Introduction to Superconducting Quantum Circuits

- Hello, Quantum World! -

Department of Electrical and Computer Engineering
Seoul National University

Seong Hyeon Park and Seungyong Hahn

14th February, 2025

Hello, Quantum World!, Introduction to Quantum Information Science

- Selected Applications of Quantum Science and Technology
  - Quantum sensing: sensors with better sensitivity and resolution
  - Quantum network: distributing quantum information
  - Quantum cryptography: privacy based on quantum mechanics
  - Quantum simulation: probes of exotic quantum physics
  - Quantum computing: computers to solve hard problems on classical computers

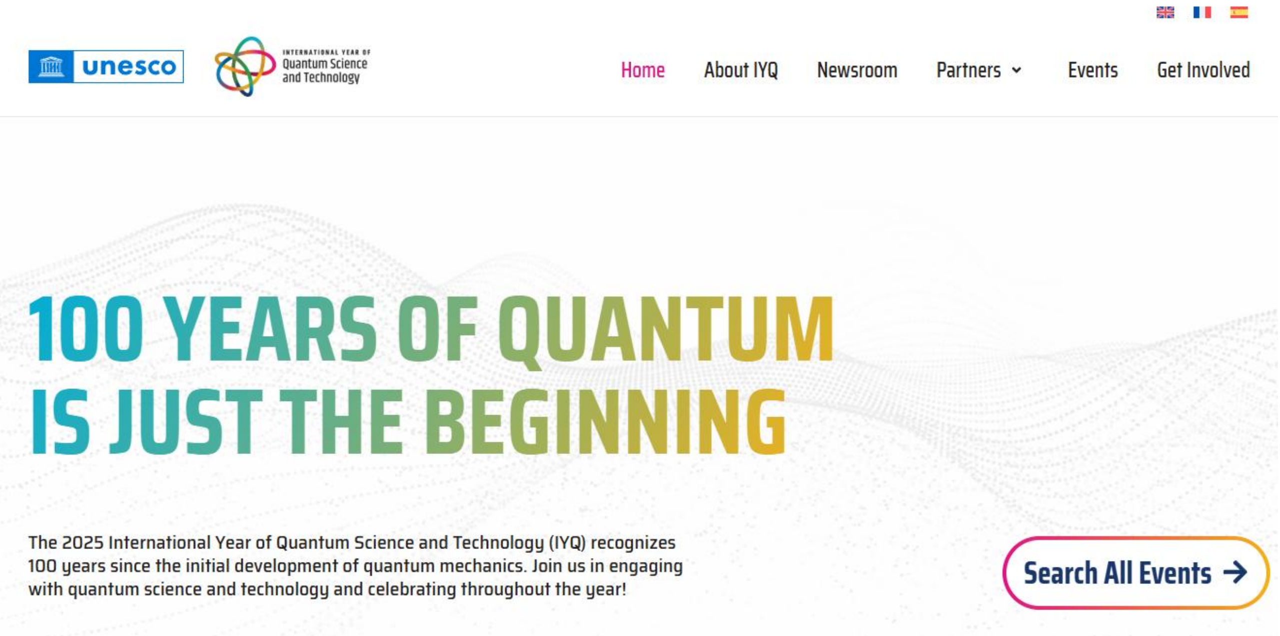


Fig. 2025 International Year of Quantum Science and Technology

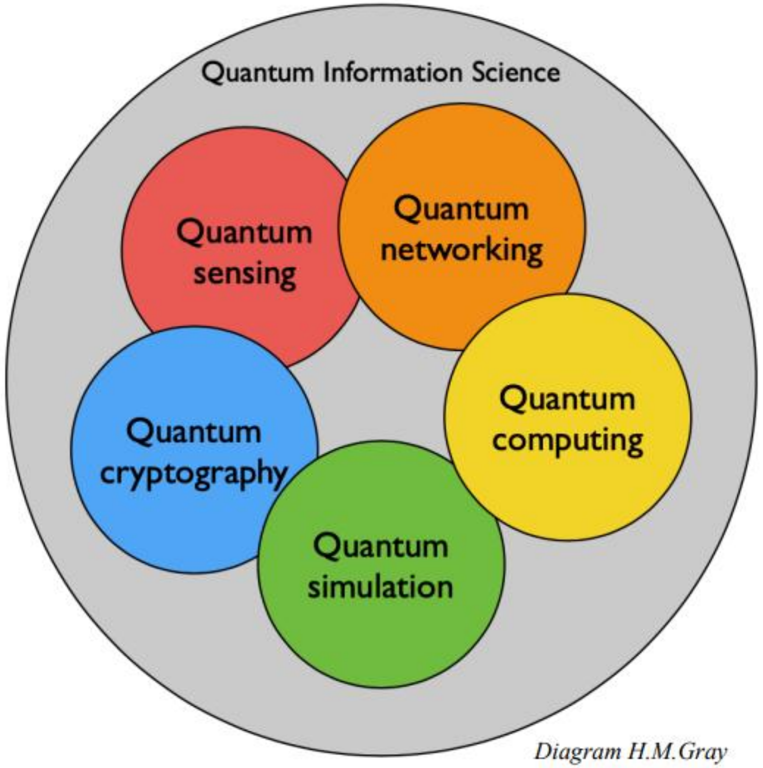


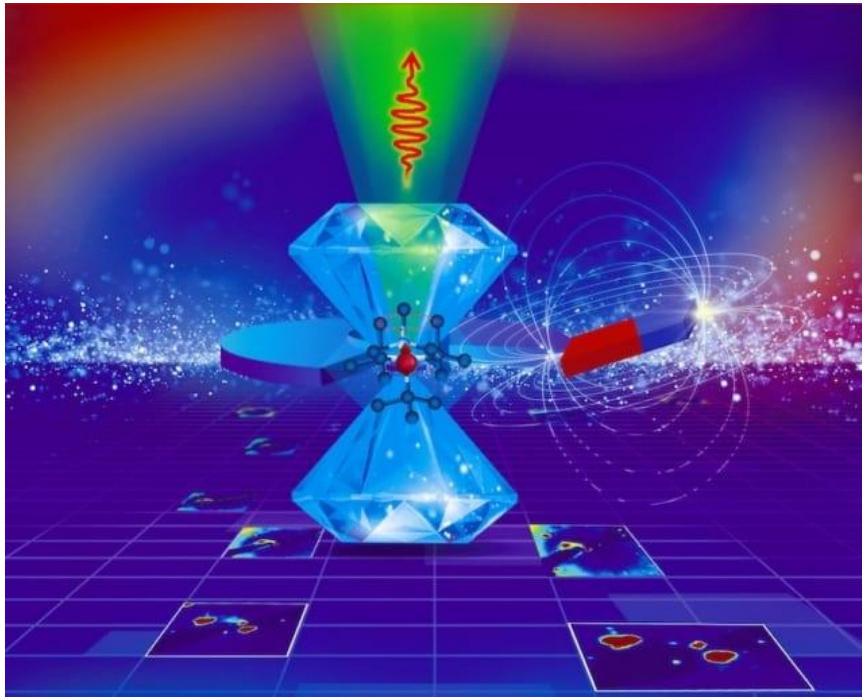
Fig. Applications of quantum information science

Image from https://indico.cern.ch/event/905399/contributions/4291625/attachments/2261097/3837872/vlimant_LHCP-QIS_June21.pdf

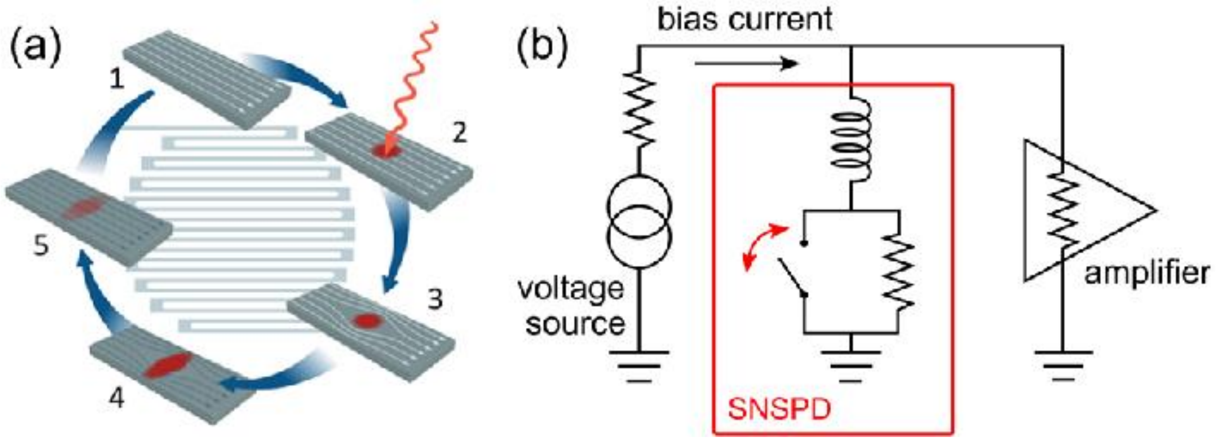
Quantum Sensing

- Since quantum systems are highly sensitive to external variations, sensors with better resolution can be developed
- Applications: (1) high-quality superconducting single-photon detectors, (2) diamond nitrogen-vacancy centers,…

Optically Detected Magnetic Resonance



Single Photon Detector



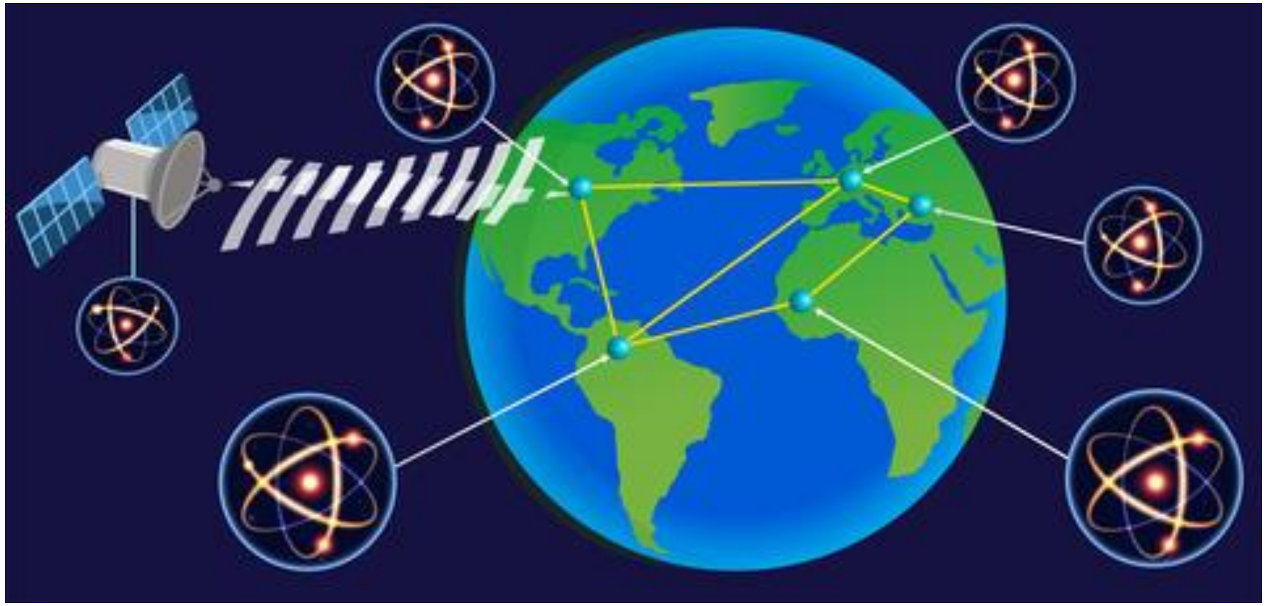
https://physicsworld.com/a/quantum-sensor-survives-at-record-high-pressures/
JA Lau *et al*., "Superconducting single-photon detectors in the mid-infrared for physical chemistry and spectroscopy," *Chem. Soc. Rev.*, **52**, 921-941 (2023).

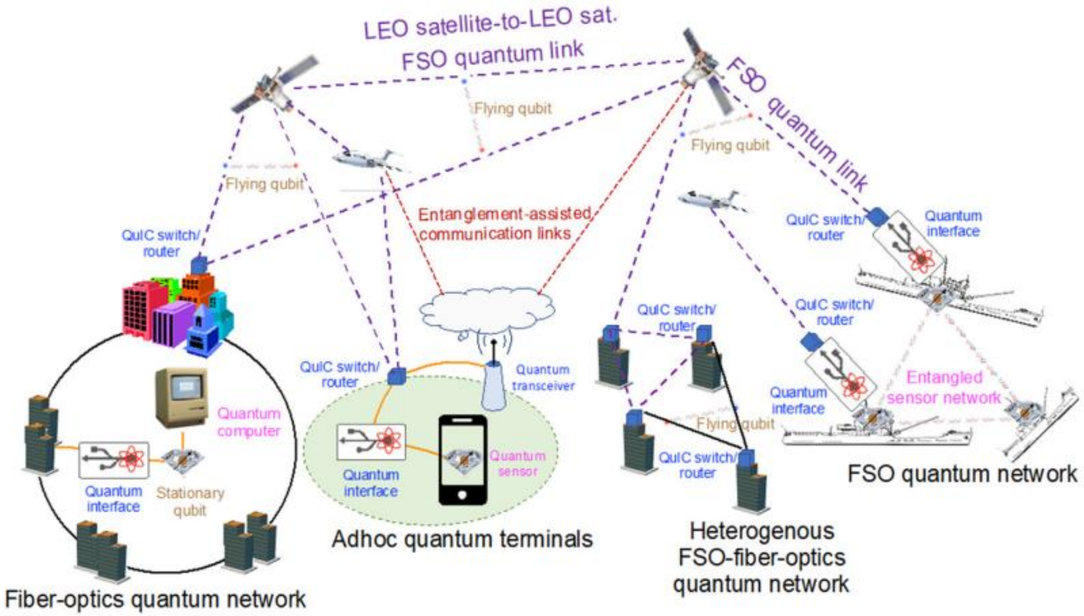
SH Park
<pajoheji0909@snu.ac.kr>

Quantum Networking

- Quantum network is a set of quantum nodes connected via quantum communication channels and auxiliary classical channels for stabilization, timing, and/or routing
- Using the quantum mechanical properties of qubits, secure communications can be developed over long-range

Conceptual Illustration of Quantum Networking

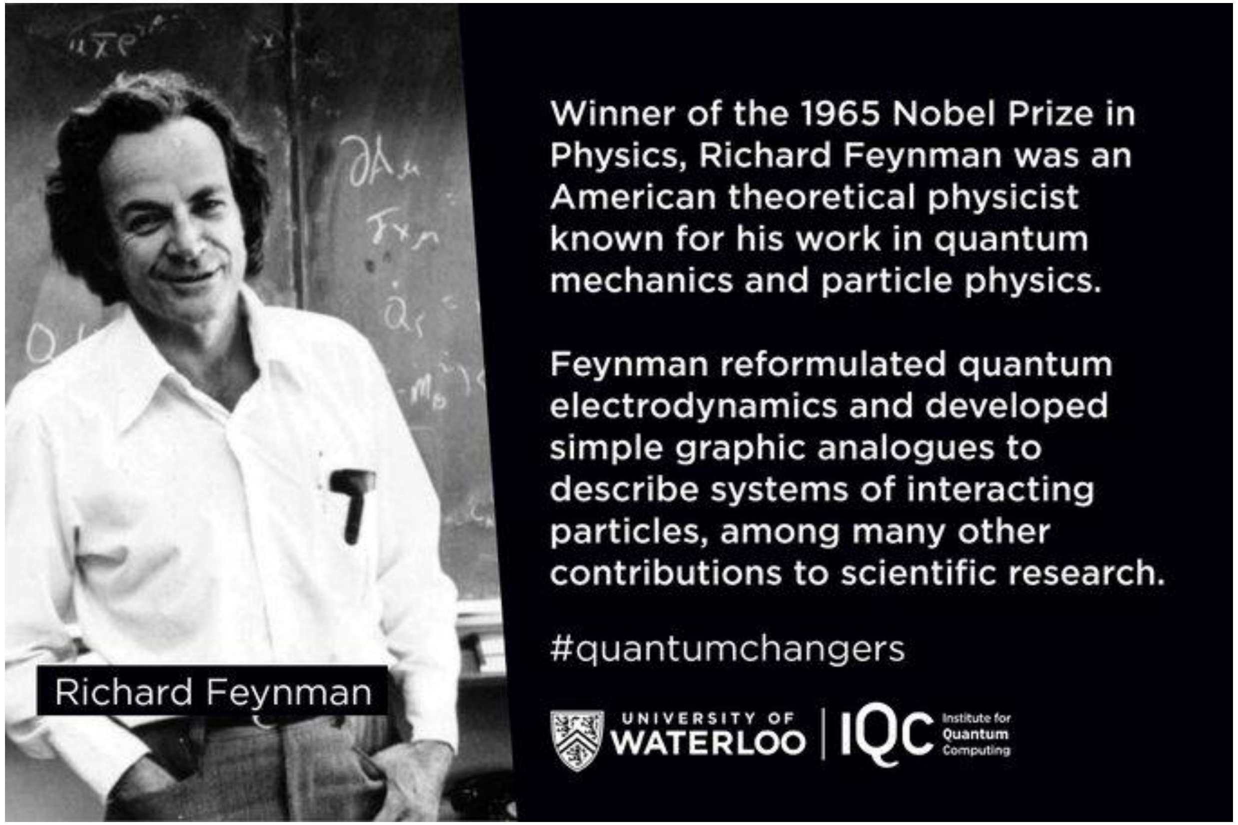




https://www.nist.gov/pml/quantum-networks-nist
AK Majumdar, *Optical Wireless Communications for Broadband Global Internet Connectivity*, Ch. 10, Elsevier (2019).

What Is “Quantum” Computing?

- Definition of Quantum Computing
  - A quantum computer is a computer that exploits quantum mechanical phenomena
  - Theoretically a large-scale quantum computer could break some widely used encryption schemes and aid physicists in performing physical simulations



Paul Benioff
(1930-2022)

Journal of Statistical Physics, Vol. 22, No. 5, 1980

The Computer as a Physical System: A Microscopic Quantum Mechanical Hamiltonian Model of Computers as Represented by Turing Machines

Paul Benioff[1,2]

Received June 11, 1979; revised August 9, 1979

In this paper a microscopic quantum mechanical model of computers as represented by Turing machines is constructed. It is shown that for each number N and Turing machine Q there exists a Hamiltonian $H_N{}^Q$ and a class of appropriate initial states such that if $\Psi_Q{}^N(0)$ is such an initial state, then $\Psi_Q{}^N(t) = \exp(-iH_N{}^Q t)\Psi_Q{}^N(0)$ correctly describes at times $t_3, t_6, \ldots, t_{3N}$ model states that correspond to the completion of the first, second,..., Nth computation step of Q. The model parameters can be adjusted so that for an arbitrary time interval Δ around $t_3, t_6, \ldots, t_{3N}$, the “machine” part of $\Psi_Q{}^N(t)$ is stationary.

KEY WORDS: Computer as a physical system; microscopic Hamiltonian models of computers; Schrödinger equation description of Turing machines; Coleman model approximation; closed conservative system; quantum spin lattices.

Introduction to Quantum Computing: (1) Qubit

Classical Bit and Quantum Bit (Qubit)

- Classical bit: “0” or “1”

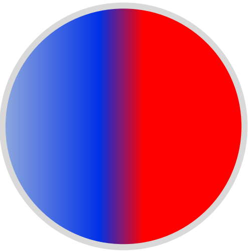
0 or 1

scales to n-bit

$\underbrace{\boxed{0 \text{ or } 1}\boxed{0 \text{ or } 1} \cdots \boxed{0 \text{ or } 1}\boxed{0 \text{ or } 1}}$

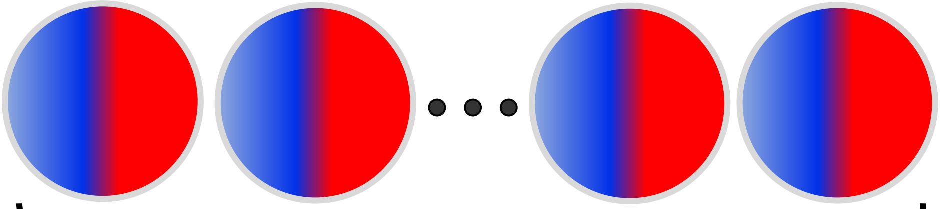
$|\psi\rangle$ is one of 2^n possible states

- Qubit: superposition of “0” and “1”

$|0\rangle$  $|1\rangle$

Superposition of $|0\rangle$ and $|1\rangle$

potential to compute 2^n states by entanglement



$$|\psi\rangle = c_1|0 \ldots 0\rangle + c_2|0 \ldots 1\rangle + \cdots + c_{2^n}|1 \ldots 1\rangle$$

- A complete description of a typical quantum state of just 300 qubits requires more bits than the number of atoms in the observable universe!

Quantum Logic Gates

- a quantum logic gate (or simply quantum gate) is a basic quantum circuit
- Quantum logic gates are the building blocks of quantum circuits, like classical logic gates (NOT and OR) are for conventional digital circuits

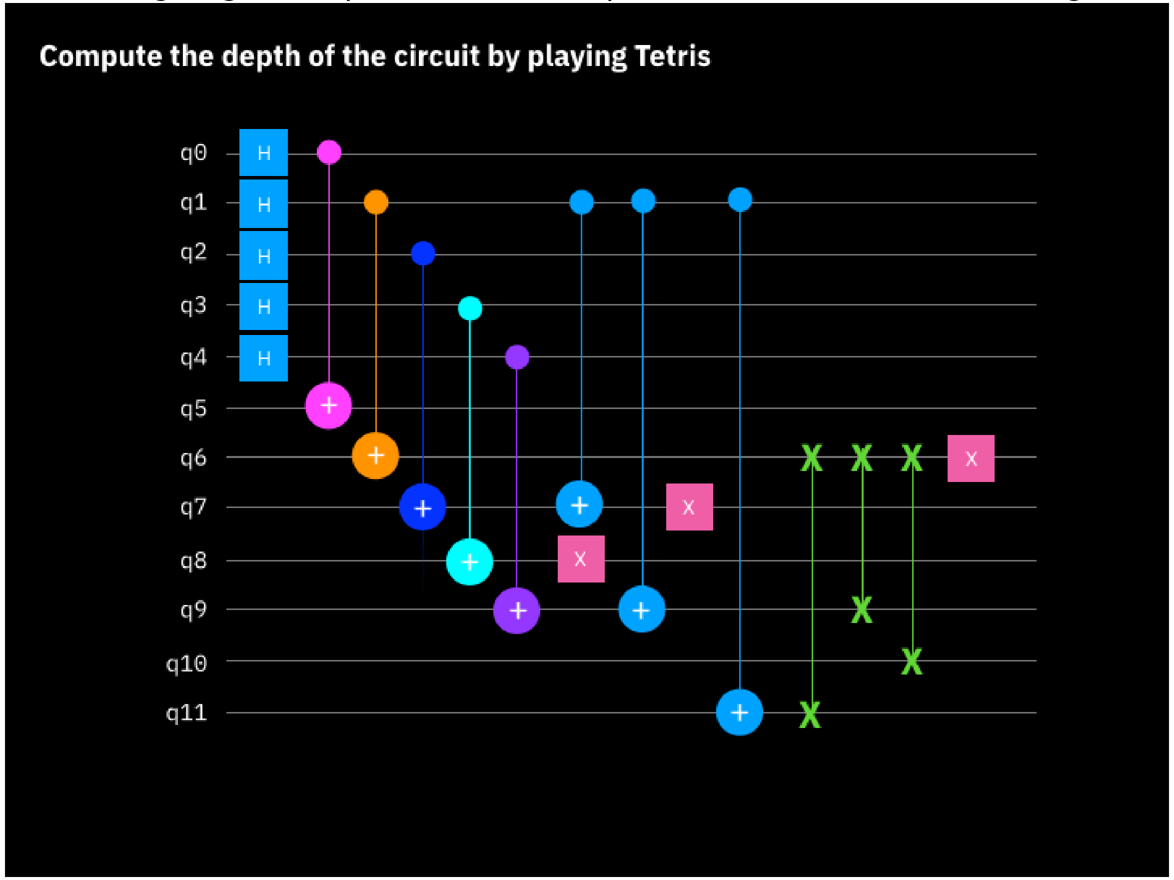


Fig. How quantum logic gates and circuits work in practice (with Qiskit)

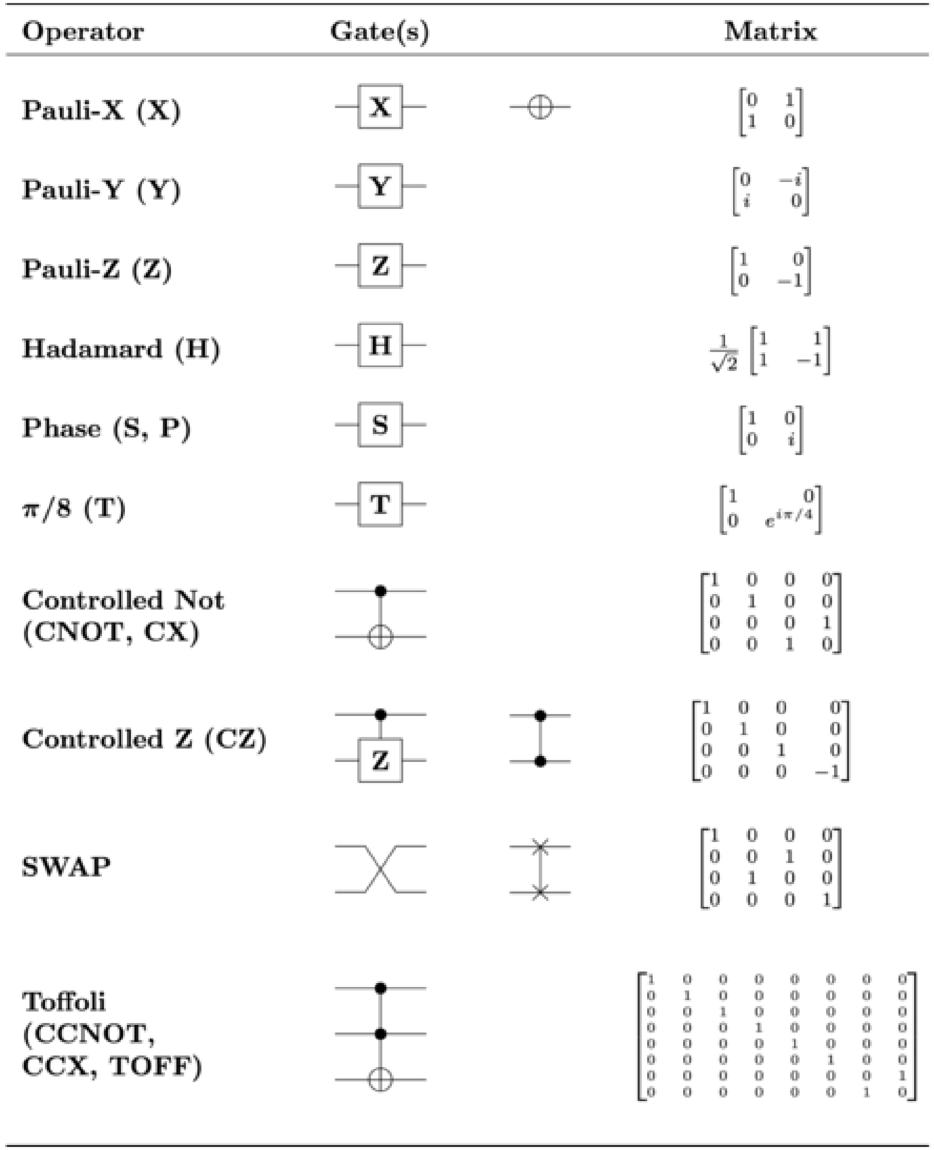


Fig. Common quantum logic gates and the corresponding unitary matrices.

- Selected Quantum Algorithms: Shor's Algorithm
  - Shor's algorithm is a quantum algorithm for finding the prime factors of an integer
  - Shor's algorithm: solves N in polynomial time
  - Classical algorithm: solves N in exponential time

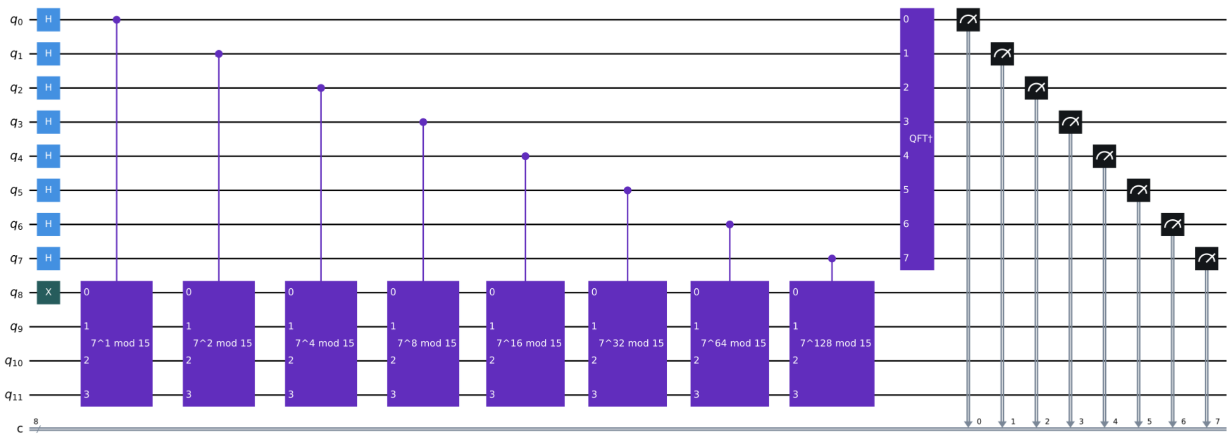


Fig. Shor's algorithm implemented using Qiskit

- Selected Quantum Algorithms: Grover's Algorithm
  - Grover's algorithm is a quantum algorithm for searching a certain data in an unsorted structure
  - Grover's algorithm: finds in $\mathcal{O}(\sqrt{N})$ where N is the size
  - Classical algorithm: finds in $\mathcal{O}(N)$ where N is the size

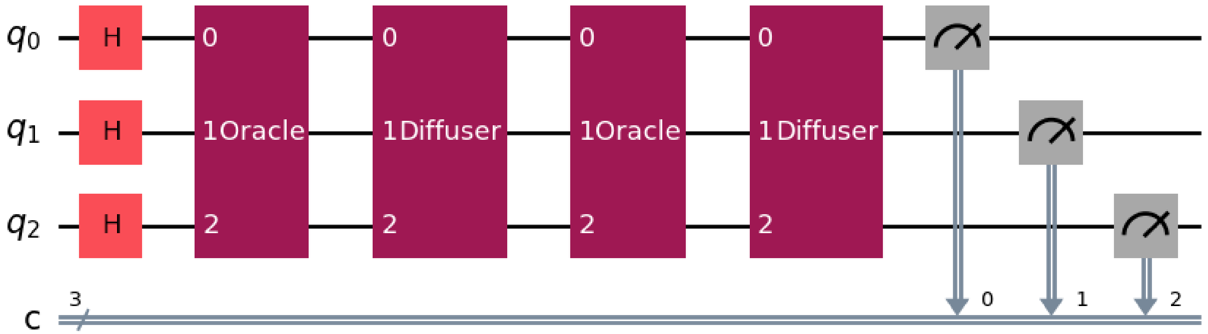


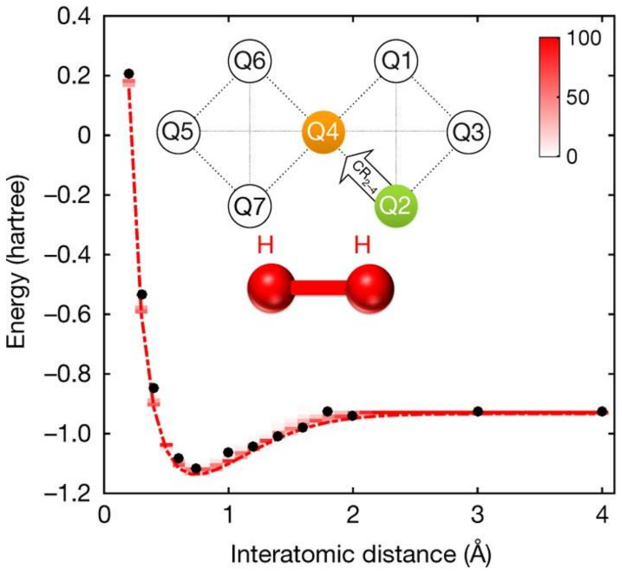
Fig. Grover's algorithm implemented using Qiskit

SH Park
<pajoheji0909@snu.ac.kr>

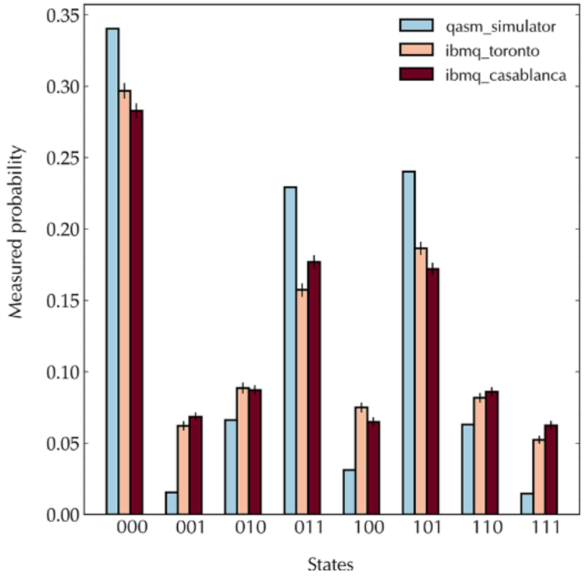
Potential Applications of Quantum Computing

- Cybersecurity, healthcare, weather forecasting, logistics optimization, financial modeling, machine learning, …
- Some quantum algorithms were demonstrated in real-world!

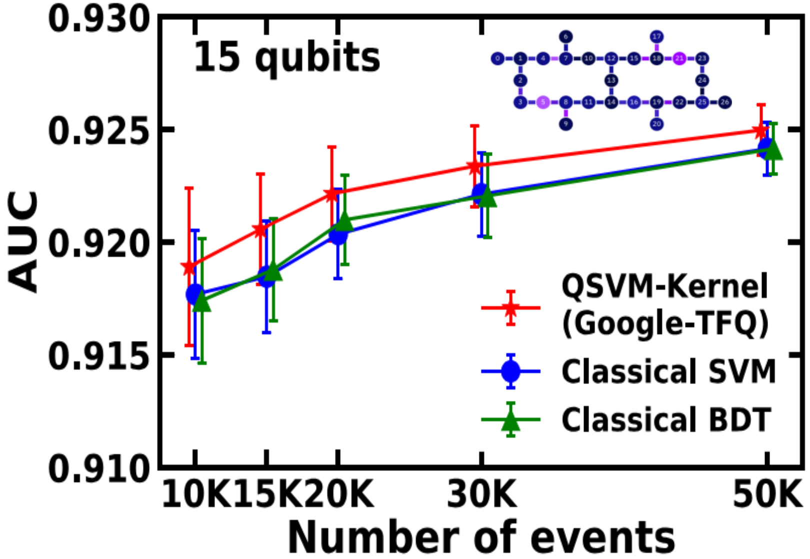
* chemistry and drug discovery



* cybersecurity and factoring



* machine learning



A Kandala, A Mezzacapo *et al.*, "Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets," *Nature,* **549**, 242-246 (2017).
U Skosana and M Tame, "Demonstration of Shor's factoring algorithm for N = 21 on IBM quantum processors," *Sci. Rep.*, **11**, 16599 (2021).
SL Wu *et al*., "Application of quantum machine learning using the quantum kernel algorithm on high energy physics analysis at the LHC," *Phys. Rev. Res.*, **3**, 033221 (2021).

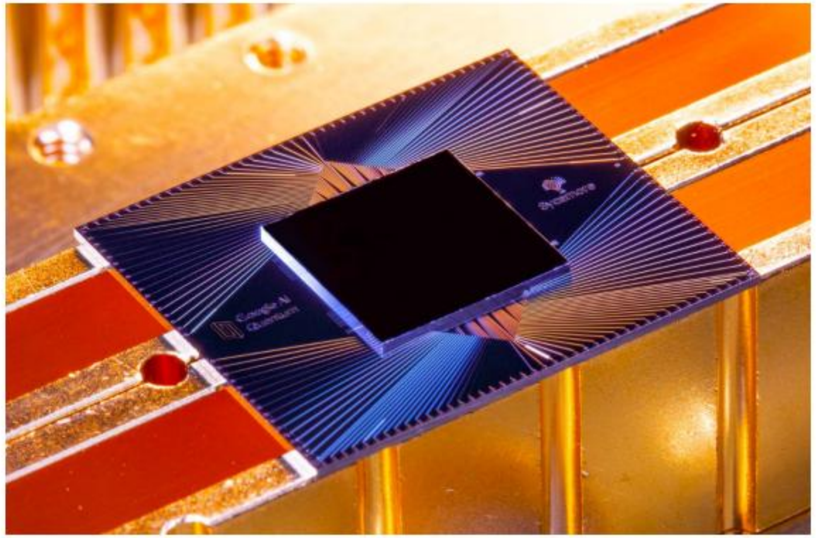
Introduction to Quantum Computing: (4) Quantum Advantages

- Quantum Advantages (also known as Quantum Supremacy)
  - A programmable quantum computer can solve a problem that no classical computer can solve in any feasible amount of time
  - Why? Classical systems cannot simulate quantum systems efficiently (but unproven conjecture)

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],

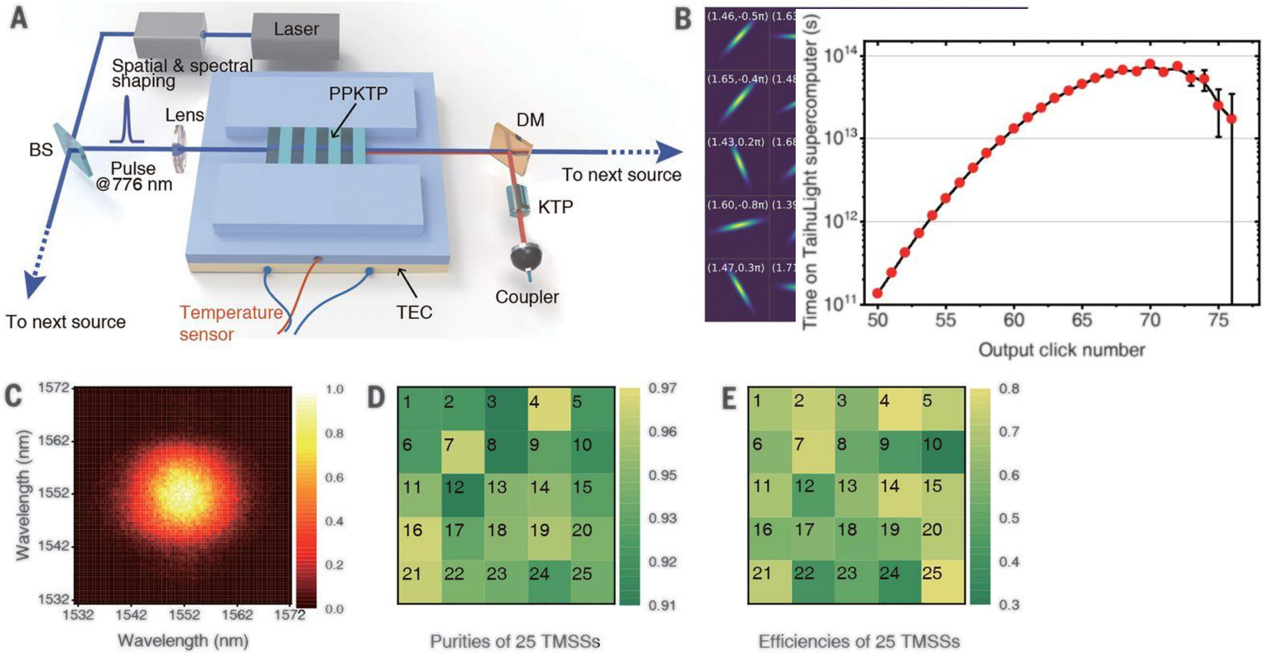


RESEARCH

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†



F Arute *et al.*, "Quantum supremacy using a programmable superconducting processor," *Nature*, **574**, 505-510 (2019).
HS Zhong *et al.*, "Quantum computational advantage using photons," *Science*, **370**, 1460-1363 (2020)

Introduction to Quantum Computing: (4) Quantum Advantages

- Quantum Advantages (also known as Quantum Supremacy)
  - Recent demonstration of quantum advantages using superconducting qubits (Dec 2024)

https://www.youtube.com/watch?v=W7ppd_RY-UE&t=13s&ab_channel=GoogleQuantumAI

History of Quantum Computing: From Birth to Global Race

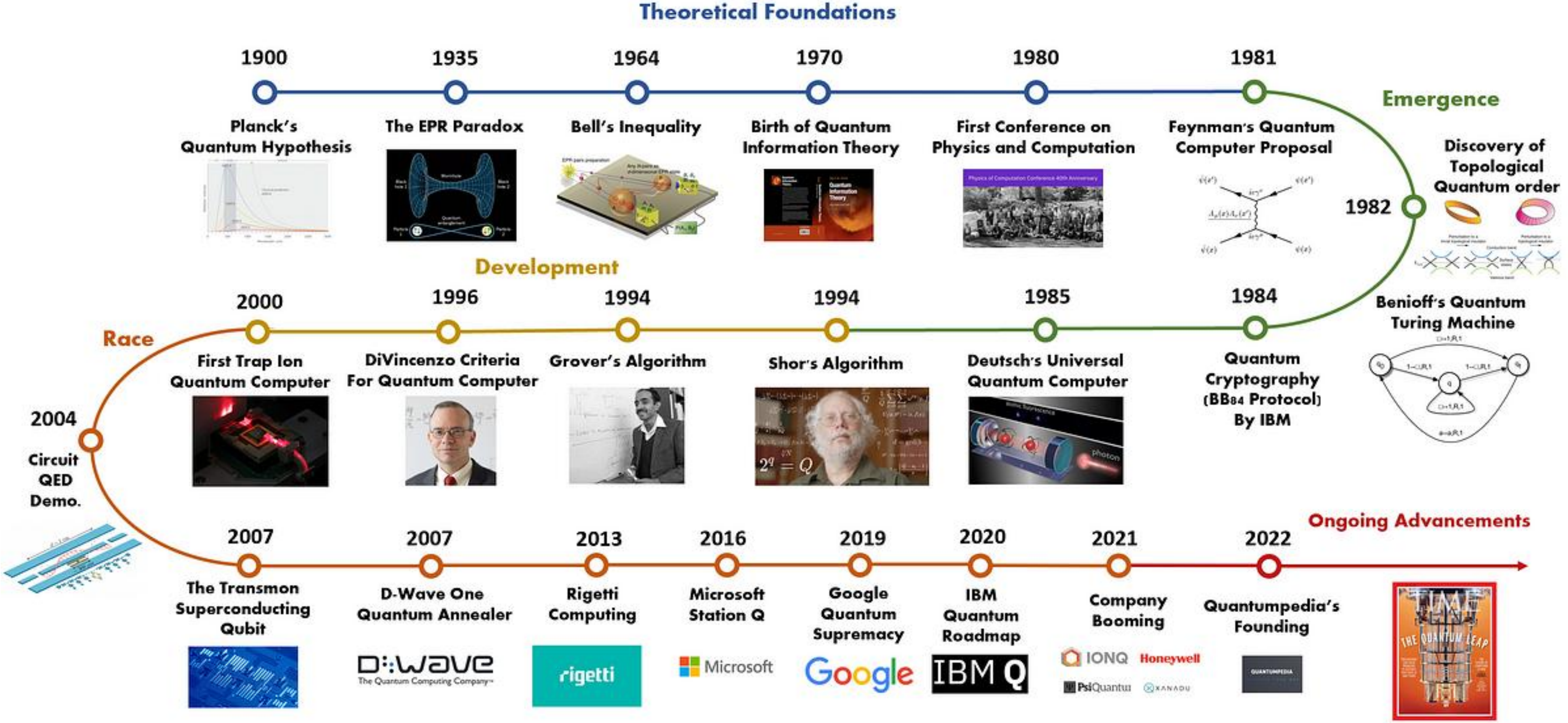


Fig. A Brief History of Quantum Computing

Image from https://quantumpedia.uk/a-brief-history-of-quantum-computing-e0bbd05893d0

Global Efforts to Quantum Science and Technology

- Global And Domestic Investments to Quantum Science and Technology

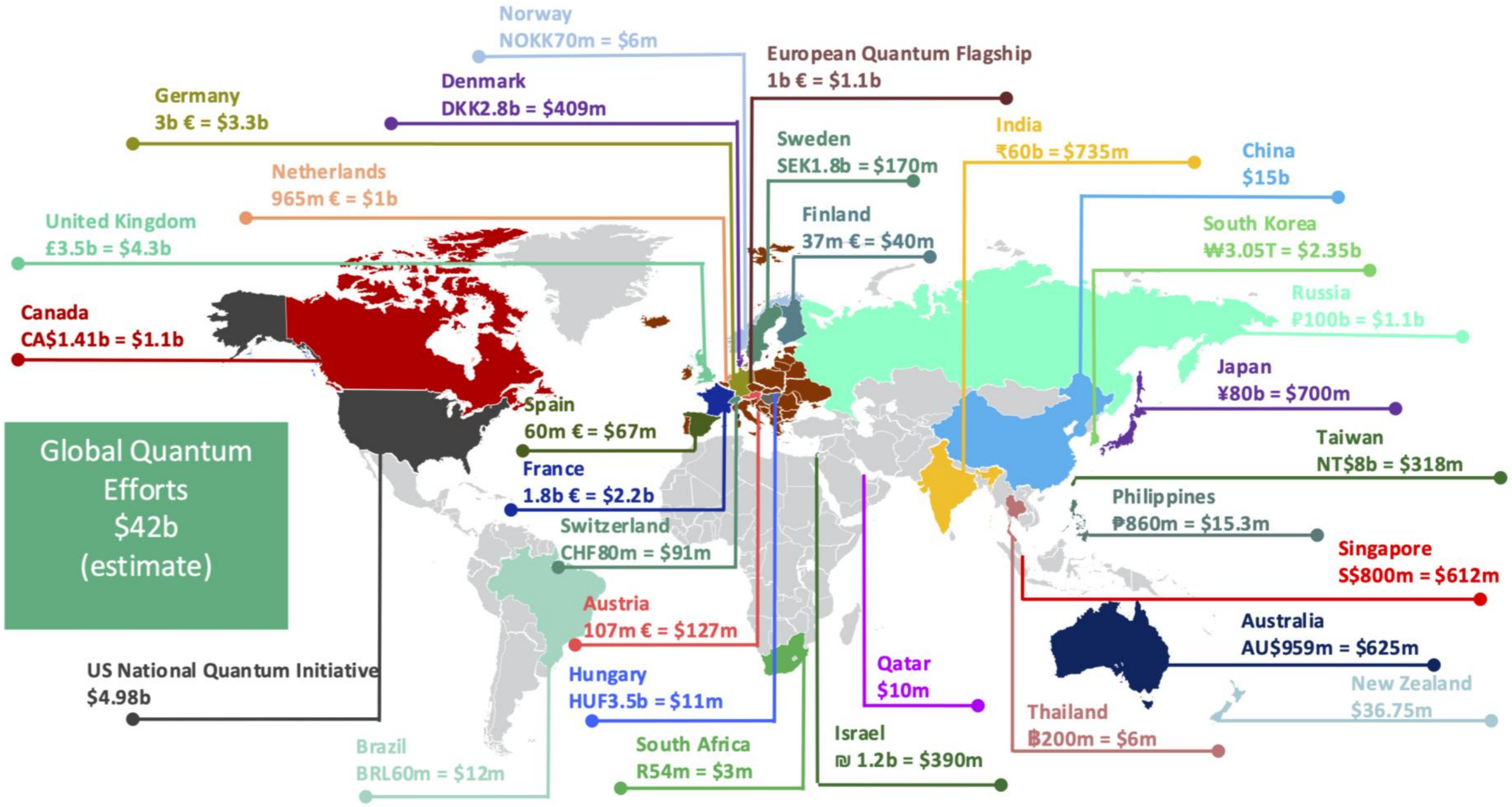
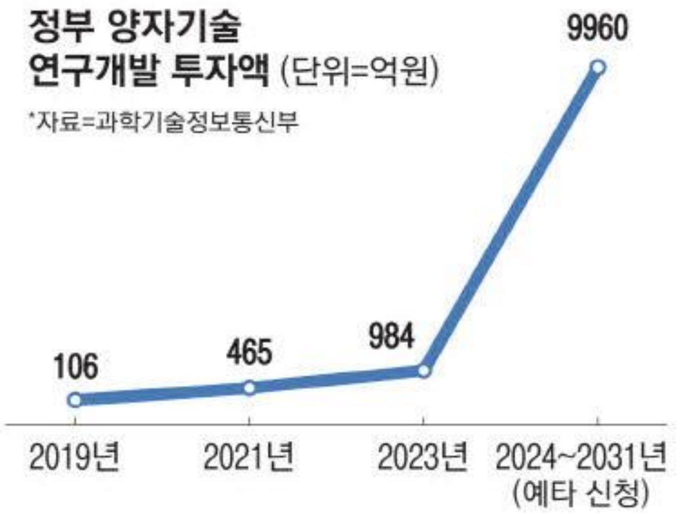


Fig. Global quantum efforts



양자컴퓨터 로드맵

2023년	20큐비트 양자컴퓨터 시연
2024년	20큐비트 양자컴퓨터 클라우드 서비스
2025년	50큐비트 양자컴퓨터 시연
2026년	50큐비트 양자컴퓨터 클라우드 서비스
2027년	500큐비트 이상 양자컴퓨터 구축 착수
2030년대 초	1000큐비트급 양자컴퓨터 개발

*자료: 신성장 4.0 전략
그래픽: 윤선정 디자인기자

Image from https://www.qureca.com/es/quantum-initiatives-worldwide/

Fig. Domestic quantum efforts

Hardware Platforms for Quantum Computing

- Potential Hardware Platforms for Quantum Computer

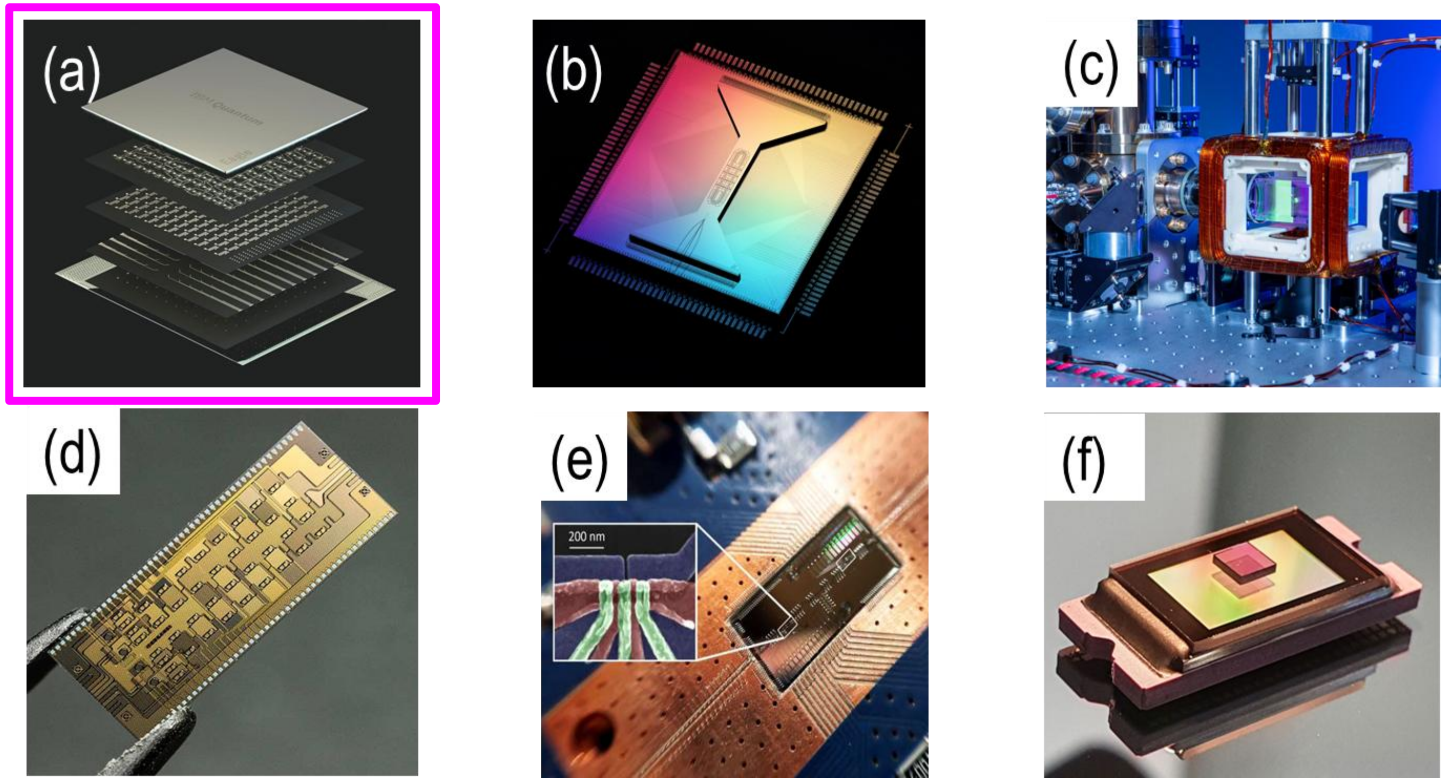


Figure. (a) superconductor, (b) ion trap, (c) neutral atom, (d) photon, (e) silicon quantum dot, and (f) nitrogen vacancy center.

- Key Characteristics of Superconducting Quantum Circuits
  - Artificially engineered macroscopic atom
  - Compatible fabrication techniques with the advanced CMOS industries
  - Compatible control & measurement techniques with the advanced RF industries

Hardware Platforms for Quantum Computing: Superconducting Qubits

- Companies and Institutes Developing Superconducting Qubits
  - Industries

Google AI Quantum
IBM Quantum
SAMSUNG SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY
Amazon Braket Get started with quantum computing
rigetti
Raytheon Technologies
imec
ALICE & BOB
IQM
Alibaba
OQC
Delft Circuits Hardware for quantum engineers
QUANTWARE
VTT

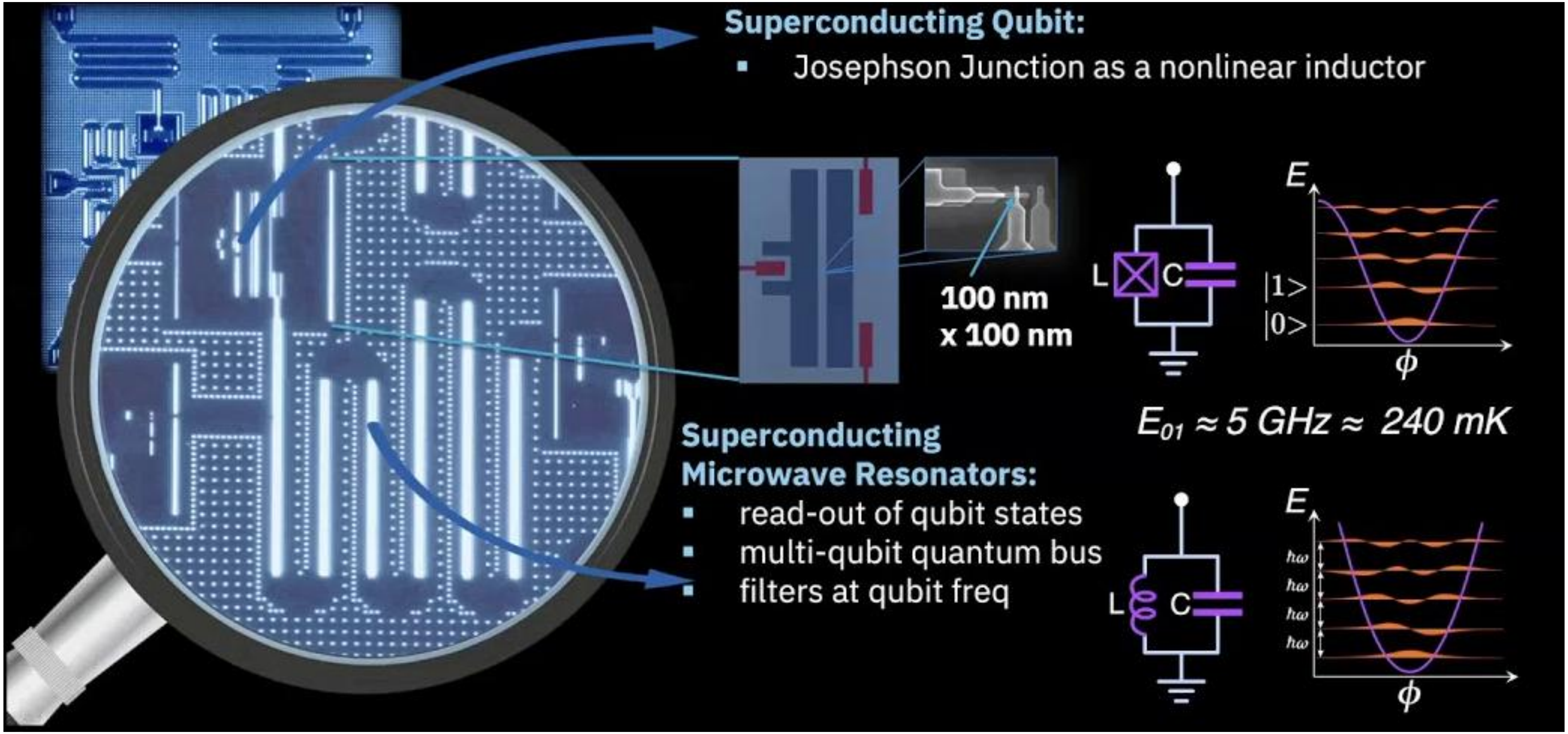
  - National labs

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER
BERKELEY LAB
Brookhaven National Laboratory
Argonne NATIONAL LABORATORY
cnrs
IFF INSTITUTO DE FÍSICA FUNDAMENTAL
RIKEN
中國科學院 CHINESE ACADEMY OF SCIENCES
KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science
국방과학연구소 Agency for Defense Development
Los Alamos NATIONAL LABORATORY
Lawrence Livermore National Laboratory
WMI
MAX-PLANCK-GESELLSCHAFT
北京量子信息科学研究院 Beijing Academy of Quantum Information Sciences

...and more!

Hardware Platforms for Quantum Computing: Superconducting Qubits

- Characteristics of Superconducting Qubits



https://www.youtube.com/watch?v=cg_sPy9IDfA

■ Current Status: Noisy Intermediate Scale Quantum (NISQ)

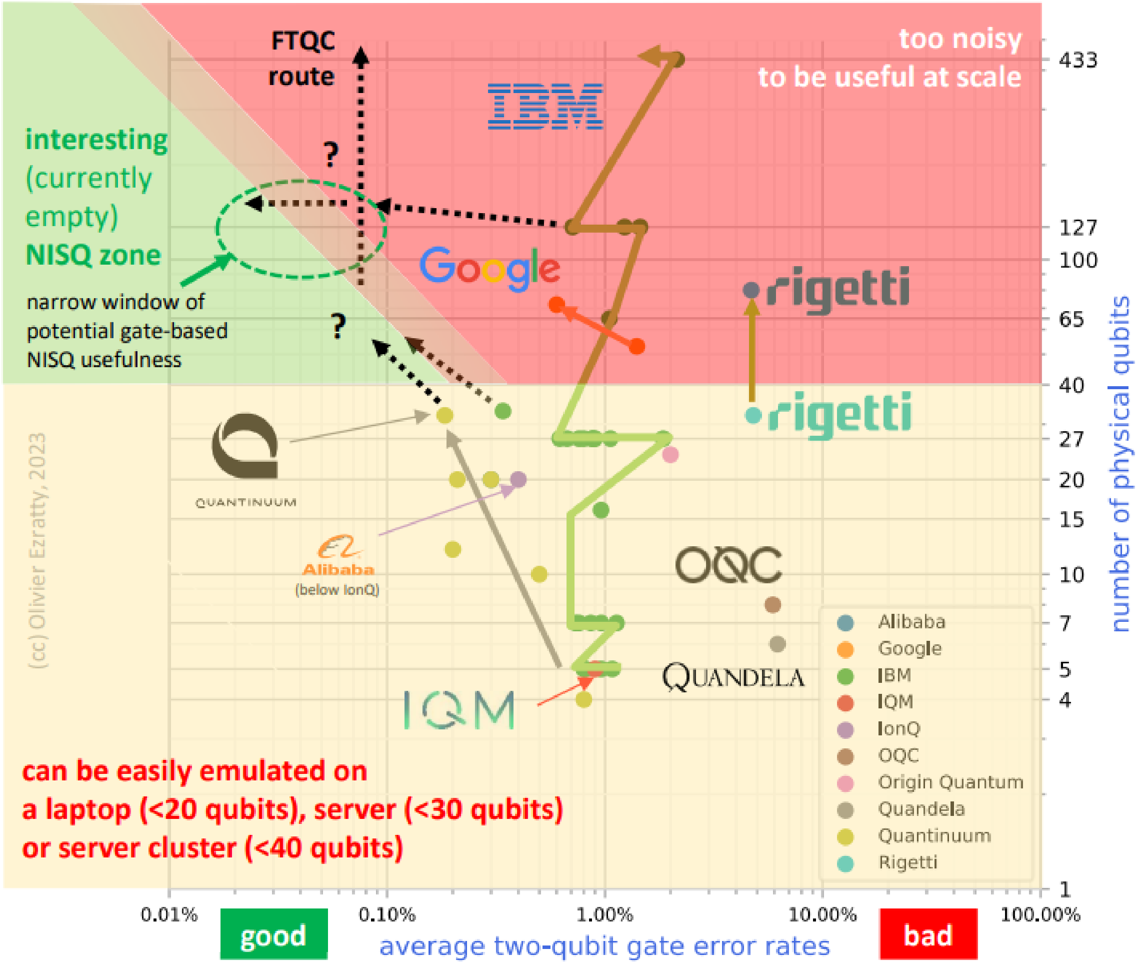


Figure. Commercial quantum computers with 2Q gate error and qubit number. Note that IonQ, Quantinuum, and Quandela are not superconducting architectures.

O. Ezratty, “Where are we heading with NISQ?” arXiv preprintarXiv:2305.09518, (2023).

John Preskill (CALTECH)

Quantum Computing in the NISQ era and beyond

John Preskill

Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA

30 July 2018

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today’s classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably. NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future. Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

- ☐ NISQ era: quantum computers with noisy 50-100 qubits
- ☐ NISQ device may be able to outperform the classical computers but not suitable to perform practical quantum algorithms, such as Shor’s algorithm
- ☐ To perform practical quantum algorithms, fault-tolerant quantum computers must be developed
- ☐ As of 2024, currently available state-of-the-art quantum computers are NISQ devices

Hardware Platforms for Quantum Computing: NISQ Era

- Current Status: Noisy Intermediate Scale Quantum (NISQ)

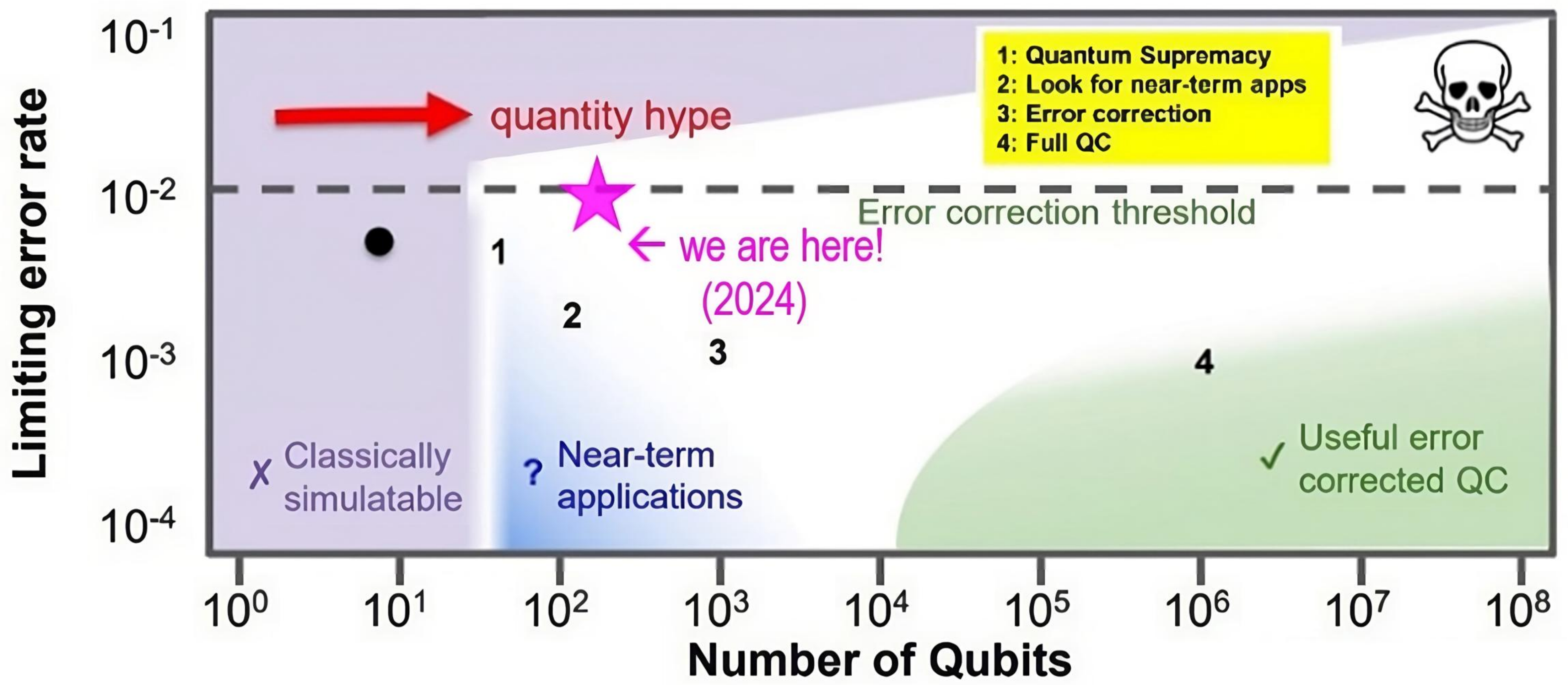


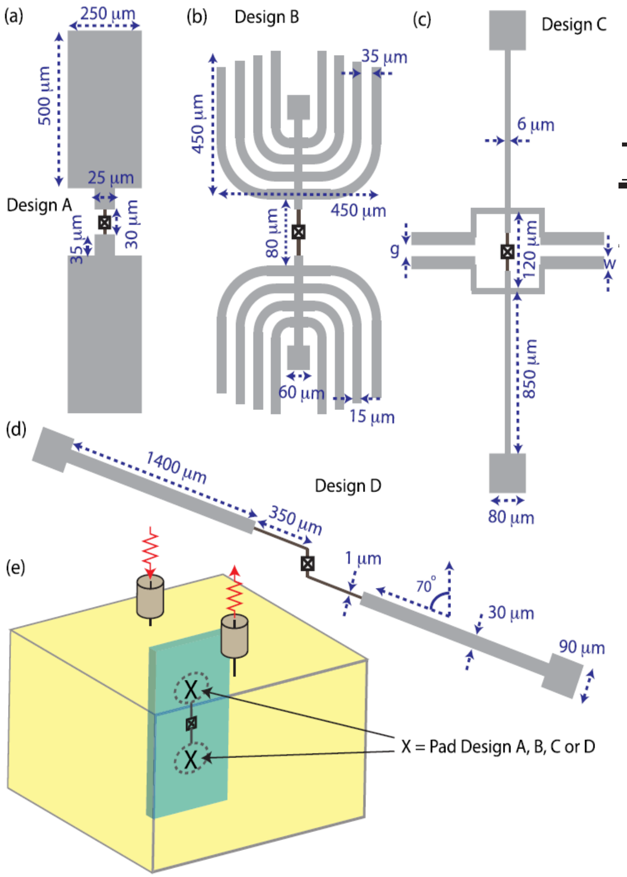
Figure. Development state and future direction of quantum computing.

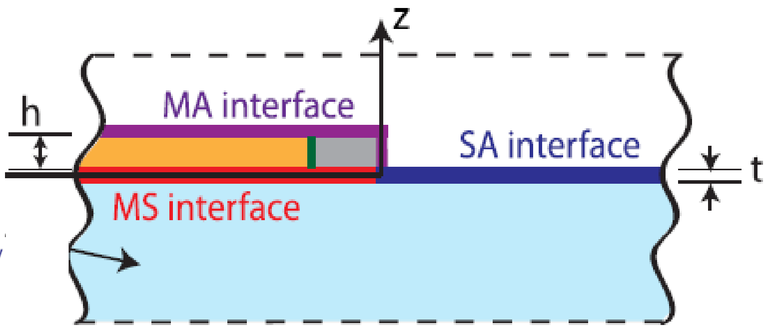
Image credit: JM Martinis, Google Quantum AI presentation

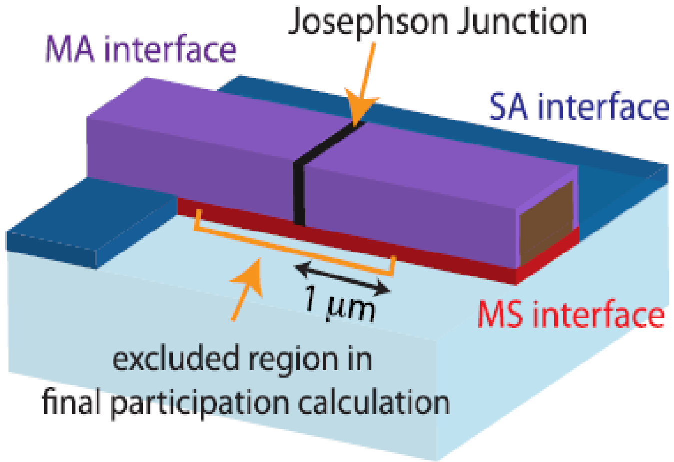
How to Improve and Engineer Superconducting Quantum Circuits?

- Challenges Towards *“Practical”* Large-scale Superconducting Quantum Circuit
  - (1) predictable design;

Coherence times of qubit depends on the surface dielectric loss!







Design	$T_1\,(\mu s)$
A	75 ± 6, 66 ± 7, 95 ± 8
B	34 ± 4, 45 ± 5, 43 ± 3
C_{30}	31 ± 3
C_{20}	25 ± 2.5, 26 ± 2.5
C_{15}	25 ± 2, 16 ± 2, 18 ± 2
C_{10}	19 ± 1.5
C_6	11 ± 1
C_3	7.5 ± 0.6
$C_{1.5}$	5 ± 1
D	39 ± 4

A Gold *et al.*, “Entanglement across separate silicon dies in a modular superconducting qubit device,” *npj Quantum Inf.*, **7**, 142 (2021).
C Wang *et al.*, “Surface participation and dielectric loss in superconducting qubits,” *Appl. Phys. Lett.*, **107**, 162601 (2015).
J heinsoo *et al.*, “Rapid high-fidelity multiplexed readout of superconducting qubits,” *Phys. Rev. Appl.*, **10**, 034040 (2018).

Lecture Overview

Week 1. Introduction to Superconducting Quantum Circuits	overall backgrounds, terminologies of quantum computing
Week 2. Review of Mathematics and Microwave Engineering	mathematical and engineering backgrounds general superconductivity
Week 3. Review of Classical and Quantum Mechanics	
Week 4. Review of Superconductivity	
Week 5. Quantum Harmonic/Anharmonic Oscillators and Light-Matter Interaction	Quantum circuit analysis
Week 6. Circuit Quantization Methods	
Week 7. Parametrically Pumped Josephson Devices	
Week 8. Design and Analysis of Superconducting Resonators	design and analysis of superconducting RF devices
Week 9. Design and Analysis of Superconducting Qubits	
Week 10. Design and Analysis of Single-Qubit Device: 3D Cavity	
Week 11. Design and Analysis of Single-Qubit Device : 2D Chip	
Week 12. Design and Analysis of Two-Qubit Device	
Week 13. Design and Analysis of Josephson Parametric Amplifier	
Week 14. Term Project	
Week 15. Term Project	

Keywords in Lectures on Introduction to Superconducting Quantum Circuits

Classical Mechanics

Newtonian
(1) Conservative Force
(2) Potential Energy, Kinetic Energy
(3) Newton's Laws of Motion

Lagrangian
(1) Principle of Least Action
(2) Euler-Lagrangian Equation

Hamiltonian
(1) Canonical Momentum
(2) Legendre Transformation
(3) Poisson Braket

Quantum Mechanics

Postulates of Quantum Mechanics
(1) Wave Function
(2) Schrödinger Equation
(3) Uncertainty Principle
(4) Ehrenfest's Theorem

Analysis of Quantum Mechanics
(1) Schrödinger Pictures
(2) Heisenberg Pictures

Applications: #1 Harmonic Oscillator
(1) Canonical Quantization
(2) Ladder Operator
(3) Eignestate, Eigenenergy

Applications: #2 Two-Level Systems
(1) Bloch Sphere
(2) Bell State
(3) Pauli Matrix
(4) Rabi Oscillator
(5) Pure State
(6) Mixed State
(7) Density Matrix

Superconductivity

Theory
(1) Bardeen-Cooper-Schrieffer Theory
(2) Mattis-Bardeen Theory

Characteristic Parameters
(1) Critical Temperature
(2) Gap Energy
(3) London Penetration Depth
(4) Coherence Length
(5) Normal-State Conductivity
(6) Electron Mean Free Path

Electromagnetic Behaviors
(1) Kinetic Inductance
(2) Surface Impedance

Application: #1 Josephson Junctions
→ Theory
(1) Current-Phase Relation
(2) AC Josephson Effect
(3) Ambegaokar-Baratoff Relation

→ Device Topologies
(1) DC-SQUID
(2) RF-SQUID
(3) SNAIL

Microwave Engineering

Key Components
(1) Amplifier
(2) Low/High/Band Filter
(3) Local Oscillator
(4) Multiplexer
(5) Directional Coupler
(6) Circulator
(7) Isolator
(8) Attenuator
(9) Bias-Tee
(10) Mixer
(11) Arbitrary Wave Generator
(12) IR-Filter

Transmission Line Theory
(1) Wave Propagation
(2) Telegrapher's Equation
(3) Characteristic Impedance
(4) Insertion Loss, Return Loss
(5) Input Impedance
(6) Impedance Matching
(7) Transverse Magnetic Mode
(8) Transverse Electric Mode
(9) Quasi-Transverse Mode

Microwave Resonators
(1) Microstrip
(2) Inverted Microstrip
(3) Coplanar Waveguide
(4) 3D Cavity
(5) Resonant Frequency
(6) Quality-Factor
(7) Characteristic Impedance

Analysis of Microwave Network
(1) Scattering Matrix
(2) Transmission Matrix
(3) Impedance Matrix
(4) Admittance Matrix
(5) Foster's Theorem
(6) Brune's Theorem

Keywords in Lectures on Introduction to Superconducting Quantum Circuits

Non-Superconducting Components

Dilution refrigerator
- Base temperature
- Cooling capacity
- Signal line attenuation

Arbitrary microwave signal controller (reader)
- Sampling rate
- IQ Mixer and local oscillator
- Channels

Microwave filters
- Low/high/band pass filters
- Infrared filter
- Insertion and return loss

Circulator (isolator)
- Matching impedance
- Number of ports
- Insertion and return loss

Amplifier
- Operating voltage and current
- Signal gain
- Noise figure

Superconducting Qubits

Device topologies
(1) Cooper-pair-box (2) Transmon (3) Phase
(4) Fluxonium (5) Bluchonium (6) 0-π qubit

Device implementations
(1) Single Josephson junction
(2) DC-SQUID (3) Superinductor (4) Capacitor

Underlying physics (transmon)
(1) Quantum anharmonic oscillator
(2) Circuit quantum electrodynamics

Design parameters (transmon)
(1) Josephson junction energy
(2) Shunt capacitor charging energy

Measurable parameters (transmon)
(1) Qubit frequency
(2) Qubit anharmonicity (3) Charge noise
(4) Quantum gate fidelity (5) T_1 (6) T_2

Superconducting Resonators

Device topologies
(1) 3D cavity resonator
(2) 2D coplanar waveguide (CPW) resonator
(3) 2D lumped-element resonator

Device implementations
(1) Bulk superconductor
(2) Thin superconducting film

Underlying physics (CPW)
(1) Telegrapher's equation
(2) Transmission line theory

Design parameters (CPW)
(1) Gap (2) Width (3) Film thickness
(4) Substrate thickness (5) Permittivity
(6) Length (7) Characteristic impedance

Measurable parameters (CPW)
(1) Resonator frequency
(2) Quality-factor (3) Frequency shifts
(4) Kinetic inductance of superconductors

Superconducting Quantum Circuits

Device topologies
(1) 3D cavity-enclosed system
(2) Single planar chip
(3) 3D-integrated multilayer chip

Device implementations
(1) Through via silicon
(2) Flip-chip
(3) Printed circuit board packaging

Underlying physics
(1) Jaynes-Cummings model
(2) Circuit quantum electrodynamics
(3) Rotating wave approximation

Design parameters
(1) Bare mode frequency
(2) Detuning frequency
(3) Coupling strength

Measurable parameters
(1) Dressed state frequency
(2) Lamb shift (3) Stark shift
(4) Self Kerr (5) Cross Kerr (6) ZZ coupling

Superconducting Parametric Amplifiers

Device topologies
(1) Josephson parametric amplifiers
(2) Traveling wave parametric amplifiers

Device implementations
(1) DC-SQUID (2) SNAIL (3) RF-SQUID array
(4) DC-SQUID array (5) Josephson junctions
(6) Thin superconducting films

Underlying physics
(1) Pumpistor model
(2) Coupled-mode network theory
(3) Harmonic balance method

Design parameters
(1) Operating frequency
(2) Operating DC and pump bias
(3) Number of resonant modes

Measurable parameters
(1) Signal gain (2) Signal gain bandwidth
(3) Ripples in the bandwidth (4) Added noise
(5) Signal-to-noise ratio