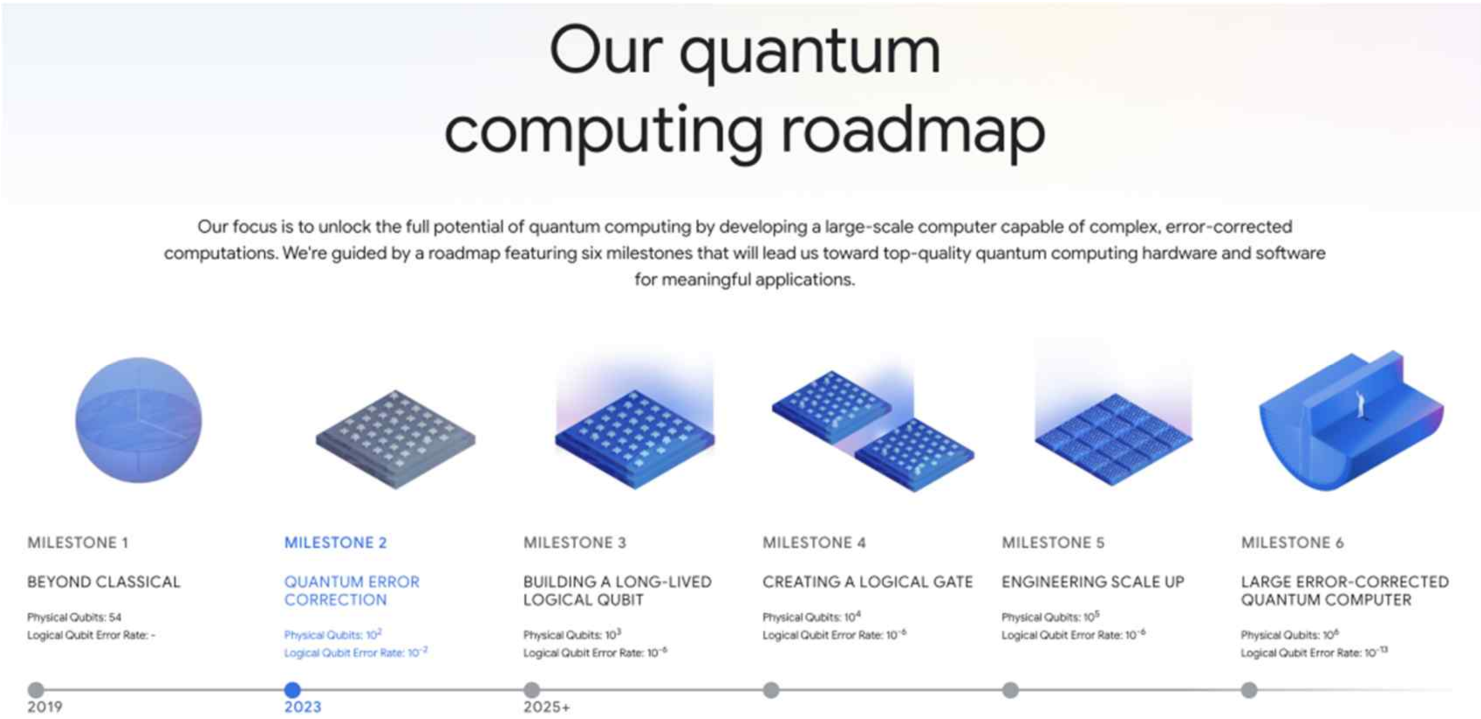
# Quantum computer



# Quantum computer



# Quantum computer




2023.2.22 at https://blog.google/inside-google/message-ceo/our-progress-toward-quantum-error-correction/

# Quantum computer


2024.12.9 at https://blog.google/technology/research/google-willow-quantum-chip/

# Random circuit sampling

**Article**

## Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5
Received: 22 July 2019
Accepted: 20 September 2019
Published online: 23 October 2019

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[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], 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]*

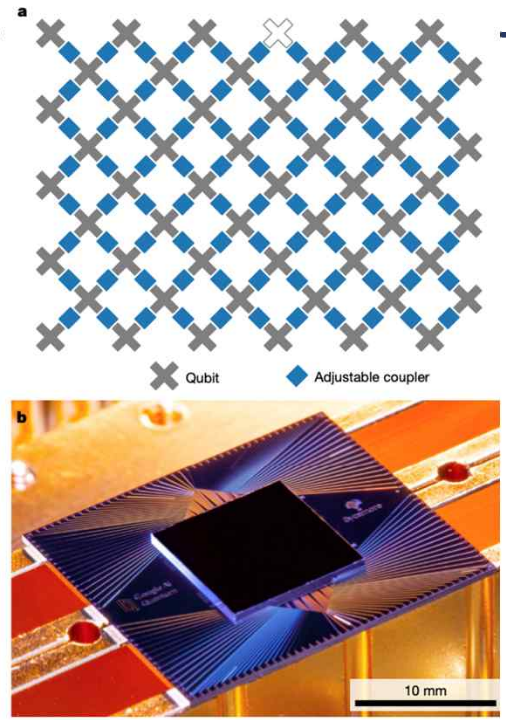


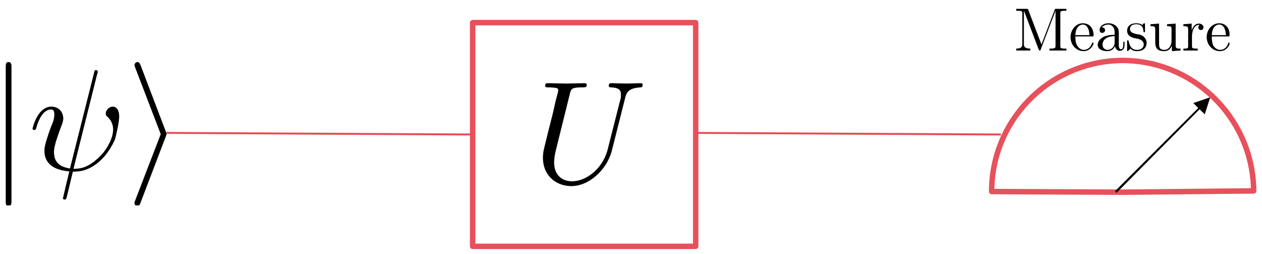

**Fig. 1 | The Sycamore processor. a**, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

# Quantum supremacy (양자 우월성)

- 샘플링

  - 통계의 목적으로 전체 분포의 특성을 파악하기 위해  모집단에서 표본을 골라내는 일

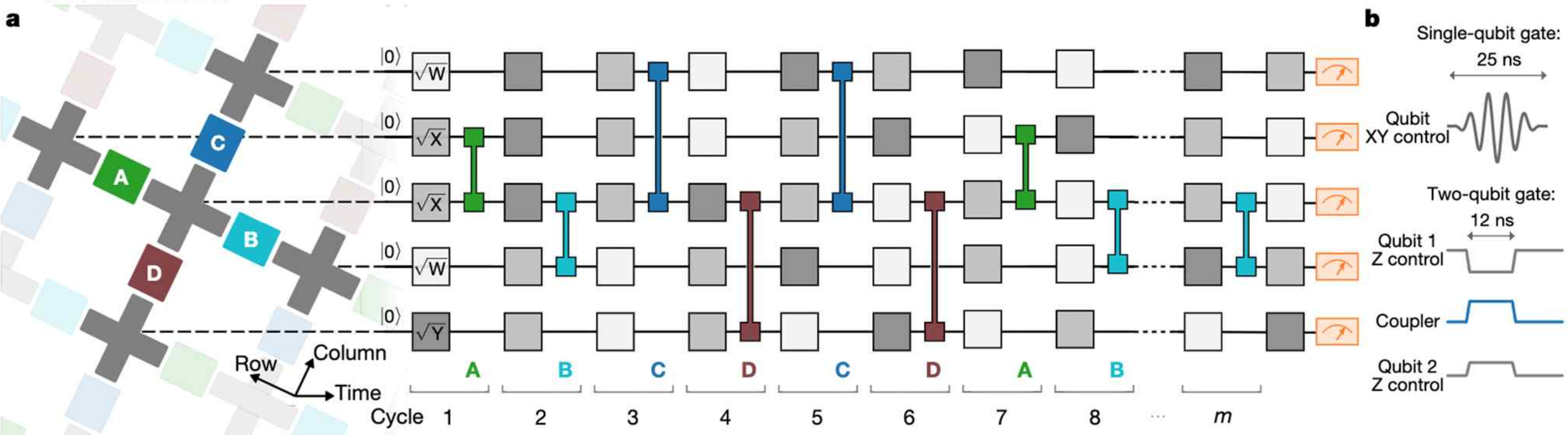
  - 양자 측정이 갖는 통계의 무작위성은 양자 역학이 갖는 가장 근본적 특성 중 하나이다.



# Quantum supremacy (양자 우월성)

- Sampling

  - In statistics, sampling is the selection of a subset (a statistical sample) of individuals from within a statistical population to estimate characteristics of the whole population



# Quantum supremacy (양자 우월성)

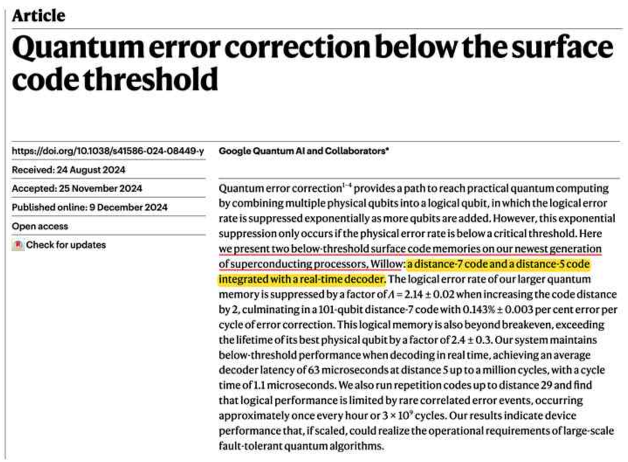
- Random Circuit Sampling (RCS)

  - The task is to take an (efficient) quantum circuit of a specific form, in which each gate is chosen randomly, and generate samples from its output distribution.

| | Worst-case hardness | Average-case hardness | Anti-Concentration | Experimentally Feasible |
|---|---|---|---|---|
| RCS | OK | OK<br>(Nature physics, 2019) | OK | OK<br>(Nature physics, 2018) |

  - Average-case hardness: showing that a distribution D is uniformly difficult to sample from corresponds to showing that for most outputs x, it is hard to compute D(x).
  - Anti-concentration states that the output distribution of random quantum circuit is ‘spread out'.

# Quantum computer



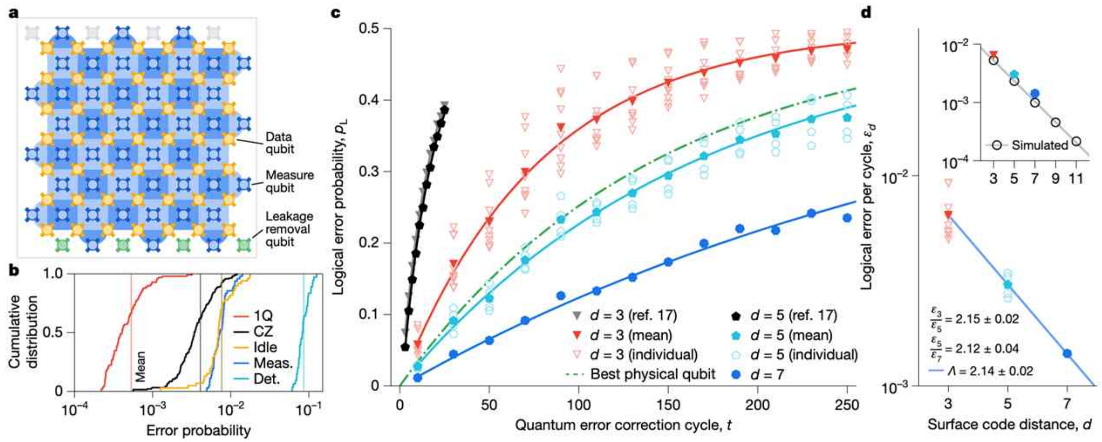
Article

**Quantum error correction below the surface code threshold**

https://doi.org/10.1038/s41586-024-08449-y
Received: 24 August 2024
Accepted: 25 November 2024
Published online: 9 December 2024
Open access
Check for updates

Google Quantum AI and Collaborators*

Quantum error correction[1-4] provides a path to reach practical quantum computing by combining multiple physical qubits into a logical qubit, in which the logical error rate is suppressed exponentially as more qubits are added. However, this exponential suppression only occurs if the physical error rate is below a critical threshold. Here we present two below-threshold surface code memories on our newest generation of superconducting processors, Willow: a distance-7 code and a distance-5 code integrated with a real-time decoder. The logical error rate of our larger quantum memory is suppressed by a factor of $\Lambda = 2.14 \pm 0.02$ when increasing the code distance by 2, culminating in a 101-qubit distance-7 code with $0.143\% \pm 0.003$ per cent error per cycle of error correction. This logical memory is also beyond breakeven, exceeding the lifetime of its best physical qubit by a factor of $2.4 \pm 0.3$. Our system maintains below-threshold performance when decoding in real time, achieving an average decoder latency of 63 microseconds at distance 5 up to a million cycles, with a cycle time of 1.1 microseconds. We also run repetition codes up to distance 29 and find that logical performance is limited by rare correlated error events, occurring approximately once every hour or $3 \times 10^9$ cycles. Our results indicate device performance that, if scaled, could realize the operational requirements of large-scale fault-tolerant quantum algorithms.




*Nature* **638**, 920–926 (2025).

# Quantum computer

## How to factor 2048 bit RSA integers with less than a million noisy qubits

Craig Gidney

Google Quantum AI, Santa Barbara, California 93117, USA

June 9, 2025

Planning the transition to quantum-safe cryptosystems requires understanding the cost of quantum attacks on vulnerable cryptosystems. In Gidney+Ekerå 2019, I co-published an estimate stating that 2048 bit RSA integers could be factored in eight hours by a quantum computer with 20 million noisy qubits. In this paper, I substantially reduce the number of qubits required. I estimate that a 2048 bit RSA integer could be factored in less than a week by a quantum computer with less than a million noisy qubits. I make the same assumptions as in 2019: a square grid of qubits with nearest neighbor connections, a uniform gate error rate of 0.1%, a surface code cycle time of 1 microsecond, and a control system reaction time of 10 microseconds.

The qubit count reduction comes mainly from using approximate residue arithmetic (Chevignard+Fouque+Schrottenloher 2024), from storing idle logical qubits with yoked surface codes (Gidney+Newman+Brooks+Jones 2023), and from allocating less space to magic state distillation by using magic state cultivation (Gidney+Shutty+Jones 2024). The longer runtime is mainly due to performing more Toffoli gates and using fewer magic state factories compared to Gidney+Ekerå 2019. That said, I reduce the Toffoli count by over 100x compared to Chevignard+Fouque+Schrottenloher 2024.

- 기존 연구 (Gidney+Ekerå, 2019)
  - 2,048비트 RSA를 소인수분해하는 데 **약 2,000만 개의 noisy qubits** 필요
  - 시간: **약 8시간**
- 본 논문의 개선점
  - 노이즈 큐비트 수 대폭 감소: **100만 개 미만의 noisy qubits**로 수행 가능
  - 시간은 증가: **1주일 이내**
- 공통 가정 (2019년과 동일):
  - 큐비트는 이웃 연결을 가지는 **정사각형 격자형 구조**
  - **게이트 오류율: 0.1%**
- **매직 스테이트 증류 공간 절약**
- 런타임 증가의 주요 원인:
  - 더 많은 Toffoli 게이트 수행
  - Magic state factory 개수 감소
- 성능 개선
  - Toffoli 게이트 수, 2024년 Chevignard 등 연구 대비 100배 이상 감소

# Quantum computer

## How to factor 2048 bit RSA integers with less than a million noisy qubits

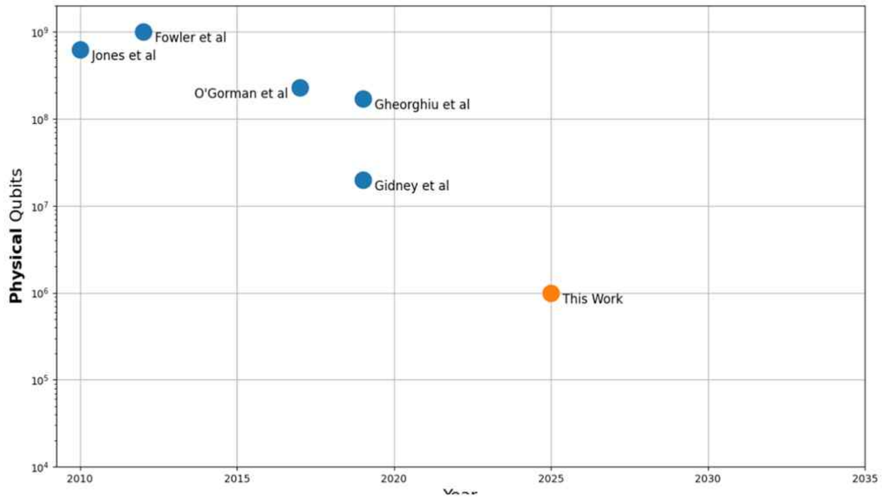
Craig Gidney

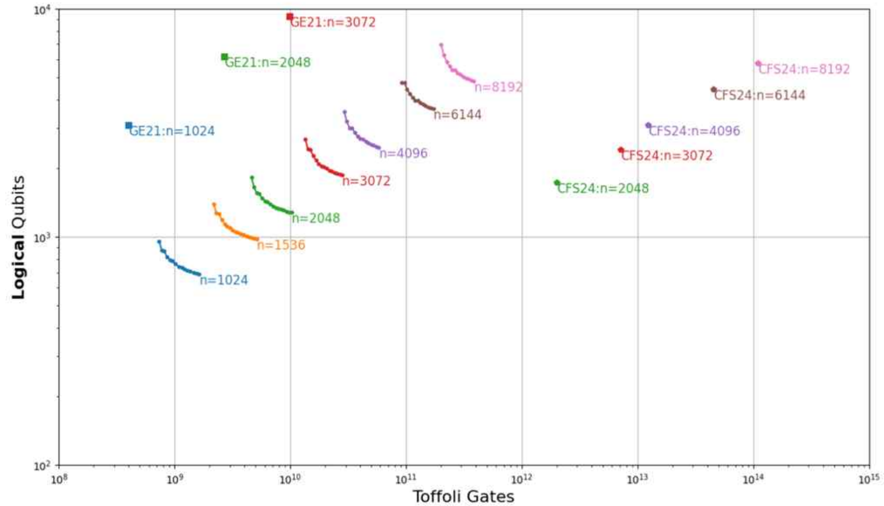
Google Quantum AI, Santa Barbara, California 93117, USA

June 9, 2025

Planning the transition to quantum-safe cryptosystems requires understanding the cost of quantum attacks on vulnerable cryptosystems. In Gidney+Ekerå 2019, I co-published an estimate stating that 2048 bit RSA integers could be factored in eight hours by a quantum computer with 20 million noisy qubits. In this paper, I substantially reduce the number of qubits required. I estimate that a 2048 bit RSA integer could be factored in less than a week by a quantum computer with less than a million noisy qubits. I make the same assumptions as in 2019: a square grid of qubits with nearest neighbor connections, a uniform gate error rate of 0.1%, a surface code cycle time of 1 microsecond, and a control system reaction time of 10 microseconds.

The qubit count reduction comes mainly from using approximate residue arithmetic (Chevignard+Fouque+Schrottenloher 2024), from storing idle logical qubits with yoked surface codes (Gidney+Newman+Brooks+Jones 2023), and from allocating less space to magic state distillation by using magic state cultivation (Gidney+Shutty+Jones 2024). The longer runtime is mainly due to performing more Toffoli gates and using fewer magic state factories compared to Gidney+Ekerå 2019. That said, I reduce the Toffoli count by over 100x compared to Chevignard+Fouque+Schrottenloher 2024.



# Quantum computer

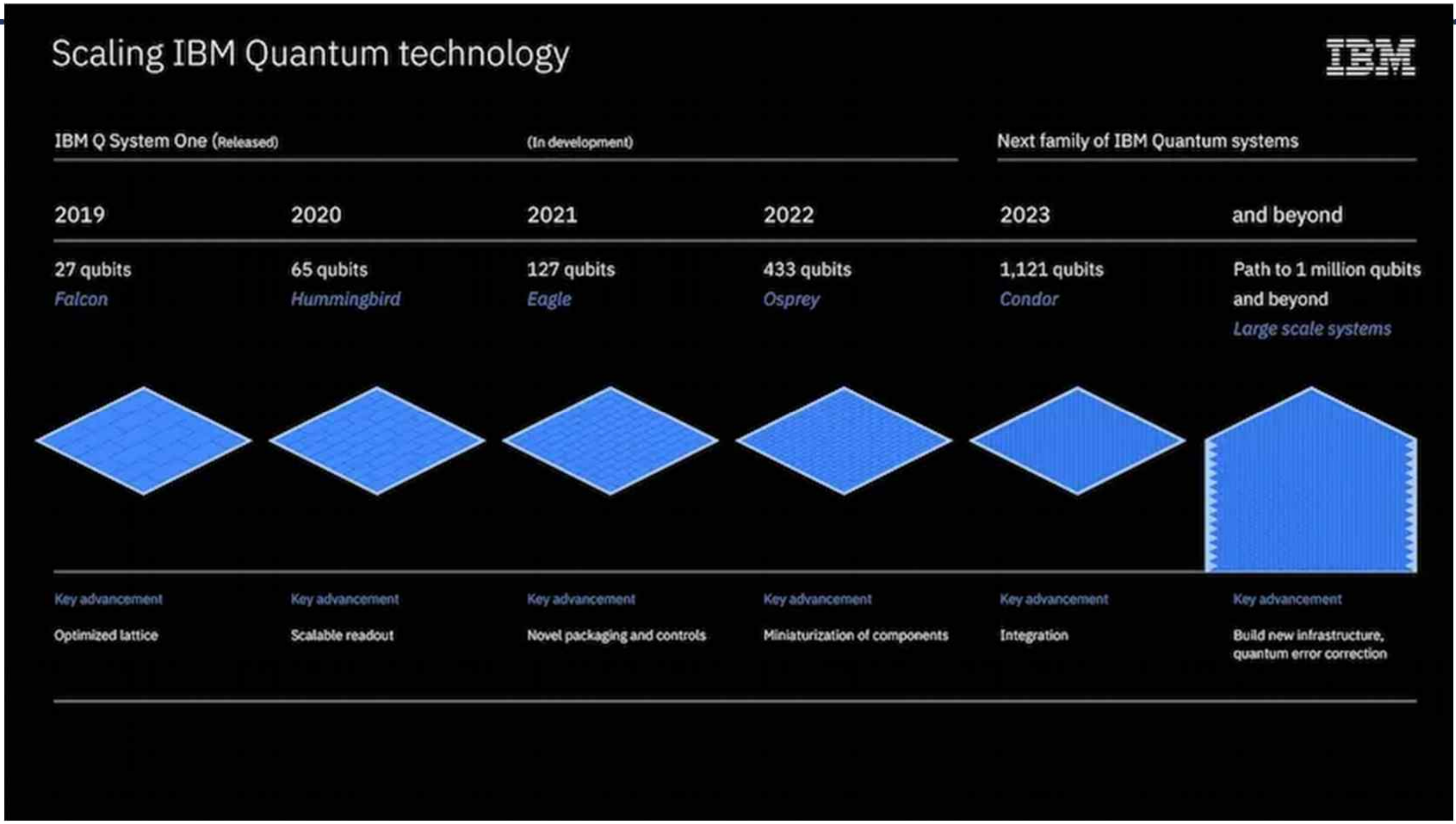
- IBM (2016)
  - Superconducting qubit (초전도 큐비트)
  - Cloud computing service



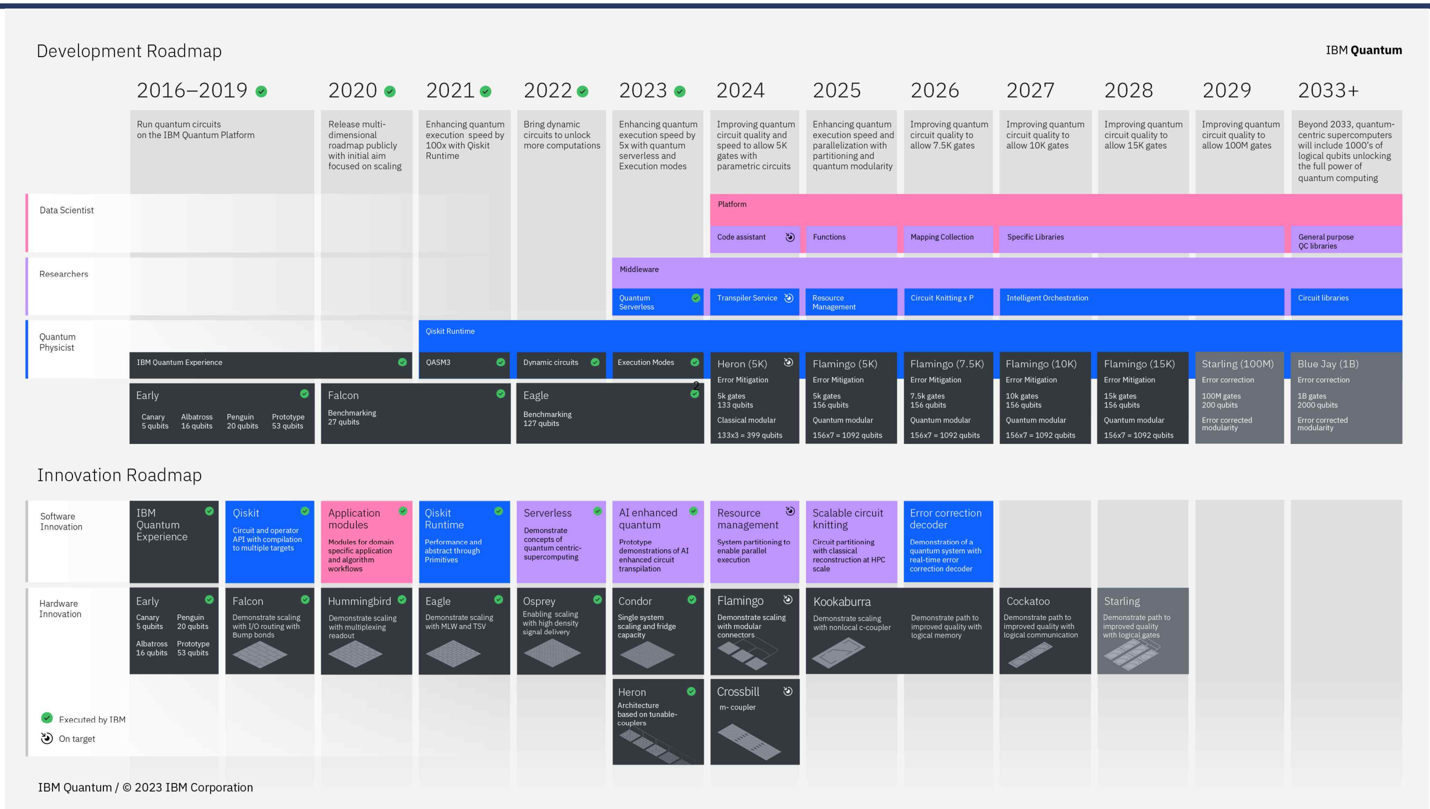
IBM 50Q System: An IBM cryostat wired for a 50 qubit system.

https://currencies.ru/ibm-rolls-out-its-first-quantum-computer-crypto-industry-19011013085120.htm
https://cdrinfo.com/d7/content/ibm-prototypes-50-qubit-quantum-computer

# Quantum computer



# Quantum computer: IBMQ Roadmap



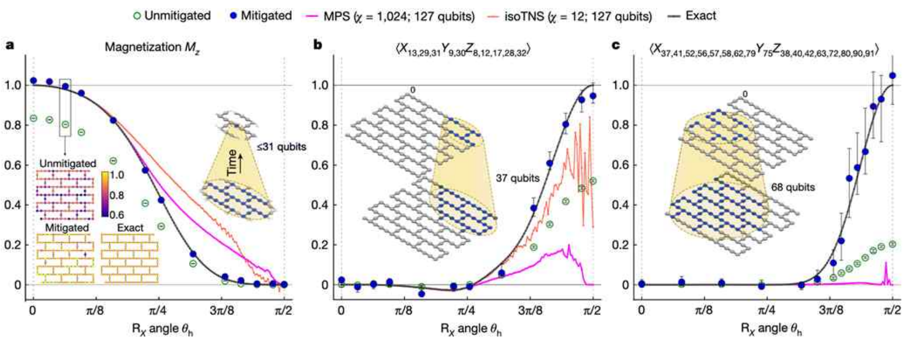
# Quantum computer

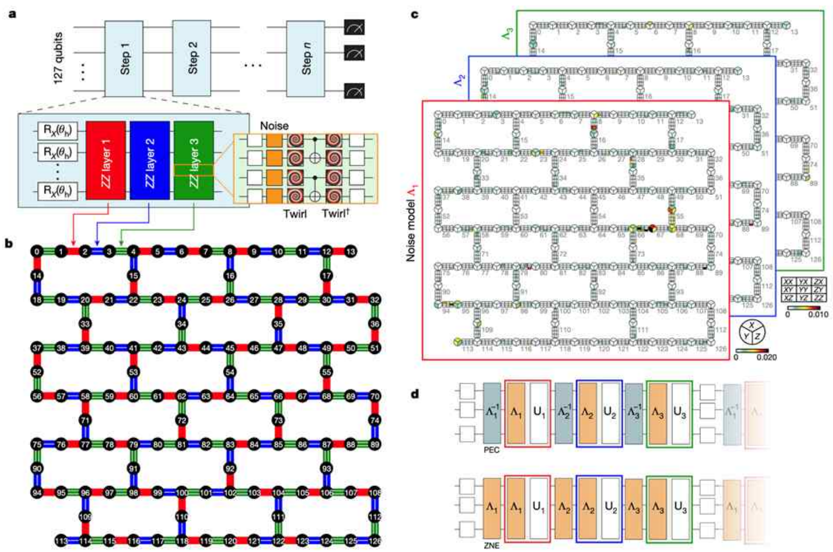
**Article**

## Evidence for the utility of quantum computing before fault tolerance

https://doi.org/10.1038/s41586-023-06096-3
Received: 24 February 2023
Accepted: 18 April 2023

Youngseok Kim[1,6✉], Andrew Eddins[2,6✉], Sajant Anand[3], Ken Xuan Wei[1], Ewout van den Berg[1], Sami Rosenblatt[1], Hasan Nayfeh[1], Yantao Wu[3,4], Michael Zaletel[3,5], Kristan Temme[1] & Abhinav Kandala[1✉]




*Nature* **618**, 500–505 (2023).

# Quantum computer

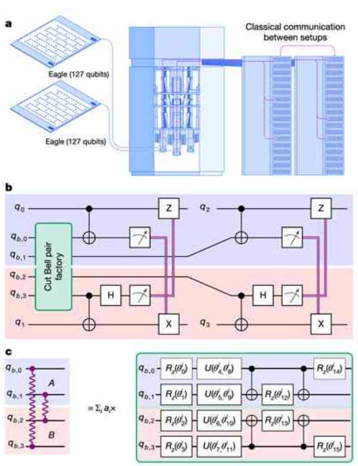
Article

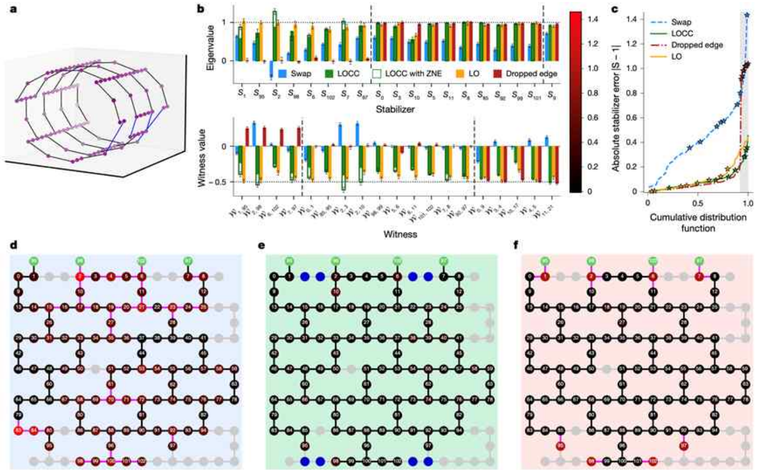
## Combining quantum processors with real-time classical communication

https://doi.org/10.1038/s41586-024-08178-2
Received: 21 March 2024
Accepted: 8 October 2024
Published online: 20 November 2024
Open access
Check for updates

Almudena Carrera Vazquez[1], Caroline Tornow[1,2], Diego Ristè[3], Stefan Woerner[1], Maika Takita[4] & Daniel J. Egger[1]✉

Quantum computers process information with the laws of quantum mechanics. Current quantum hardware is noisy, can only store information for a short time and is limited to a few quantum bits, that is, qubits, typically arranged in a planar connectivity[1]. However, many applications of quantum computing require more connectivity than the planar lattice offered by the hardware on more qubits than is available on a single quantum processing unit (QPU). The community hopes to tackle these limitations by connecting QPUs using classical communication, which has not yet been proven experimentally. Here we experimentally realize error-mitigated dynamic circuits and circuit cutting to create quantum states requiring periodic connectivity using up to 142 qubits spanning two QPUs with 127 qubits each connected in real time with a classical link. In a dynamic circuit, quantum gates can be classically controlled by the outcomes of mid-circuit measurements within run-time, that is, within a fraction of the coherence time of the qubits. Our real-time classical link enables us to apply a quantum gate on one QPU conditioned on the outcome of a measurement on another QPU. Furthermore, the error-mitigated control flow enhances qubit connectivity and the instruction set of the hardware thus increasing the versatility of our quantum computers. Our work demonstrates that we can use several quantum processors as one with error-mitigated dynamic circuits enabled by a real-time classical link.




*Nature* **636**, 75–79 (2024).

# Quantum computer

Article

## High-threshold and low-overhead fault-tolerant quantum memory

https://doi.org/10.1038/s41586-024-07107-7

Received: 25 August 2023

Accepted: 23 January 2024

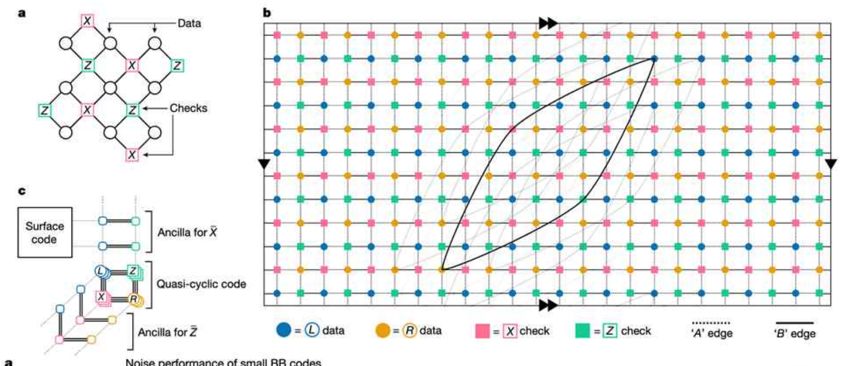
Published online: 27 March 2024

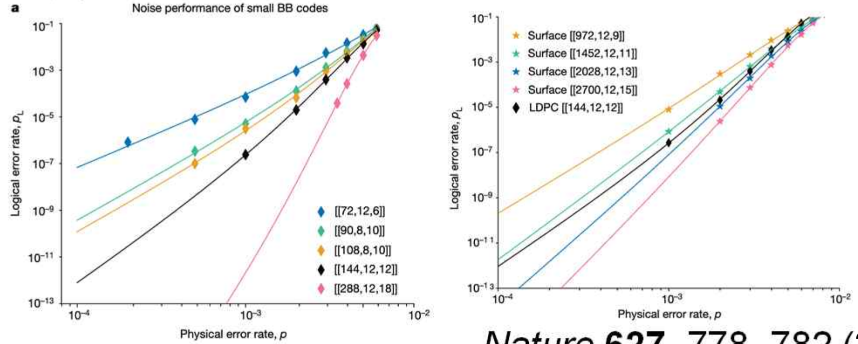
Open access

Check for updates

Sergey Bravyi[1], Andrew W. Cross[1], Jay M. Gambetta[1], Dmitri Maslov[1]✉, Patrick Rall[2] & Theodore J. Yoder[1]

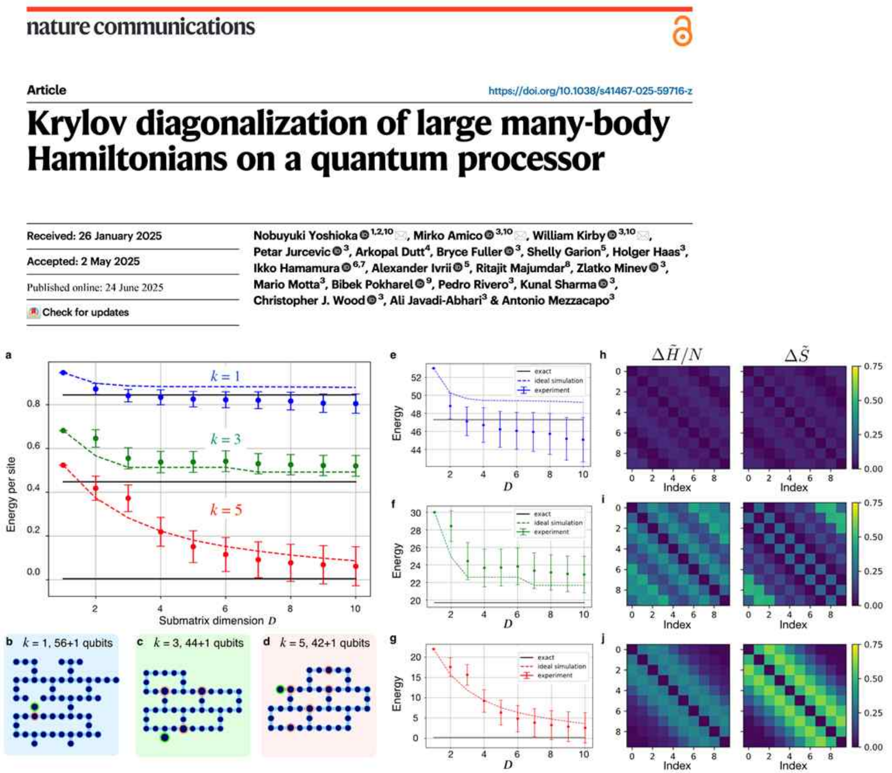
The accumulation of physical errors[1–3] prevents the execution of large-scale algorithms in current quantum computers. Quantum error correction[4] promises a solution by encoding $k$ logical qubits onto a larger number $n$ of physical qubits, such that the physical errors are suppressed enough to allow running a desired computation with tolerable fidelity. Quantum error correction becomes practically realizable once the physical error rate is below a threshold value that depends on the choice of quantum code, syndrome measurement circuit and decoding algorithm[5]. We present an end-to-end quantum error correction protocol that implements fault-tolerant memory on the basis of a family of low-density parity-check codes[6]. Our approach achieves an error threshold of 0.7% for the standard circuit-based noise model, on par with the surface code[7–10] that for 20 years was the leading code in terms of error threshold. The syndrome measurement cycle for a length-$n$ code in our family requires $n$ ancillary qubits and a depth-8 circuit with CNOT gates, qubit initializations and measurements. The required qubit connectivity is a degree-6 graph composed of two edge-disjoint planar subgraphs. In particular, we show that 12 logical qubits can be preserved for nearly 1 million syndrome cycles using 288 physical qubits in total, assuming the physical error rate of 0.1%, whereas the surface code would require nearly 3,000 physical qubits to achieve said performance. Our findings bring demonstrations of a low-overhead fault-tolerant quantum memory within the reach of near-term quantum processors.




*Nature* **627**, 778–782 (2024).

# Quantum computer


nature communications

Article

https://doi.org/10.1038/s41467-025-59716-z

**Krylov diagonalization of large many-body Hamiltonians on a quantum processor**

Received: 26 January 2025

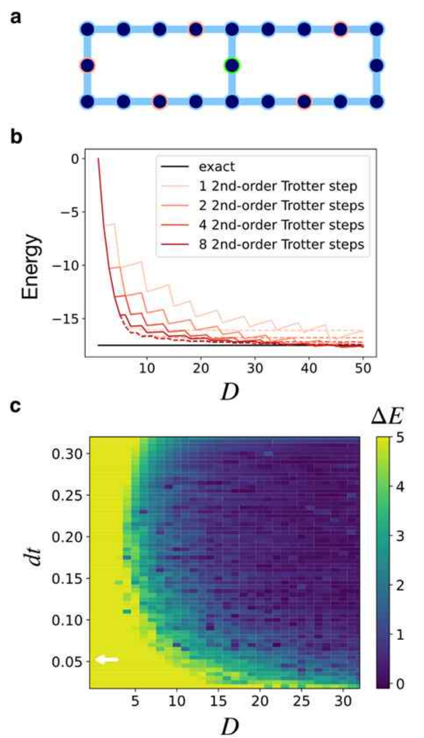
Accepted: 2 May 2025

Published online: 24 June 2025

Check for updates

Nobuyuki Yoshioka[1,2,10], Mirko Amico[3,10], William Kirby[3,10], Petar Jurcevic[3], Arkopal Dutt[4], Bryce Fuller[3], Shelly Garion[5], Holger Haas[3], Ikko Hamamura[6,7], Alexander Ivrii[5], Ritajit Majumdar[8], Zlatko Minev[3], Mario Motta[3], Bibek Pokharel[9], Pedro Rivero[3], Kunal Sharma[3], Christopher J. Wood[3], Ali Javadi-Abhari[3] & Antonio Mezzacapo[3]



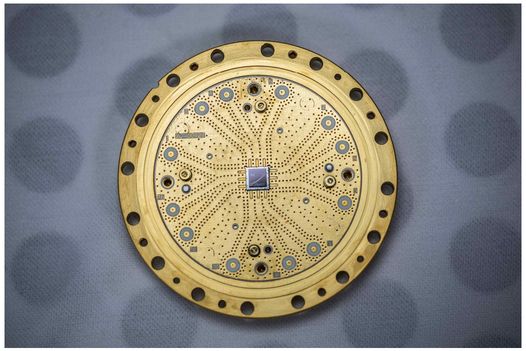



*Nat. Commun.* **16**, 5014 (2025).

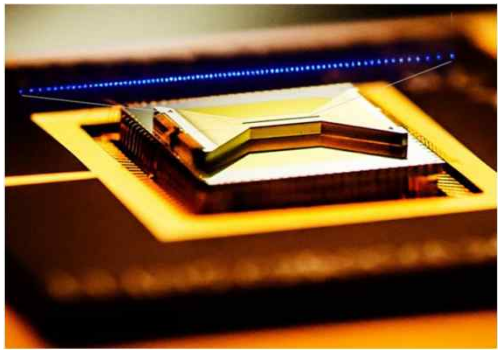
# Quantum computer

- Amazon (2019)

rigetti | IONQ | D:Wave The Quantum Computing Company™



Superconducting qubit

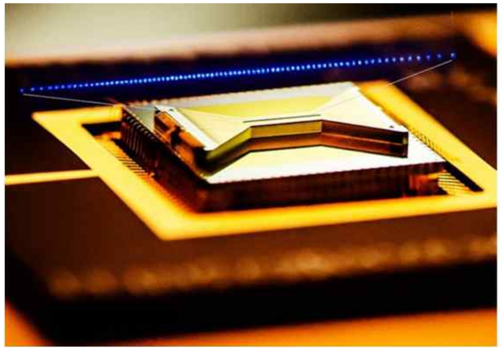


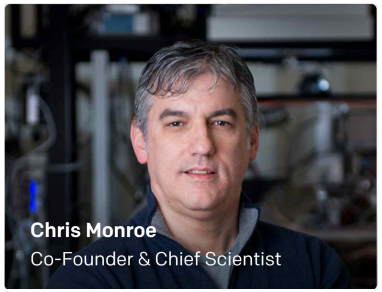
Trapped ion qubit

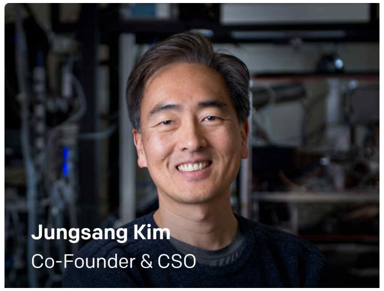
Superconducting

# Quantum computer

- IONQ (2015) IONQ





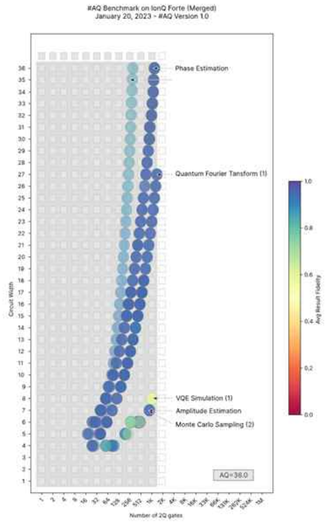




## #AQ 36

**With Configurable Error Mitigation**

Forte is the world's most useful quantum computer. #AQ measures the usefulness of a quantum computer. For example, with Forte's configurable error mitigation, #AQ 36 would mean you could successfully run quantum algorithms of ~980 entangling gates on up to 36 qubits.

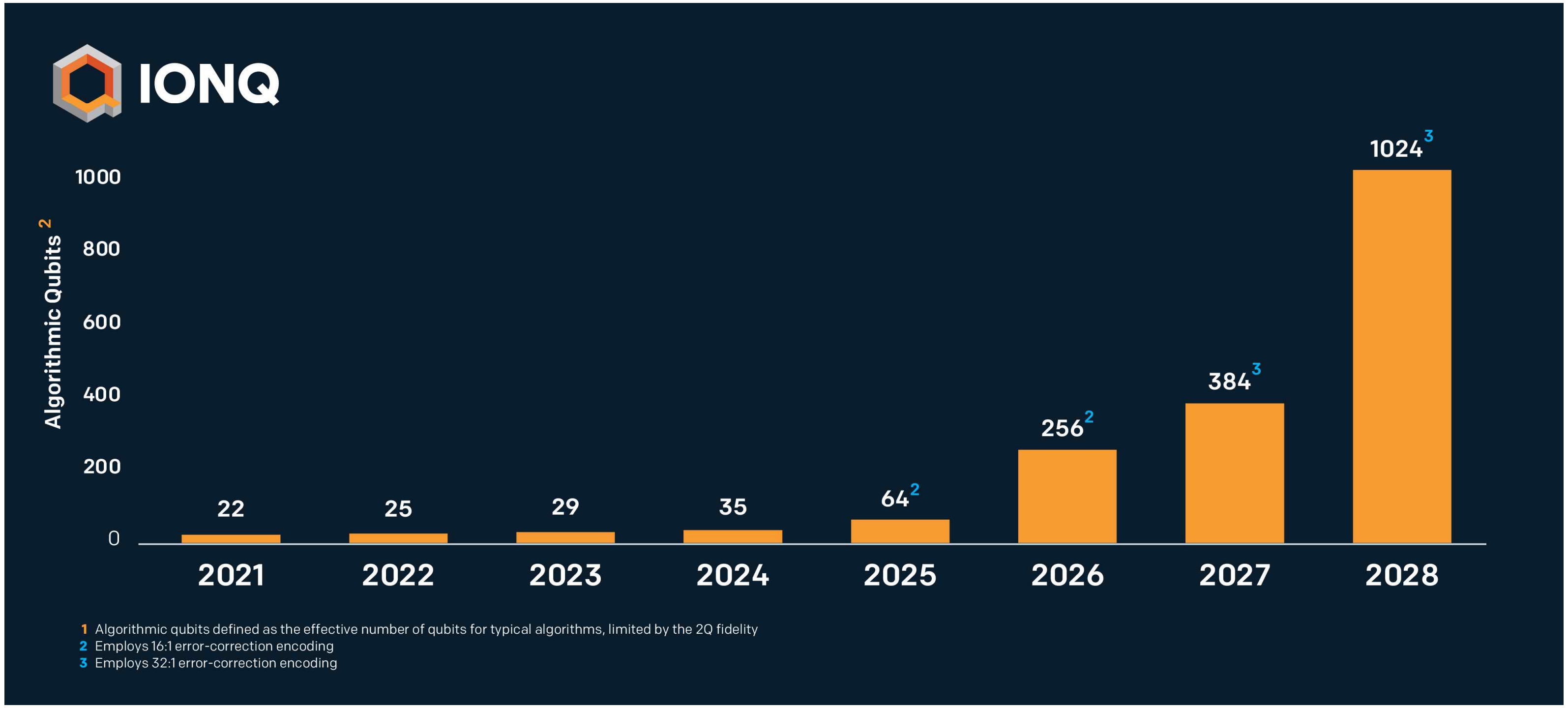
Learn more about AQ →




The above figure shows the measurement results for the various industry used benchmark algorithms on IonQ Forte

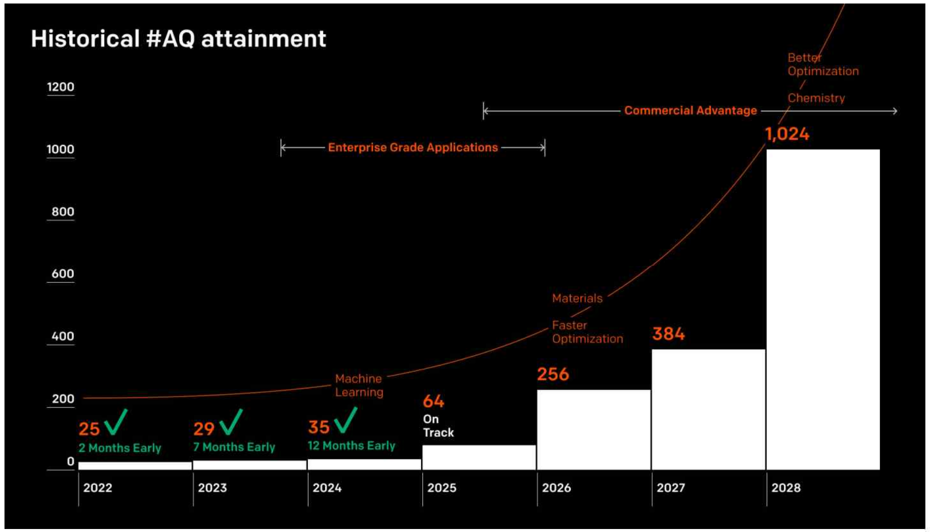
| | | |
|---|---|---|
| **36**<br>#AQ<br>With Configurable Error Mitigation | **36**<br>Qubit Count | **0.02%**<br>1-Qubit Gate Error |
| **0.4%**<br>2-Qubit Gate Error | **0.5%**<br>SPAM Error | **10–100s, ~1s**<br>T1 & T2 Time |

# Quantum computer




https://ionq.com/blog/december-09-2020-scaling-quantum-computer-roadmap

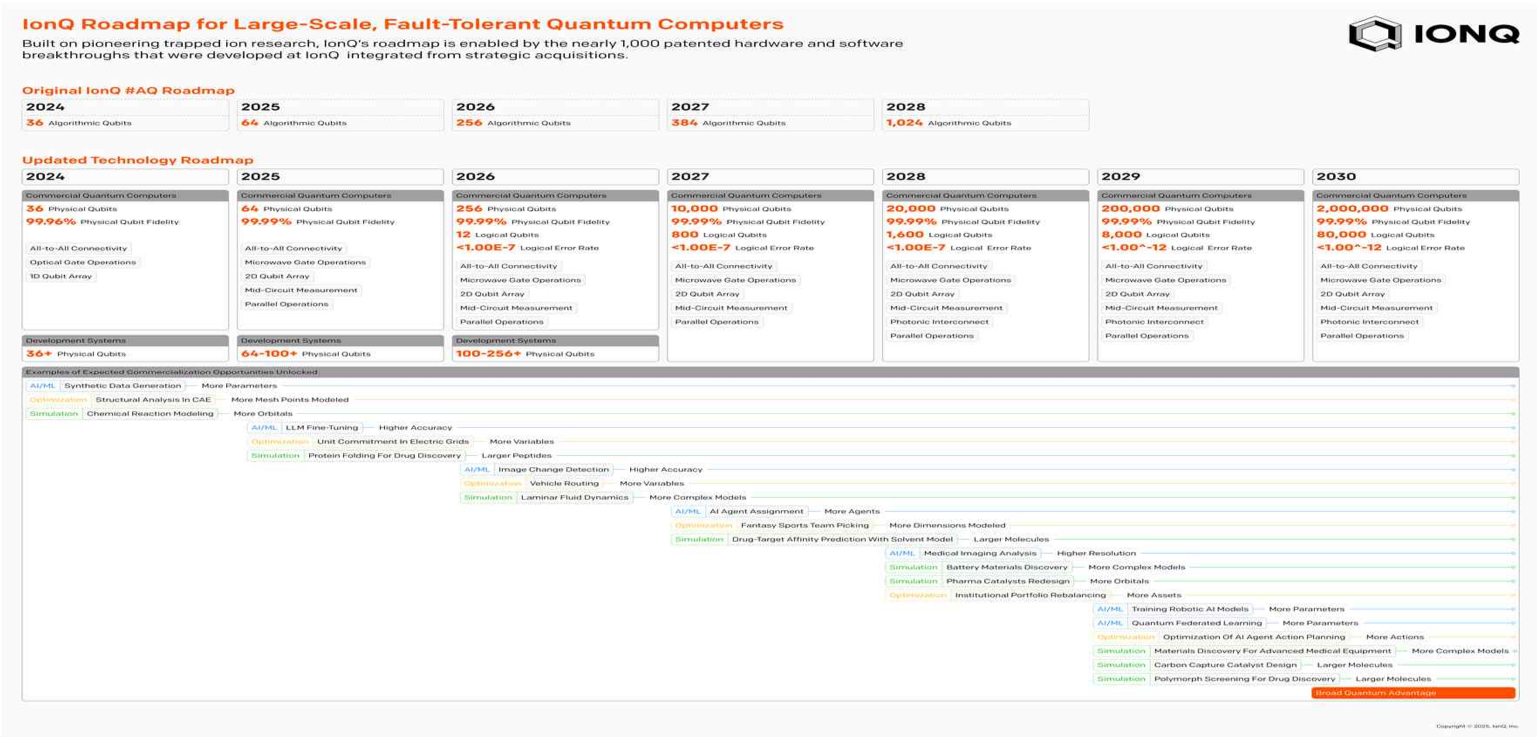
# Quantum computer: IonQ Roadmap




| | IonQ Aria<br>Learn More | Forte<br>Learn More | Forte Enterprise<br>Learn More |
|---|---|---|---|
| **System Availability** | | | |
| Commercial Availability | ✓ | ✓ | ✓ |
| System Sales | — | ✓ | ✓ |
| **Performance** | | | |
| Algorithmic Qubits (#AQ) | #AQ 25 | #AQ 36 | #AQ 36<br>Target |
| Physical Qubits | 25 | 36 | 36 |
| 2QG Fidelity | 99.4% | 99.6% | 99.6%<br>Target |
| 1QG Fidelity | 99.94% | 99.98% | 99.98%<br>Target |
| **Specifications** | | | |
| Connectivity | All-to-all | All-to-all | All-to-all |
| Operating System | First Gen | First Gen | First Gen |
| Laser System | Acousto-Optic Modulator | Acousto-Optic Deflector | Acousto-Optic Deflector |
| Error Mitigation | ✓ | ✓ | ✓ |

https://ionq.com/blog/how-we-achieved-our-2024-performance-target-of-

# Quantum computer: IonQ Roadmap




https://ionq.com/blog/ionqs-accelerated-roadmap-turning-quantum-ambition-into-reality

감사합니다.