Solid State Systems for Quantum Information (PHYS-464)

spring term 2023

Lectures & Exercises: **Pasquale Scarlino, Vincent Jouanny, Guillaume Beaulieu**

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moodle: https://moodle.epfl.ch/course/view.php?id=16956

What is this course about?

Introduction to experimental realizations of systems for quantum information processing (QIP) and quantum technology

Central Questions:

What makes quantum physics still a vibrant research topic a century after its theoretical foundation?

How does one use quantum systems to store and process information?

How do we build and operate physical systems for this purpose?

What makes superconducting circuits and semiconducting spin systems one of today's most versatile experimental systems to study quantum information science?

Basic Structure of the course

Part I: **Introduction** to Quantum Information Processing (QIP)
- basic concepts: qubits, gate operations, measurement
- circuit model of quantum computation

Part II: **Superconducting Quantum Electronic Circuits** for QIP
- superconductivity, Josephson junctions, coherence
- physical realization of qubit control, qubit/qubit interactions and read-out
- interfacing qubits and photons: cavity quantum electrodynamics
- realizations of algorithms and protocols

Part III: **SPIN qubits** for QIP
- electronic spins in semiconductor quantum dots
- (Topological qubits, Novel qubits) if time will allow it.

Example of Questions that you will be able to answer by the end of this course

- What is a superconductor?
    - Why are superconductors useful for making quantum circuits?
    - How do we describe a superconductor quantum mechanically?
- What is a Josephson junction?
    - How can be use these to make qubits?
    - Why is it essential that the Josephson junction has a non-linear energy?
- What are the common superconducting qubits?
- How do we couple controlled microwave signals to superconducting qubits?
- How are quantum gates and quantum measurements performed on superconducting qubits?
- How can we use microwave resonators to implement two-qubits gates and to readout qubits?

Paper clubs and presentations

Topics: experimental implementations of quantum information processing

In order to link the lectures and exercises to the frontier of research, several exercises classes (for the first 30-45 min) will be dedicated to **paper reading and discussions**. Paper discussions will occur in small groups of ~3 students presenting and 3 students responsible of asking questions (but everybody is more than welcome to ask questions) with TAs helping the discussions.
Papers will be allocated in advanced and presented by one person in each group.

A joint event with Prof. Brantut's class will take place at the end of the semester.

- Goal: present key features of implementation and judge its relevance/prospects
- Material: research papers and review articles
- Preparation: teams of 3 students, ~ 5 slots for teams available in 5 exercise class
- Coaching and support by TAs
- Duration: presentation + discussion (30+15 minutes)
- Presentation: blackboard, transparencies, PowerPoint …
- Feedback on both content and presentation of your talk

Exercises

A two-hours slot is available on **Tuesdays from 15:00 to 17:00 in MAA 331** for the exercises.
Exercises are the most important part of the weekly schedule, putting you in position to get familiar with the concepts and apply them to models close to actual quantum machines. For some of the exercises you will be asked to run small guided simulations with Python. If you do not have it installed yet on your computer, here are the links (The first one is to install python with the anaconda distribution, where it install a lot of packages that are super useful. The second one, is to install qutip):
https://www.anaconda.com/products/individual
https://anaconda.org/conda-forge/qutip

Reading

For a review of the basics of Quantum Information and Computing:

- Quantum computation and quantum information / Michael A. Nielsen & Isaac L. Chuang. Cambridge Press; 2001

For a review of superconducting quantum technology and circuit Quantum Electrodynamics:

- Girvin, S. M. (2011), Circuit QED: superconducting qubits coupled to microwave photons.
- P. Krantz, et al., A quantum engineer's guide to superconducting qubits, Applied Physics Reviews 6, 021318 (2019); https://doi.org/10.1063/1.5089550
- Mahdi Naghiloo, Introduction to Experimental Quantum Measurement with Superconducting Qubits, arXiv:1904.09291
- A. Blais, A. L. Grimsmo, S.M. Girvin, and A. Wallraff, Circuit quantum electrodynamics, Rev. Mod. Phys. 93, 025005 (2021).

For a review of semiconductor Spin Qubits:

- W. G. van der Wiel, S. De Franceschi, J. M. Elzerman, T. Fujisawa, S. Tarucha, and L. P. Kouwenhoven, Electron transport through double quantum dots, Rev. Mod. Phys. 75, 1 (2002).
- R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen, Spins in few-electron quantum dots, Rev. Mod. Phys. 79, 1217 (2007)

Exam

Content of exam:

- The aural exam will consist of a 30 min timeslot during summer or winter exam session.
- During the first 20 min of the exam, you will be provided with an exercise similar to the one solved during the course and some questions. This will be the starting point of the discussion that we will have in the remaining 20 min of the exam.

- The questions will focus on the main topics studied during the main lectures and they are randomly selected from a list of numbered questions. The main questions are all based on the material covered in the lectures.
- The lecture slides will be available, and additionally we provide background material to help you understand the concepts presented in the lectures. We will not ask questions about concepts covered in the background material which has not been covered in the lectures.

See the document: '**Example questions oral exam Solid State Systems for Quantum Information – Spring 2023**' for a list of questions we will use to start the exam.

Quantum technologies IS THE NEWs

OUT THERE? The New York Times

Quantum Computing Is Coming, Bit by Qubit

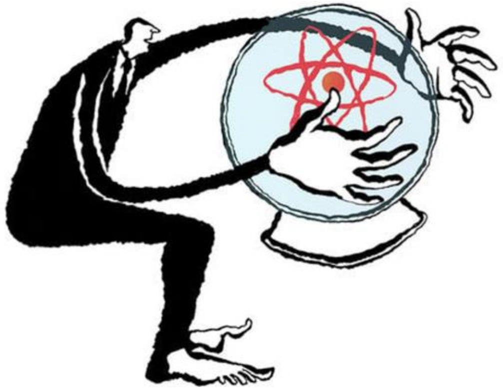
With transmons and entanglement, scientists strive to put subatomic weirdness to work on the human scale.

Technology Quarterly | Commercial breaks

The uses of quantum technology

The most exciting thing about a quantum-enhanced world is that no one yet knows what it will bring

The Economist



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CIO JOURNAL

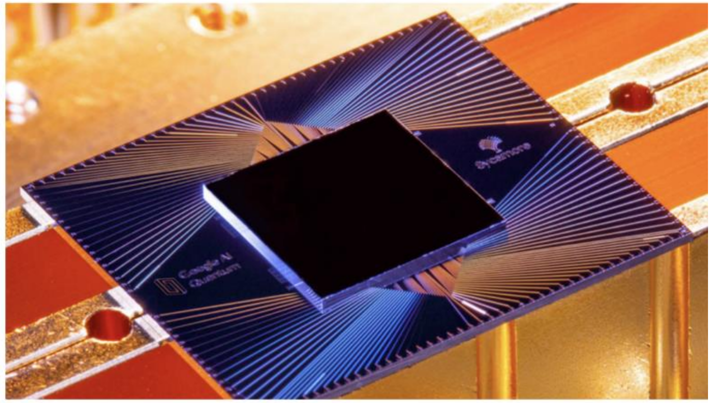
Financial Firms Seek Edge in Algorithms Inspired by Quantum Computing

Some firms are running algorithms used for quantum computers on advanced machines for risk analysis and portfolio optimization

NEWS QUANTUM PHYSICS

Google officially lays claim to quantum supremacy

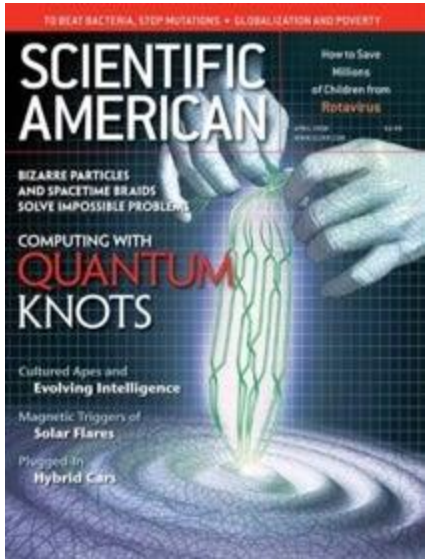
A quantum computer reportedly beat the most powerful supercomputers at one type of calculation



IBM Unveils 400 Qubit-Plus Quantum Processor and Next-Generation IBM Quantum System Two

Company Outlines Path Towards Quantum-Centric Supercomputing with New Hardware, Software, and System Breakthrough

Nov 9, 2022



Quantum Computing Race – European and Swiss Initiatives and Technological Corporations

R&D (public and private) investments reach $35.5 billion by 2022 across a range of quantum technologies.

Swayne, Matt, “TQI Annual Report Looks Back at 2021 in Quantum.” The Quantum Insider, 6 January 2022

Huge investments in developing quantum science and technology

- EU Quantum Flagship

QUANTUM FLAGSHIP

- Swiss Initiative

QSIT Quantum Science and Technology

NCCR SPIN

- Largest Tech Companies:

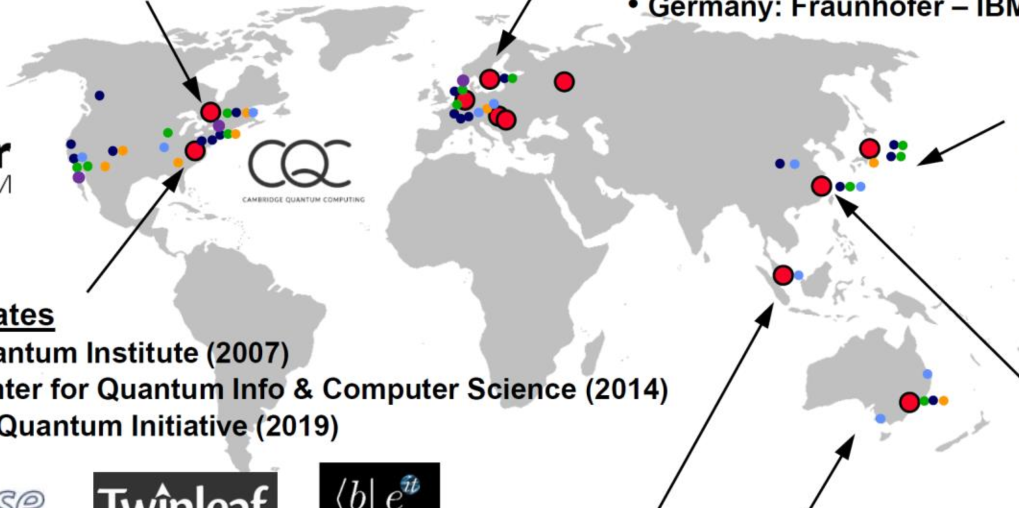

nature International weekly journal of science
Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video
Archive > Volume 532 > Issue 7600 > News > Article
NATURE | NEWS
Europe plans giant billion-euro quantum technologies project
Third European Union flagship will be similar in size and ambition to graphene and human brain initiatives.

Google	IBM	intel	Microsoft	D-Wave The Quantum Computing Company	rigetti
SC Qubits	SC Qubits	SC and spin Qubits	Topological qubits	SC Qubits	SC Qubits

Quantum Worldwide (not exaustive list)

Canada
- Inst. for Quantum Computing (2002)
- Inst. Quantique (2015)

Europe
- Netherlands: QuTech (2014)
- United Kingdom: National Quantum Technologies Program, \$0.5B (2014)
- EU: Quantum Flagship, \$1B (2016)
- Sweden: Wallenberg Center for Quantum Technology, \$0.2B (2017)
- Germany: Fraunhofer – IBM alliance, \$0.8B (2019)



Japan
- Gate-model and QA
- JST, RIKEN, AIST, NICT

United States
- Joint Quantum Institute (2007)
- Joint Center for Quantum Info & Computer Science (2014)
- National Quantum Initiative (2019)

China
- Key Lab, Quantum Information, CAS (2001)
- Satellite quantum communication (2016)
- Alibaba – CAS cloud computer - \$15B (2018)

Australia
- ARC Centers of Excellence
  - Center for Quantum Computing Technology (2000)
  - Engineered Quantum Systems (2011)
- CommBank – Telstra – UNSW (2015)

Singapore
- Research Center on Quantum Information Science and Technology (2007)

• Superconducting qubits • Ion trap qubits • Semiconducting qubits • Quantum optics • NV centers

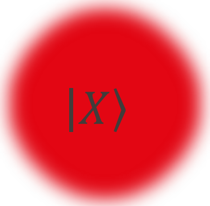
* European Commission

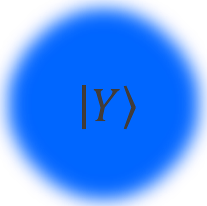
Key ingredient for Quantum Technology: Superposition, Entanglement

Quantum State
Dirac Notation $|\boldsymbol{\Psi}\rangle$

Contains all the information about the systems

- A particle localized at the position x, $|X\rangle$
- A particle localized at the position y, $|Y\rangle$





SUPERPOSITION: Quantum Mechanics is a linear theory: all the possible sum of the possible states is also a state allowed.

$\frac{1}{\sqrt{2}}(|X\rangle + |Y\rangle)$ is also an allowed state for our system

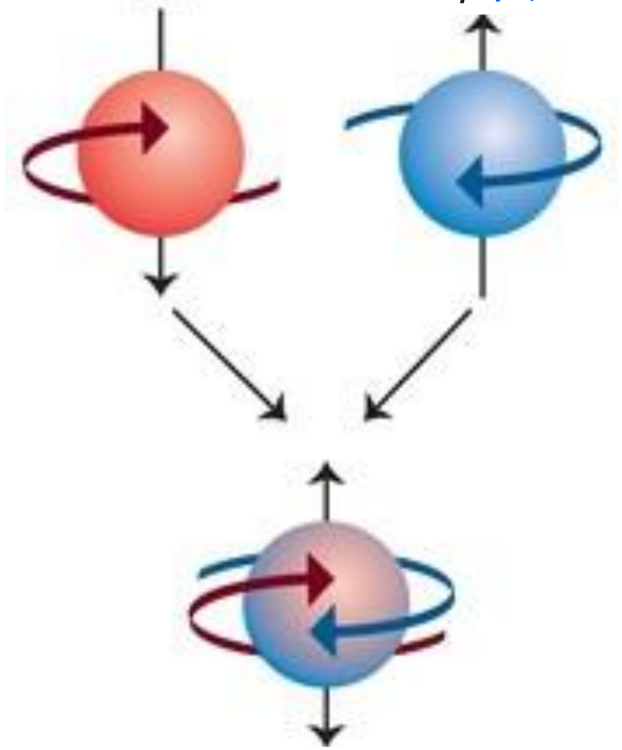
A particle in two places at once???
Convenient, but shocking!

The possibility of superposing states even in multiple-particle systems naturally results in the concept of **ENTANGLEMENT**.

A prototipe for every artificial 2-level systems (qubits) is the spin of an electron

- An electron can have a spin ↓, $|\downarrow\rangle$
- An electron can have a spin ↑, $|\uparrow\rangle$

$\alpha\,|\downarrow\rangle$ $\beta|\uparrow\rangle$



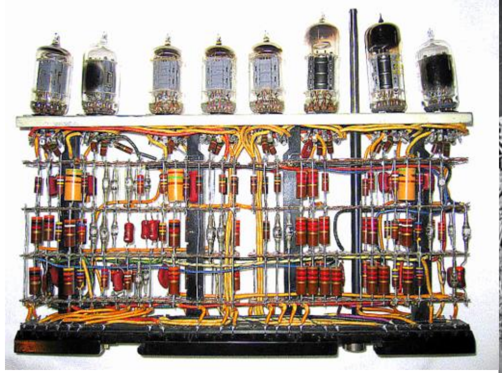
$$|\boldsymbol{\Psi}\rangle = \alpha\,|\downarrow\rangle + \beta|\uparrow\rangle$$

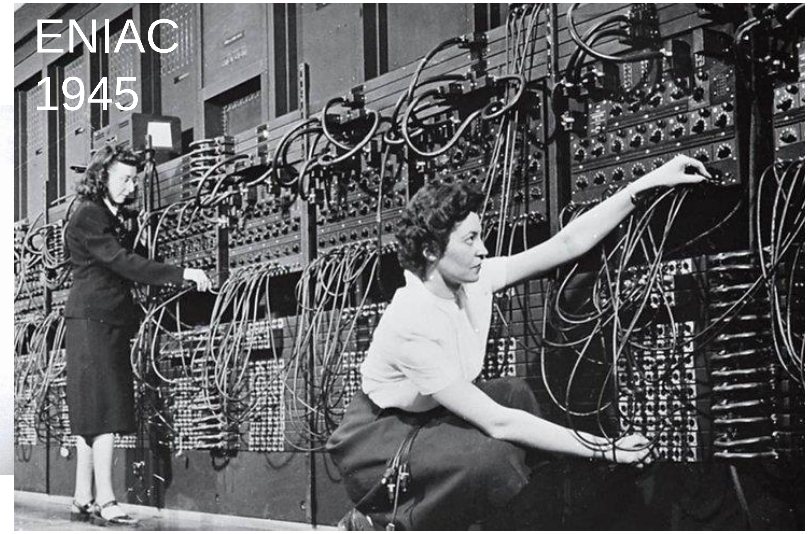
$$|\alpha|^2 + |\beta|^2 = 1$$

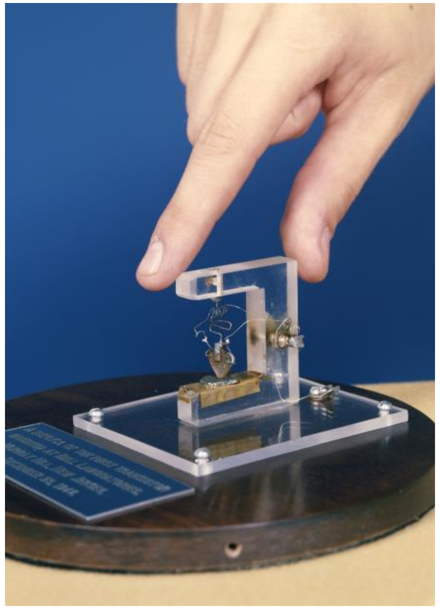
First Quantum Revolution in Information Technology

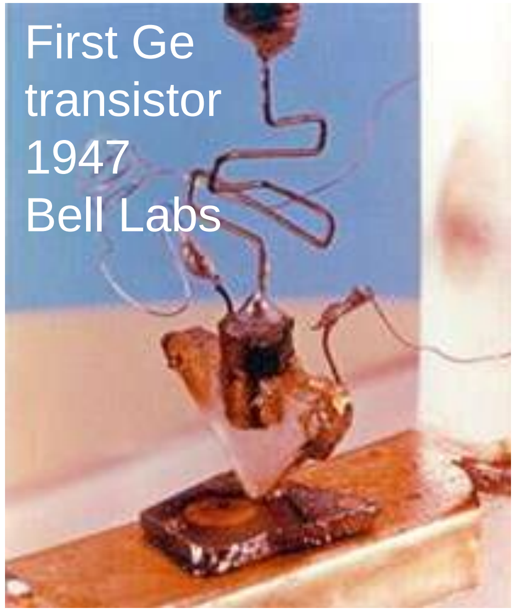
- Unprecedented series of success which provided us with novel extraordinary experimental tools.
- A revolutionary societal and economic impact:
  - large part of GDP results from quantum technology;
  - no information society without lasers;
  - longer life expectation thanks to NMR;

vacuum tube computer

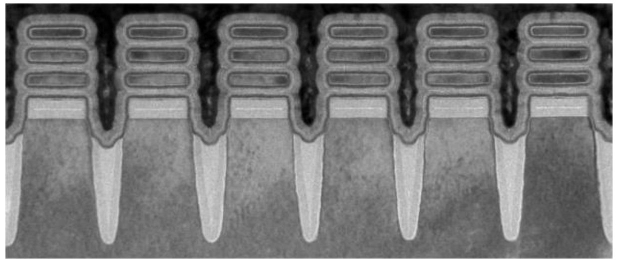




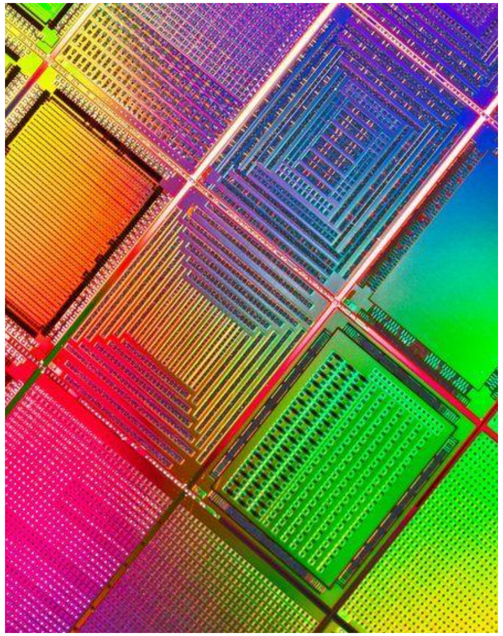




IBM 2-nanometer (nm) node 2021



50 billion transistors in a space roughly the size of a fingernail

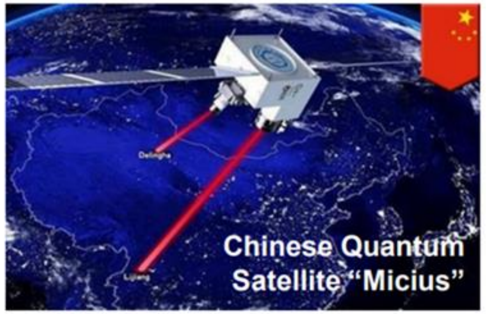


Second Quantum Revolution: New Technology Powered by Quantum Physics

Quantum Sensing

Improves sensitivity, drift, & spatial resolution

Quantum Networks

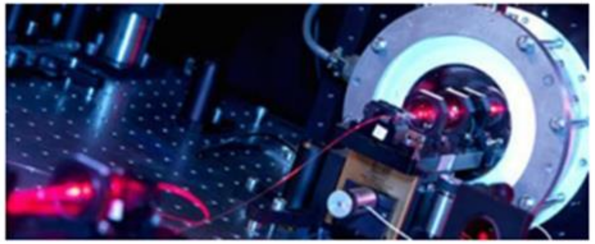


Enables distributed quantum states

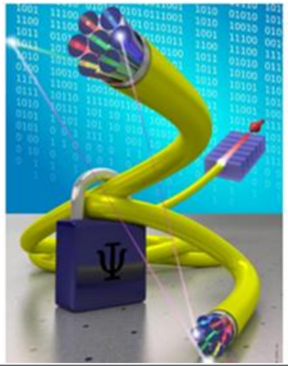
Quantum Computing Quantum Simulation

Solves select problems that are intractable with classical computing

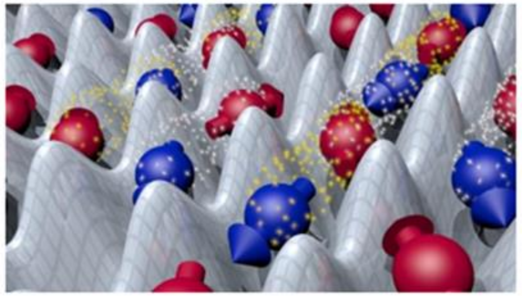
Measurement precision beyond the classical limit



Unconditionally secure communication



Increased understanding of complex physical systems

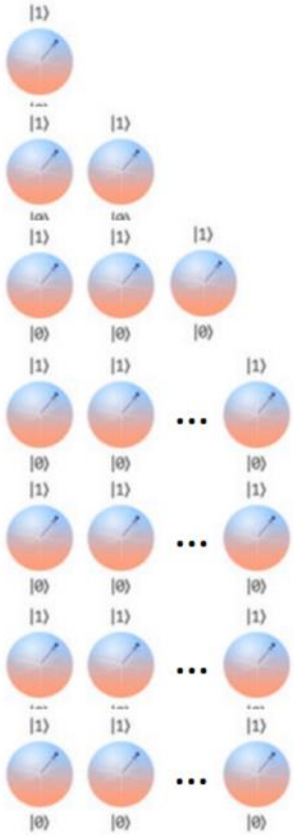


Quantum Information Science utilizes a quantum mechanical description of nature to sense, communicate, and process/compute information in ways unobtainable by means based on a classical description of nature

Exponential Complexity of Quantum Systems

Advantages for computing & Enormous Quantum Power

Information can be encoded on properties of single quantum particles which can be found in superposition states



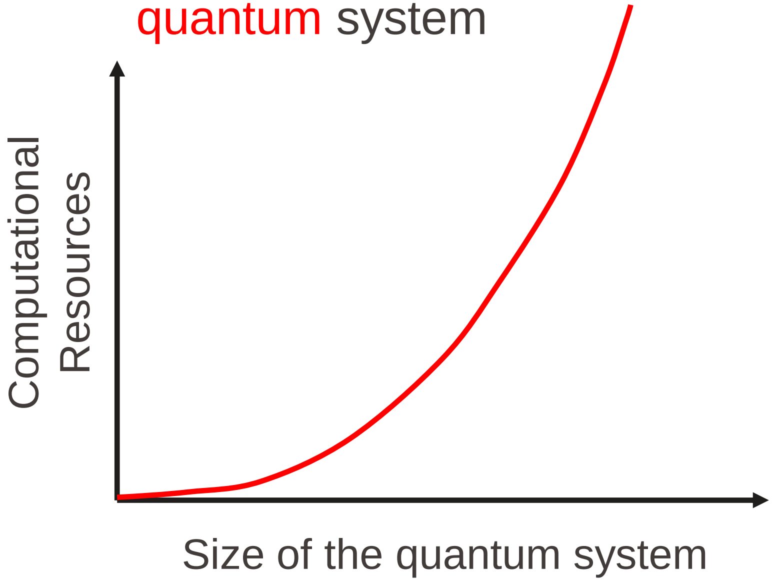
1	$\|0\rangle, \|1\rangle$	$2^1=2$
2	$\|00\rangle, \|01\rangle, \|10\rangle, \|11\rangle$	$2^2=4$
3	$\|000\rangle, \|001\rangle, \ldots, \|111\rangle$	$2^3=8$
10	$\|00\ldots0\rangle, \|00\ldots1\rangle, \ldots, \|11\ldots1\rangle$	$2^{10}=1k$
20	$\|00\ldots0\rangle, \|00\ldots1\rangle, \ldots, \|11\ldots1\rangle$	$2^{20}=1M$
30	$\|00\ldots0\rangle, \|00\ldots1\rangle, \ldots, \|11\ldots1\rangle$	$2^{30}=1G$
40	$\|00\ldots0\rangle, \|00\ldots1\rangle, \ldots, \|11\ldots1\rangle$	$2^{40}=1T$

Adding qubits increases storage exponentially

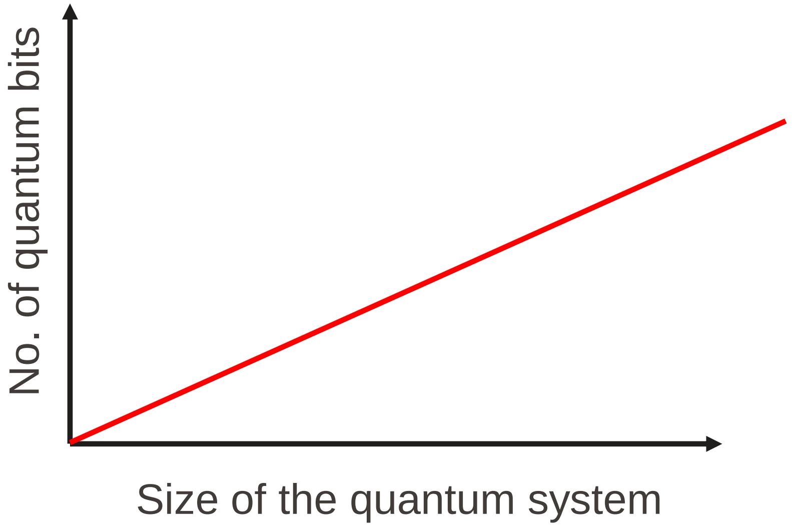
- Quantum computer doubles the power with every added qubit
  - To double the power of a digital computer 32bits -> 64 bits
  - To double the power of a quantum computer 32qubits -> 33 qubits

Exponential Complexity of Quantum Systems

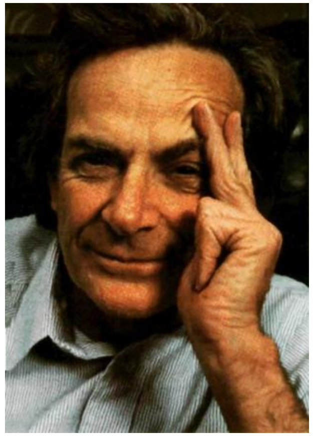
Classical computer simulating a quantum system



Quantum computer simulating a quantum system



Performing logic operations with entangled states allows the quantum evolution to sample multiple states … effectively massive parallel computation



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

The second quantum revolution

Active manipulation of single quantum particles and interaction between multiple particles for applications

Some complex problems benefit from this exponential scaling, enabling solutions of otherwise insolvable problems.

Quantum Simulation

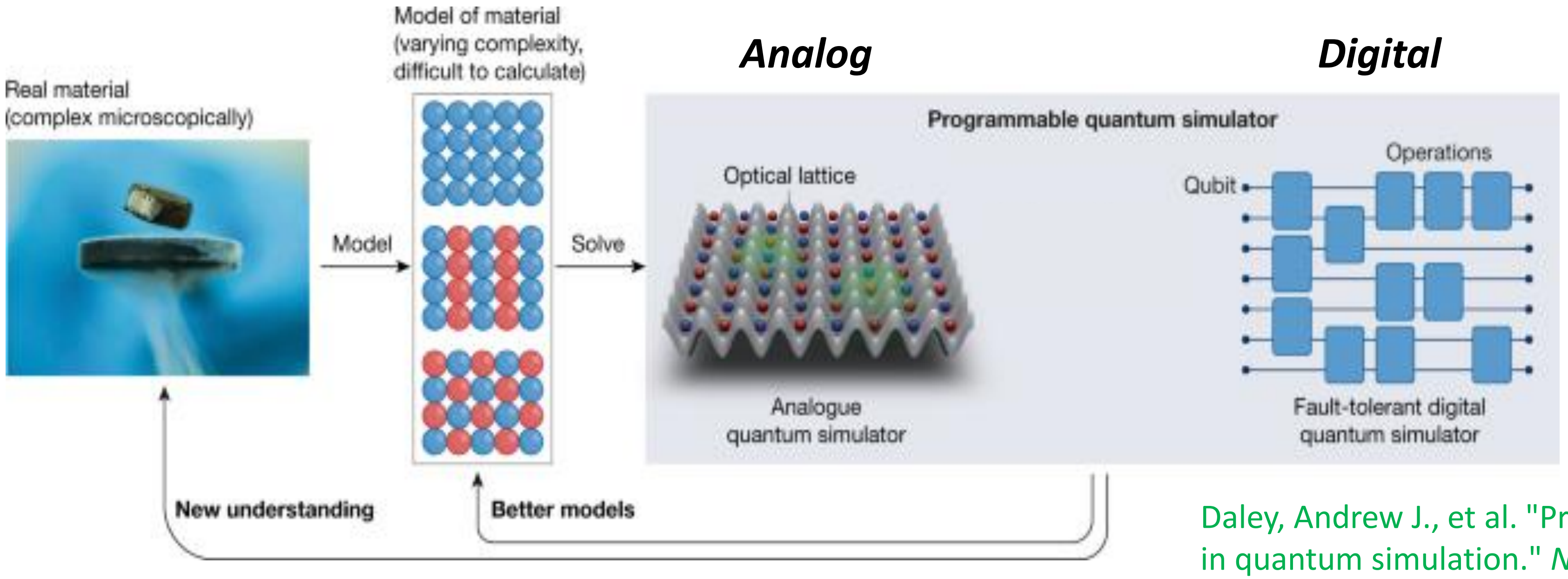
Quantum many-body systems are in general **computationally untreatable**: resources scale **exponentially with the size** of the system

A resource, not a limitation!

Use a quantum system to simulate a quantum system

Analog quantum simulation: Mapping a quantum system on another, more controllable quantum system

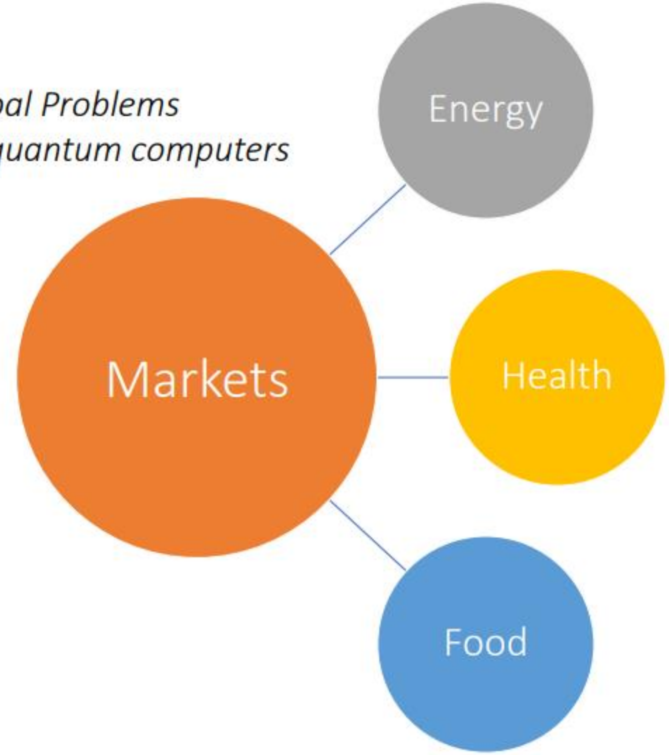
Digital quantum simulation: Mapping a quantum system on an algorithm for a digital quantum computer



Daley, Andrew J., et al. "Practical quantum advantage in quantum simulation." *Nature* **607**, 7920 (2022).

Useful for what?
The (middle-height) hanging fruits

Global Problems
for quantum computers



Renewable energy storage

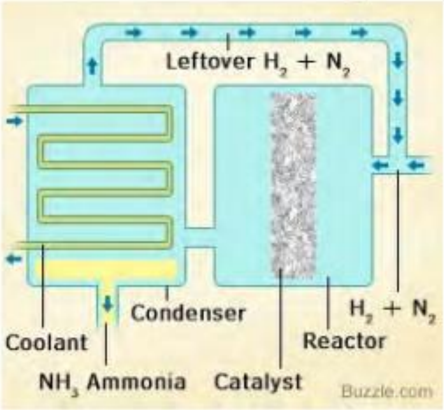
Design of new
pharmaceuticals

Fertilizer production

"A billion dollar device needs a billion dollar application…"

The nitrogenase enzyme and its secret ingredient:

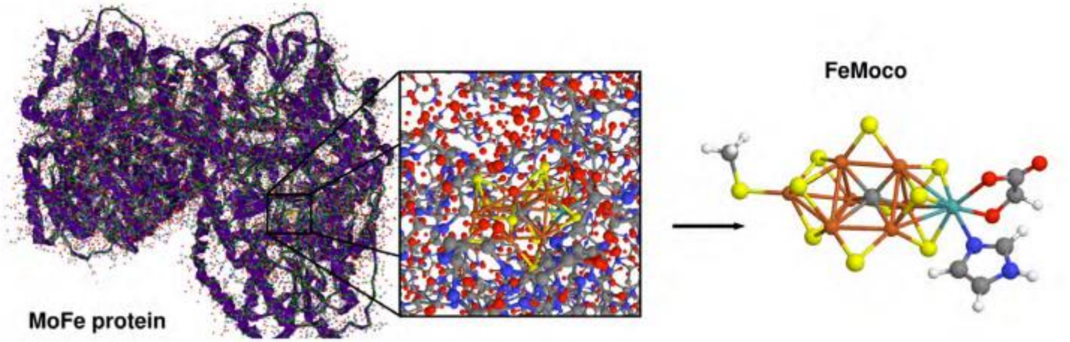
Haber Bosch Process (1910)



500°C, 20 Mpa

Bacteria don't need high temperatures or pressure to make ammonia!

Design and understanding new molecular systems



Needed 10^6 operations

A few 100 qubits but error-free!

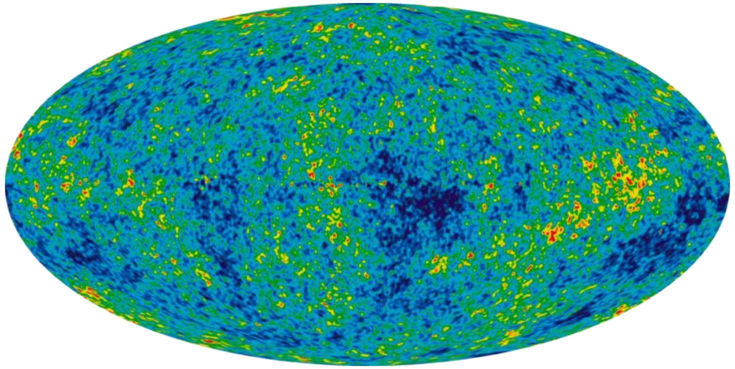
Design of a new catalyst

Reiher, M., Wiebe, N., Svore, K. M., Wecker, D. & Troyer, M. Elucidating reaction mechanisms on quantum computers. *Proc. Natl. Acad. Sci.* U.S.A. **114**, 7555–7560 (2017)

Quantum Mechanics is valid at all scales

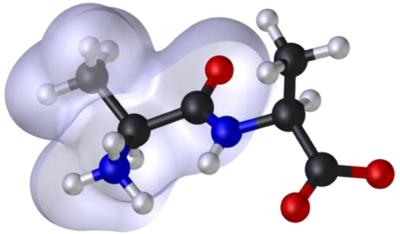
Unprecedented series of success…

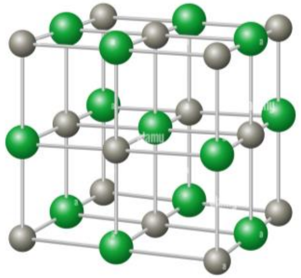
Huge range of applications and extremely precise predictions:



- From elementary particles and sub-constituents of a particle
  $10^{-35}\mathrm{m}$ to $10^{-15}\mathrm{m}$
- To cosmological structures
  $10^{26}\mathrm{m}$
- Througth atoms, molecules and solids
  $10^{-10}\mathrm{m}$

But reality around us is classic



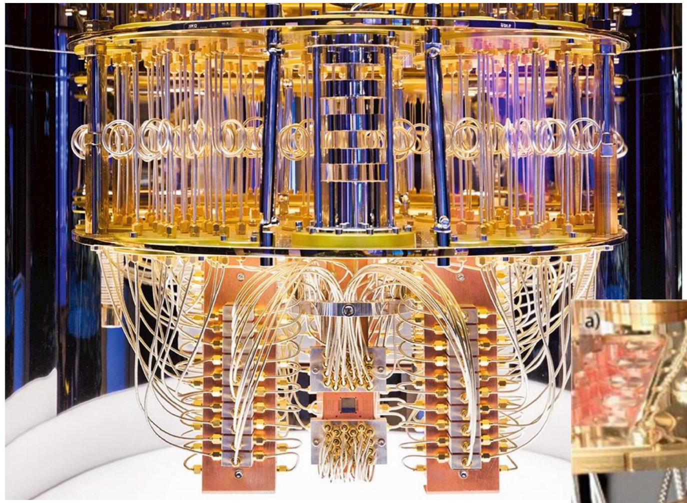


HOWEVER **Quantum Properties are extremely fragile respect to the interaction with the environment → decoherence and relaxation**

- Quantum decoherence is the loss of superposition, because of the spontaneous interaction between a quantum system and its environment.
- Preventing decoherence remains the biggest challenge in building quantum computers.

How can one actually build and operate such devices?

What do we need? The coherent quantum state has to be preserved

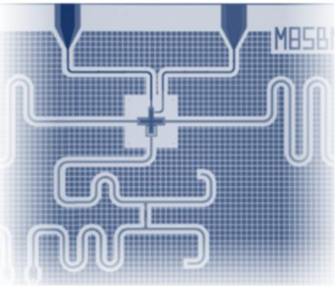
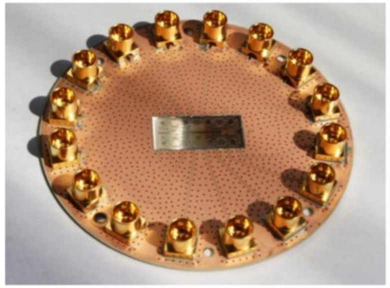
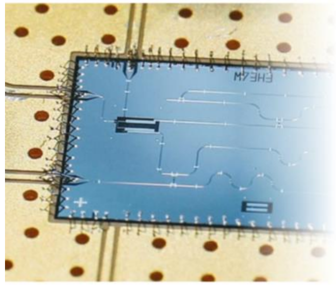
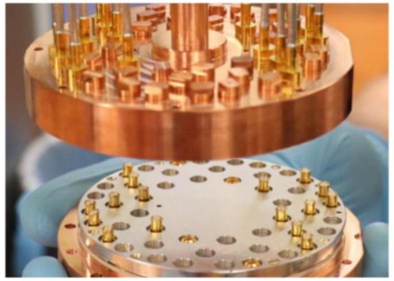
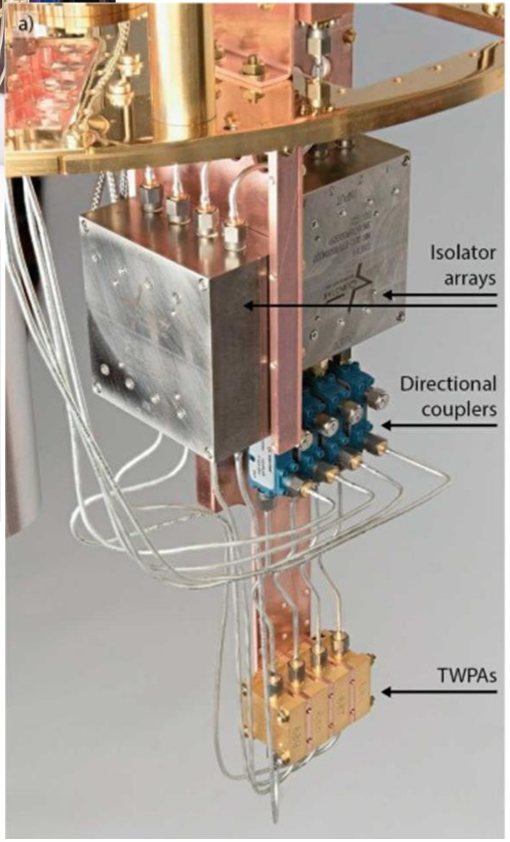


Recipe:

- avoid dissipation
- work at low temperatures
- isolate quantum circuit from environment

BUT

- Engineer a high control for:
    - Initial state preparation (initialization);
    - Timing of unitary evolution (gates);
    - Measurement of the final state(s)

How can one actually build and operate such circuits?

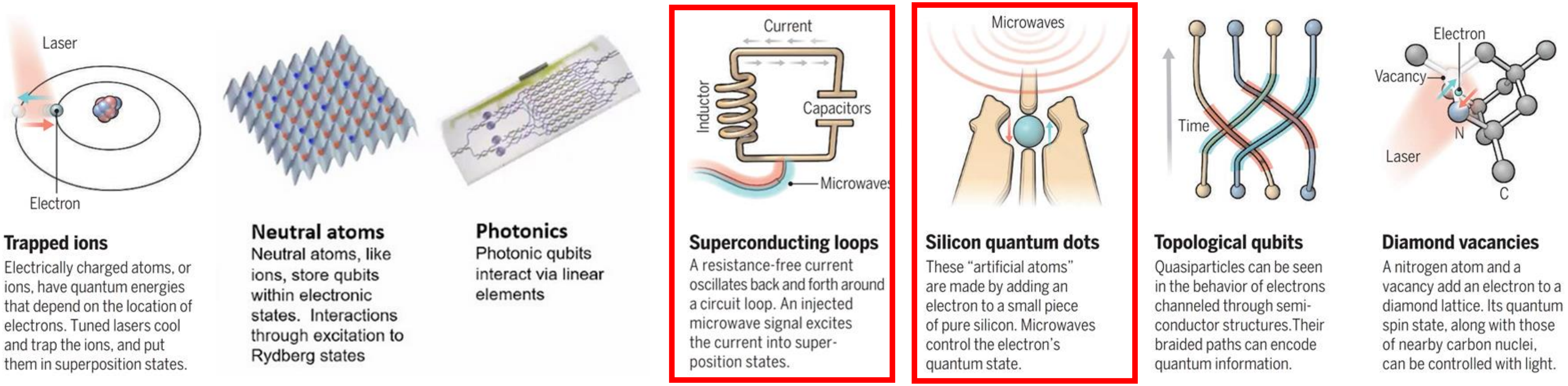
So the difficult part is to find a **mescoscopic system** that we can implement and control in our lab, where quantum properties live long enough to try to benefit for them.

Multiple Quantum Platforms

Popkin, G.. "Quest for qubits." (2016): 1090-1093.

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

Natural Qubits	Syntetic Qubits



Pros

- "Clean" quantum systems: long quantum coherence

Cons

- Many parameters are fixed and cannot be tuned
- Hard to couple with each other

Pros

- Parameters can be designed for specific purpose
- Many parameters can be also controlled *in situ*

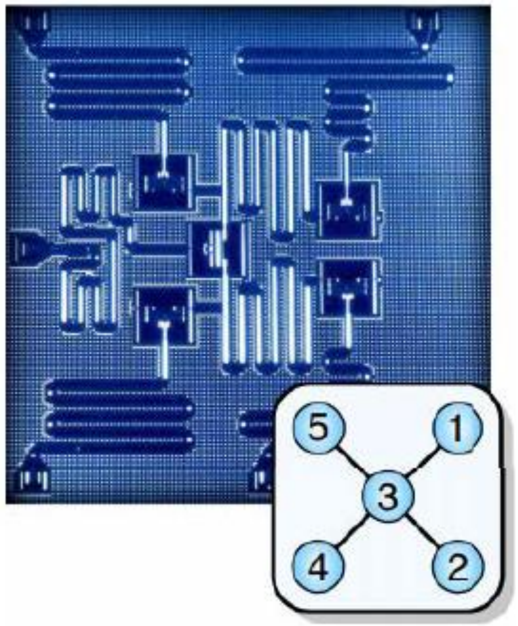
Cons

- Typically, solid-state fabricated structure hence relatively "dirty"

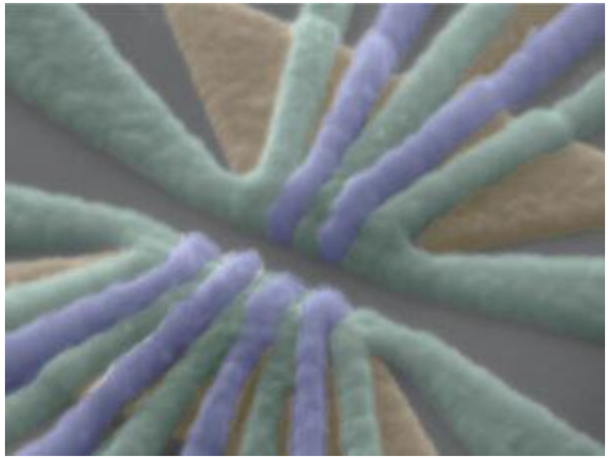
Quantum hardware is ANALOG, not DIGITAL

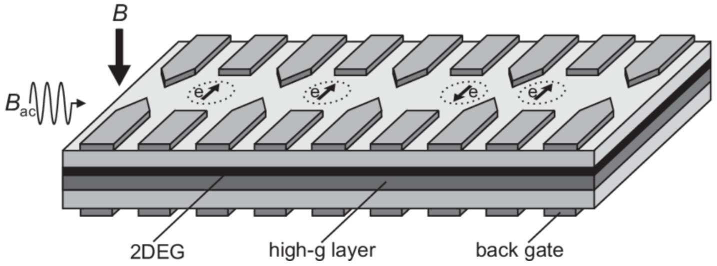
In this course we will focus on:

SUPERCONDUCTIGN QUBITS

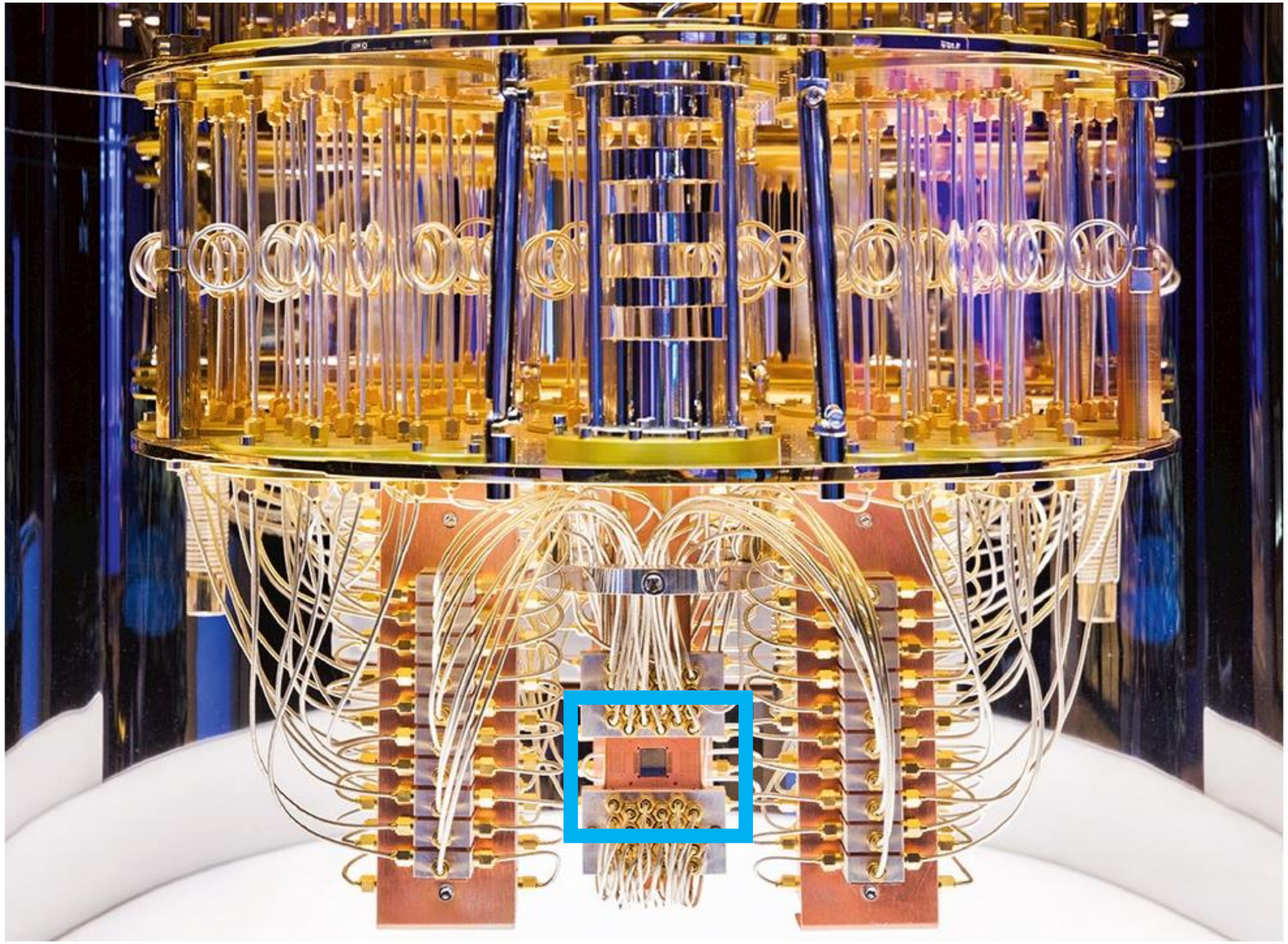


SPIN QUBITS

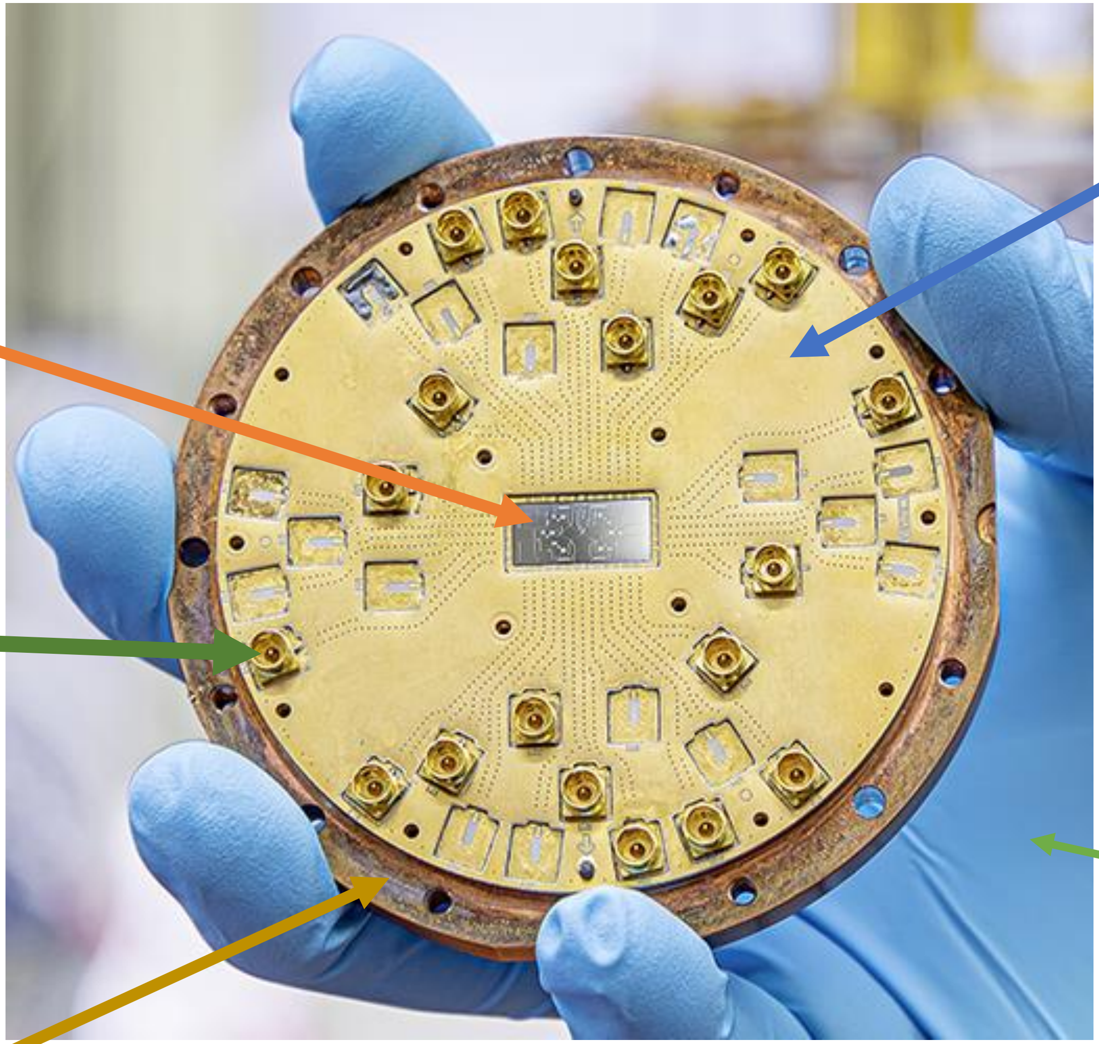




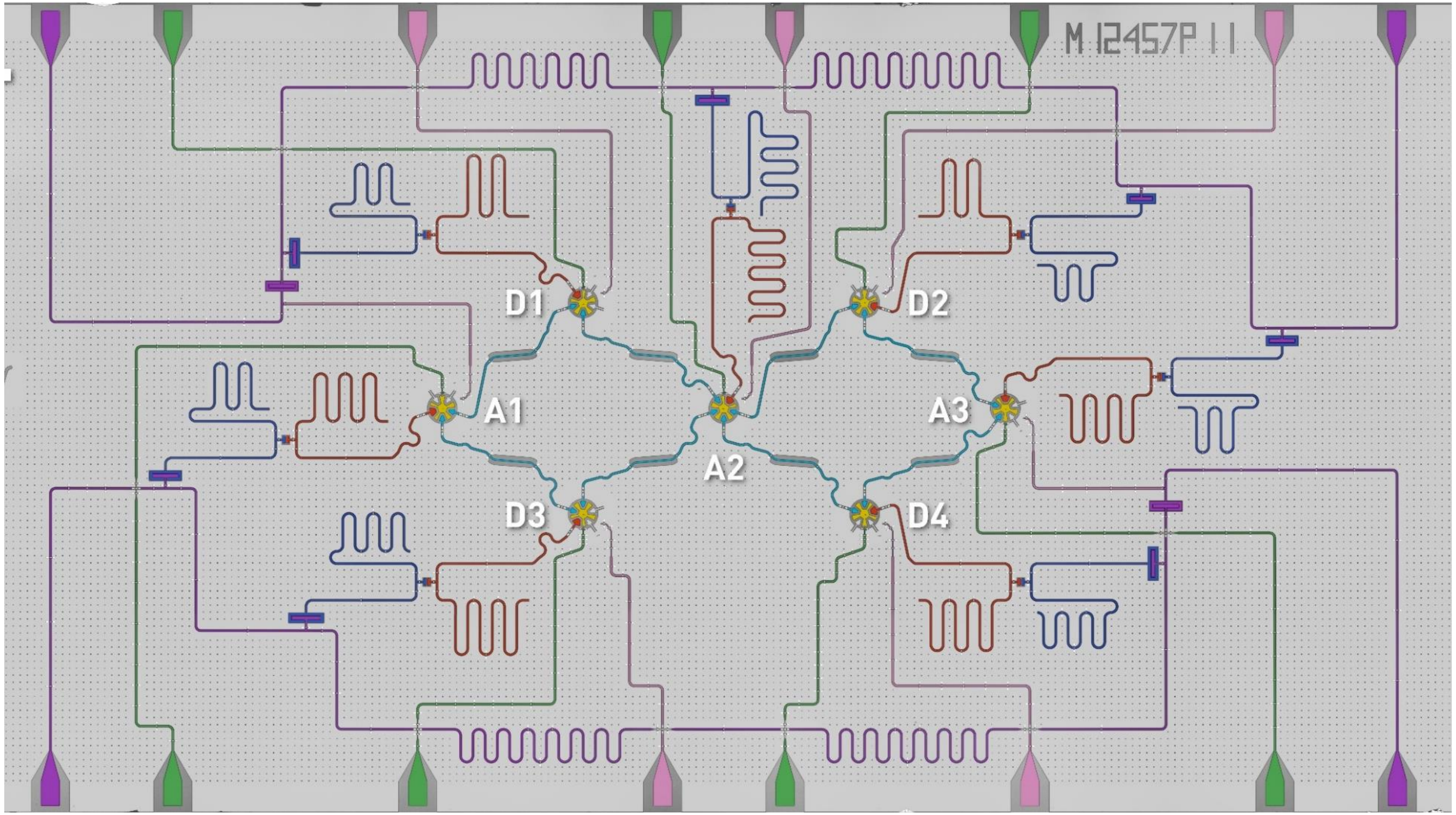
Quantum computing (searching on Google)



A superconducting quantum processor

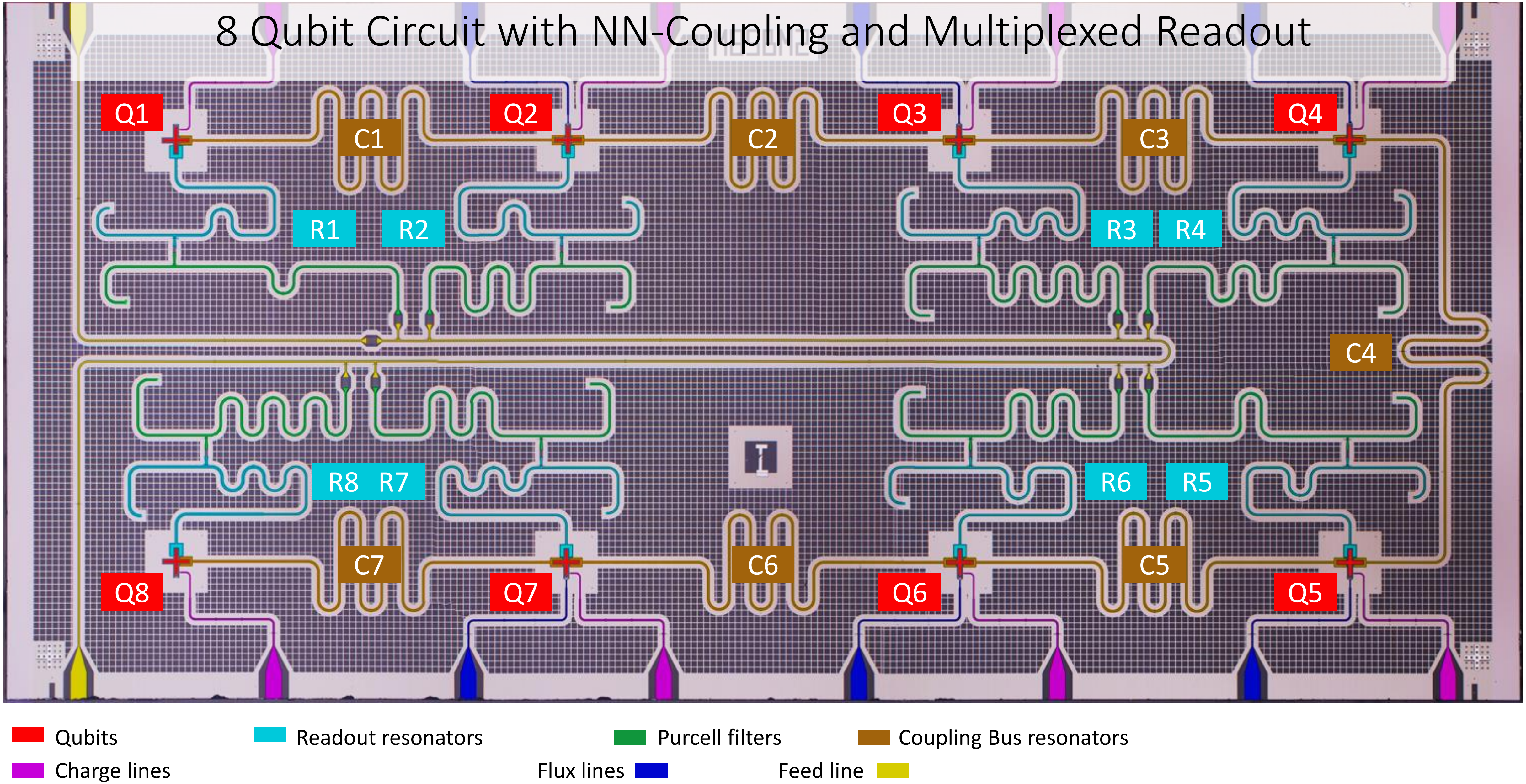


How to Build and Control superconducting qubits

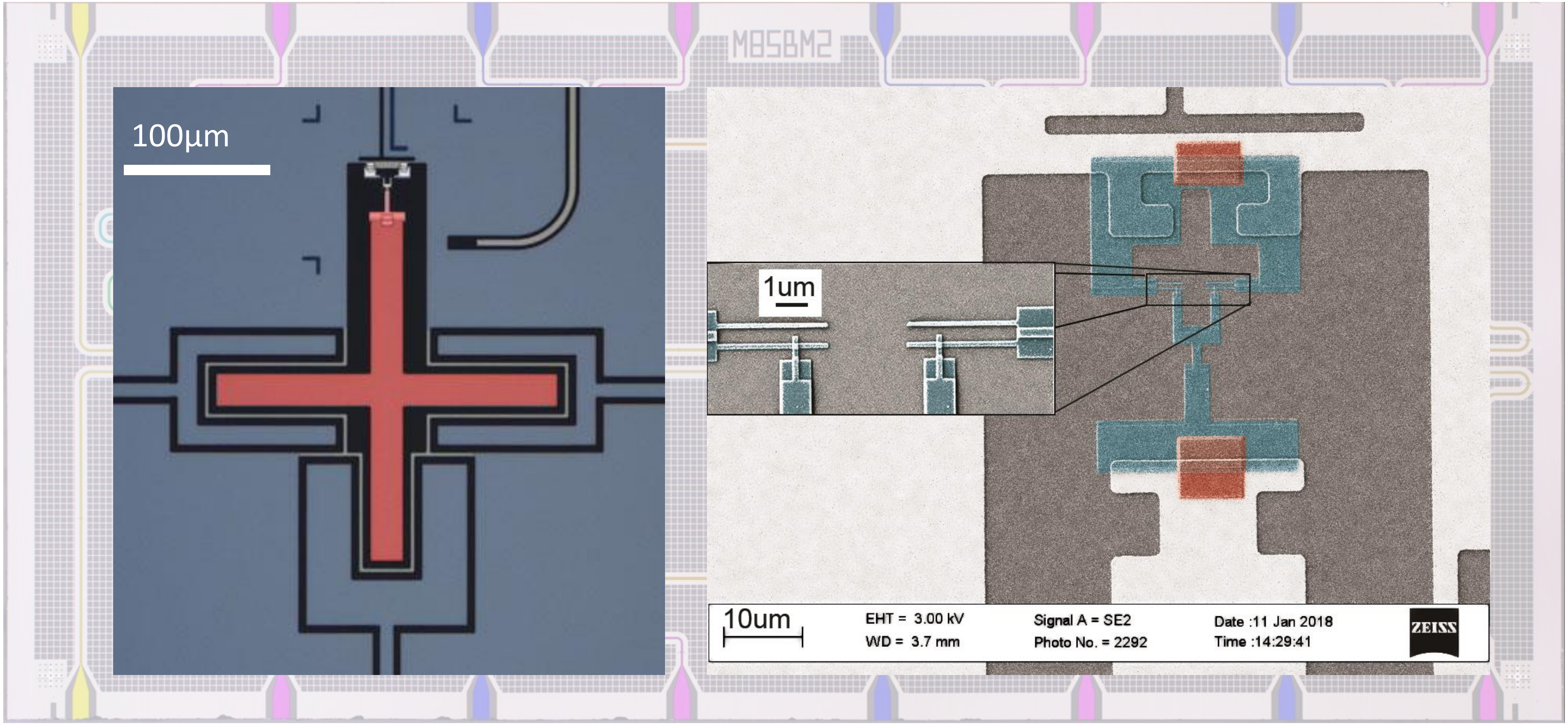


C. K. Andersenet al., *Nat. Physics* **16**, 875 (2020)

8 Qubit Circuit with NN-Coupling and Multiplexed Readout

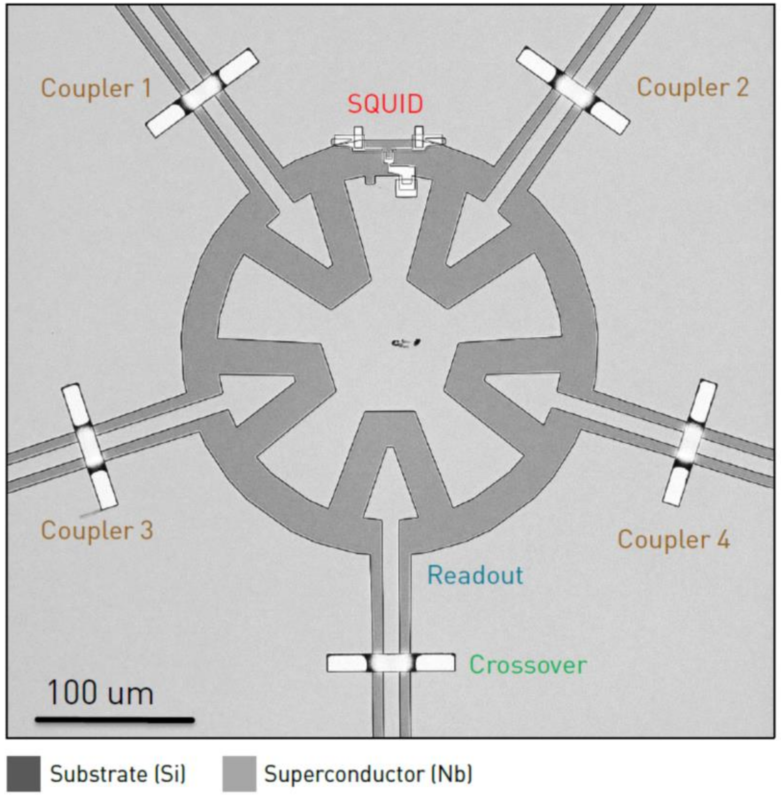


From C. EICHLER, QSSC (2020)

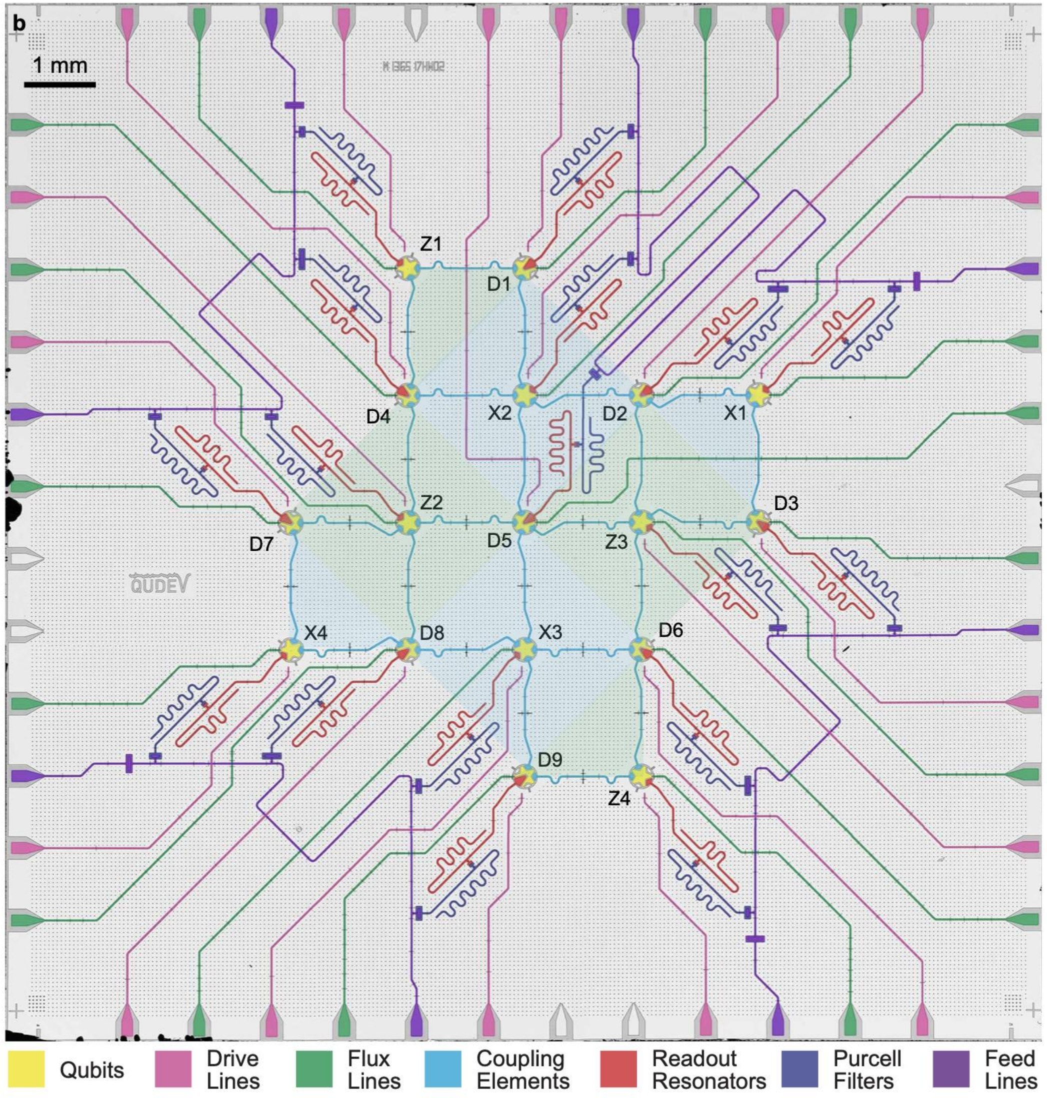


From C. EICHLER, QSSC (2020)

How to Build and Control superconducting qubits



17 transmon qubit device from [Krinner]



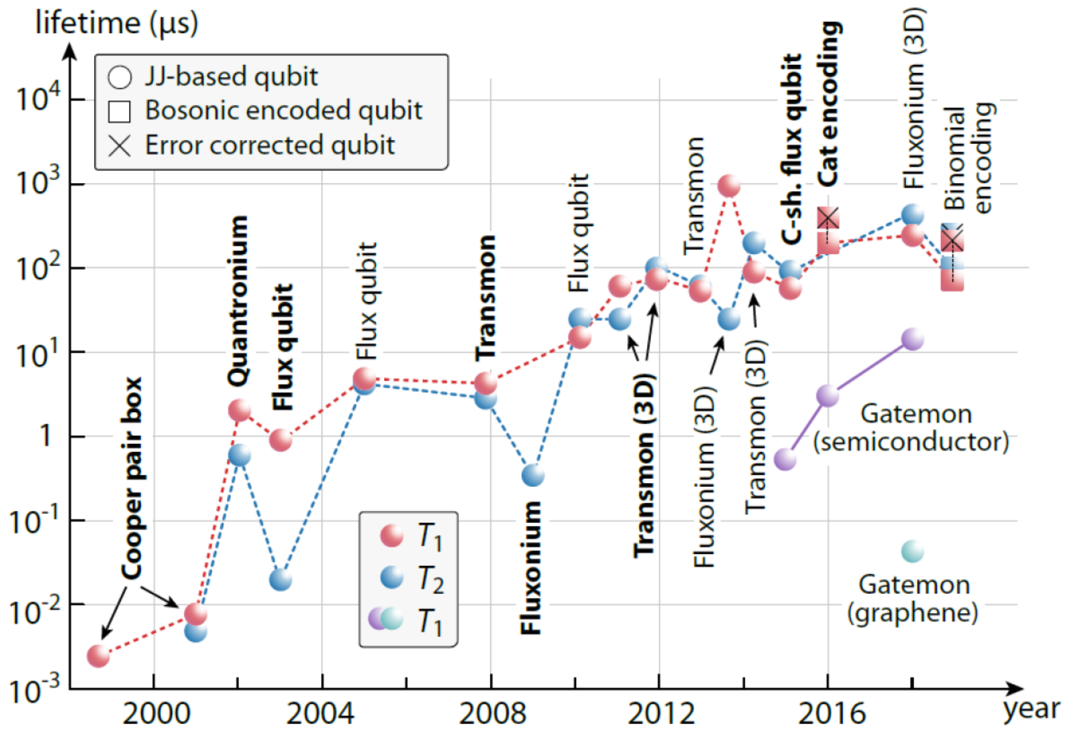
📖 S. Krinner et al., *Realizing repeated quantum error correction in a distance-three surface code*, Nature 605, 669–674 (2022)

Engineering Improves Coherence

- Remarkable improvement in $T_{1,2}$
  - Materials
  - Fabrication
  - Design
- Major qubit types at MIT & LL
  - Flux qubit: T_2 = 23 us
  - 2D transmon: T_2 = 100 us
  - 3D transmon: T_2 = 150 us
  - C-shunt flux qubit: T_2 = 100 us
  - Gatemon (C): T_2 = 50 ns

Remarkable improvement in coherence from improvements to materials, fabrication, and design

“Moore’s Law” for T_2



M. Kjaergaard, WDO, et al., arXiv:1905.13641

P. Krantz, WDO, et al., Appl. Phys. Rev. 6, 021318 (2019); arXiv:1905.13641

WDO & Welander, MRS Bulletin (2013)

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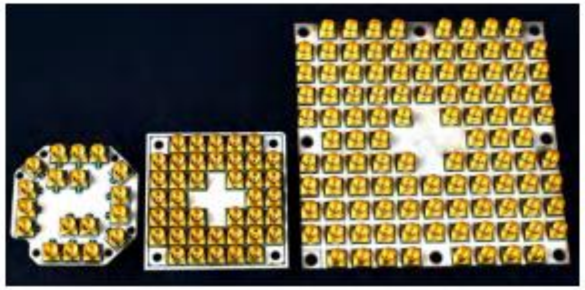
Superconducting Systems Scaling up

The numbers game

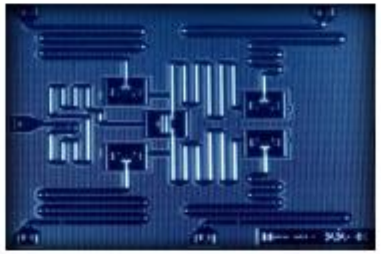
7 17 49



January 2018

March 2020 – Nov 2022

Dropped supercond. qubits (focusing now on spin qubits in Si)

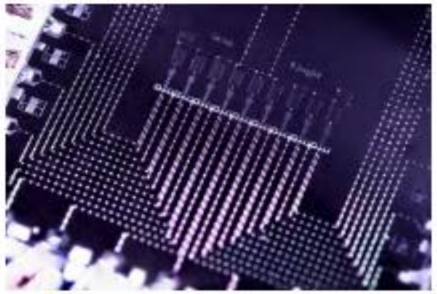


Quantum Experience

5 & 20 qubit chips available online (working, 2017)

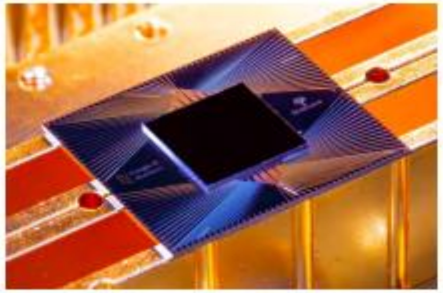
5~~0~~3 qubit chip announced ("launching soon" 09/2019)

127 qubit chip (Jan 2022), 433 qubit chip (Nov 2022)



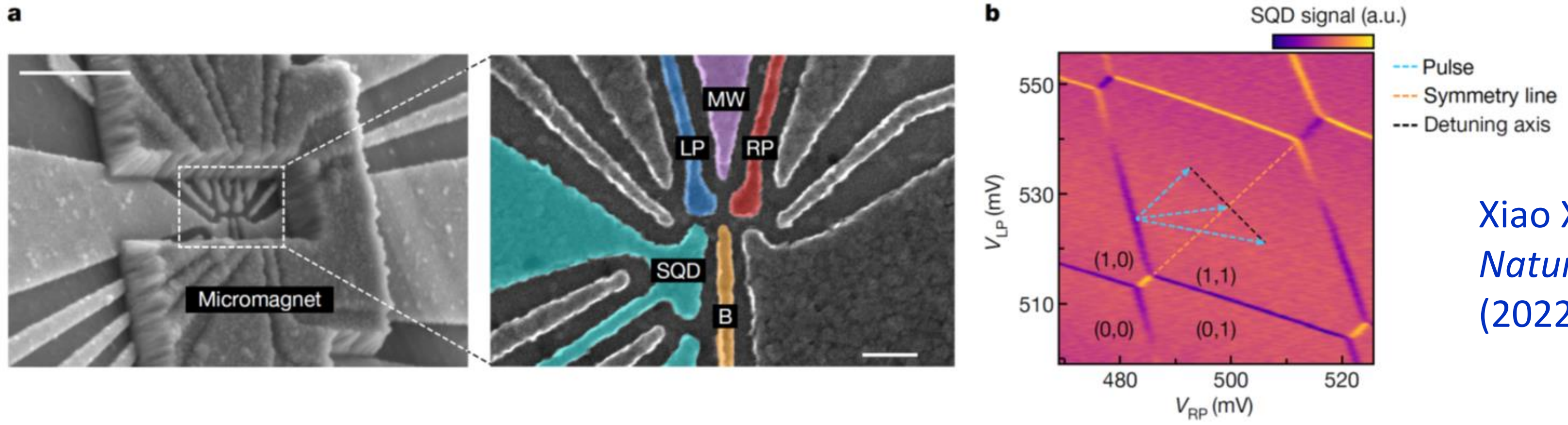
9 excellent qubits

72 qubits? X

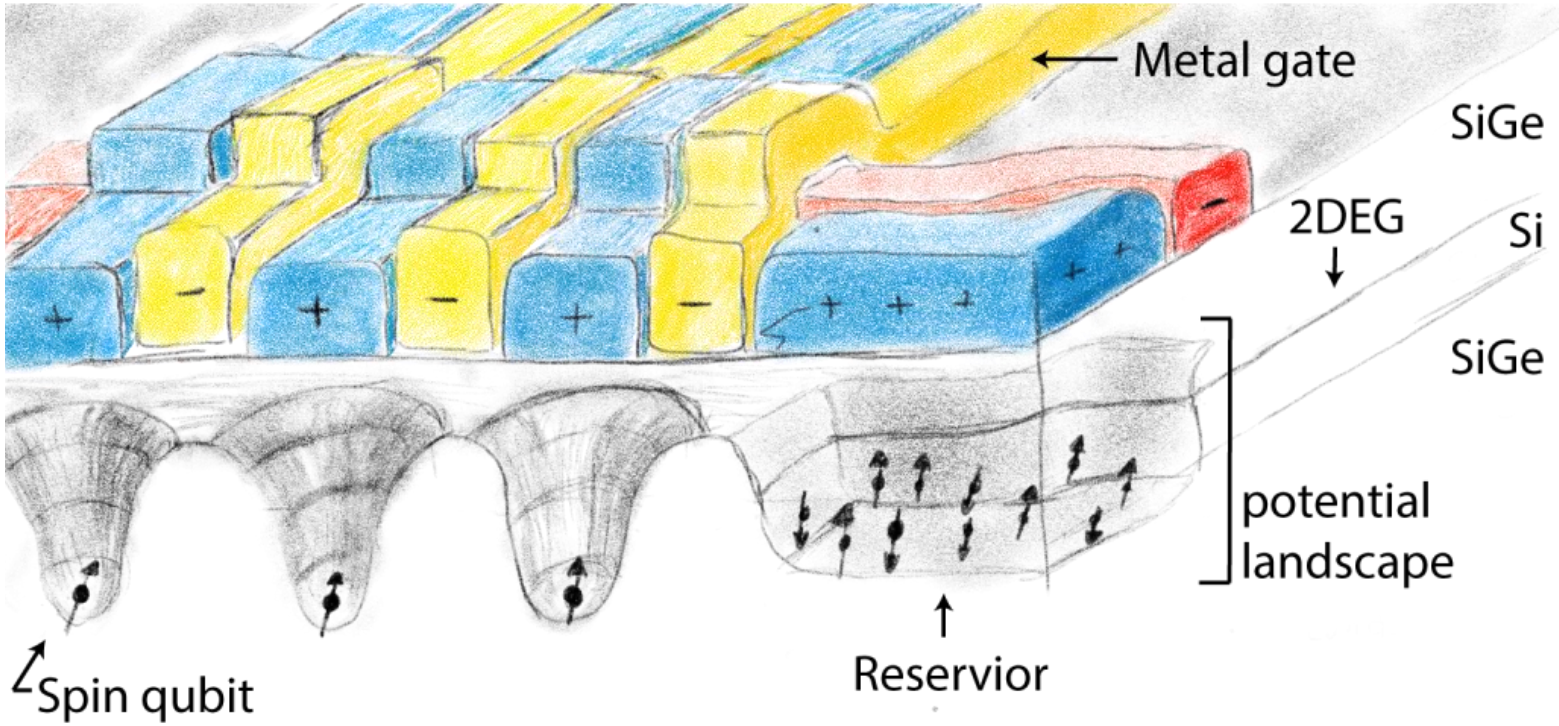


~~54~~ 53 qubits (2019)

Semiconducting SPIN QUBITs



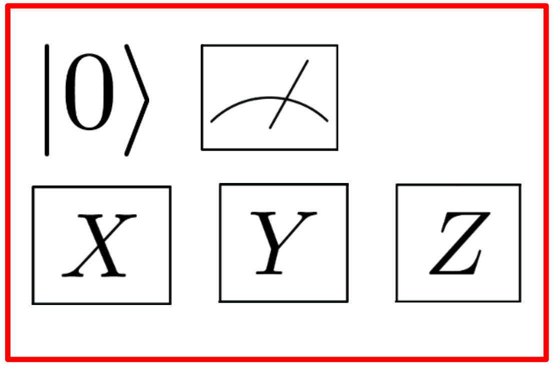
Xiao Xue, et al., *Nature* **601**, 343 (2022)

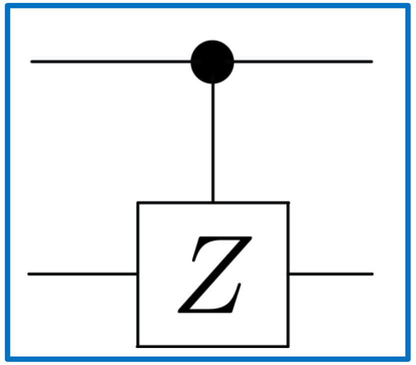


https://blog.qutech.nl/2018/04/20/making-quantum-computers-with-spin-qubits/

Long Coherence spins in silicon

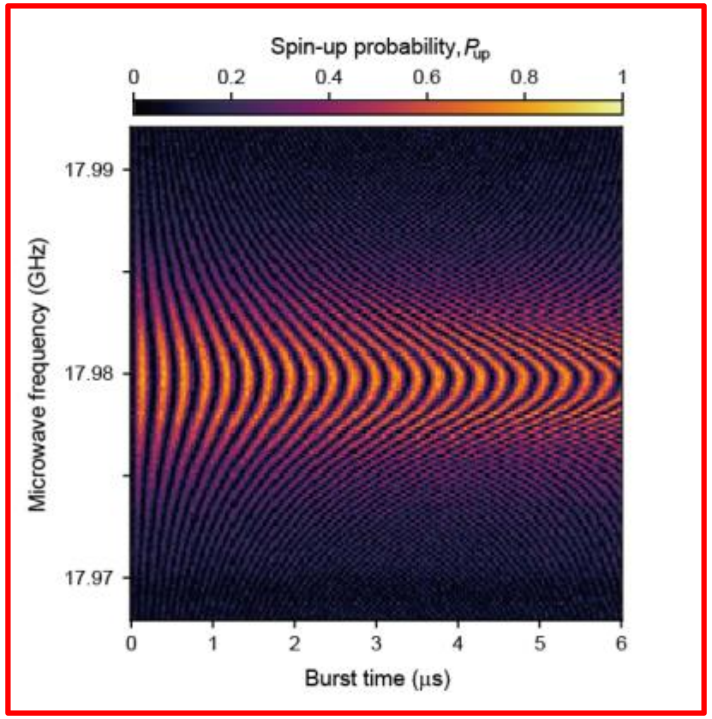
Single Qubit Gates





Two Qubits Gates

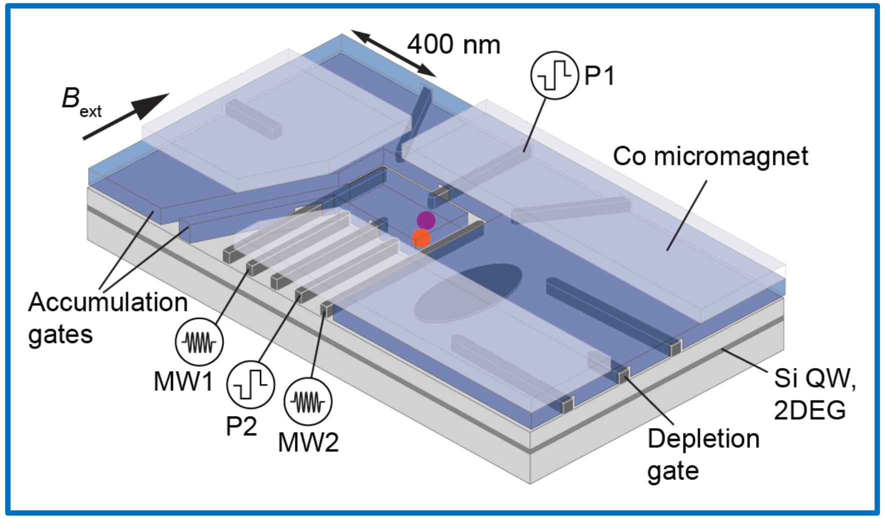
SiGe



Yoneda, et al. *Nat. Nanotech* **13**, 102 (2018)

For electron spin:
T_2^*= 200us
T_2 = 28ms
T_1 = 100 ms to s
F_C = 99.9%

SiGe



Watson et al., *Nature* **555**, 633 (2018)

Xiao Xue, et al., *Nature* **601**, 343 (2022)

Computing with spin qubits at the surface code error threshold

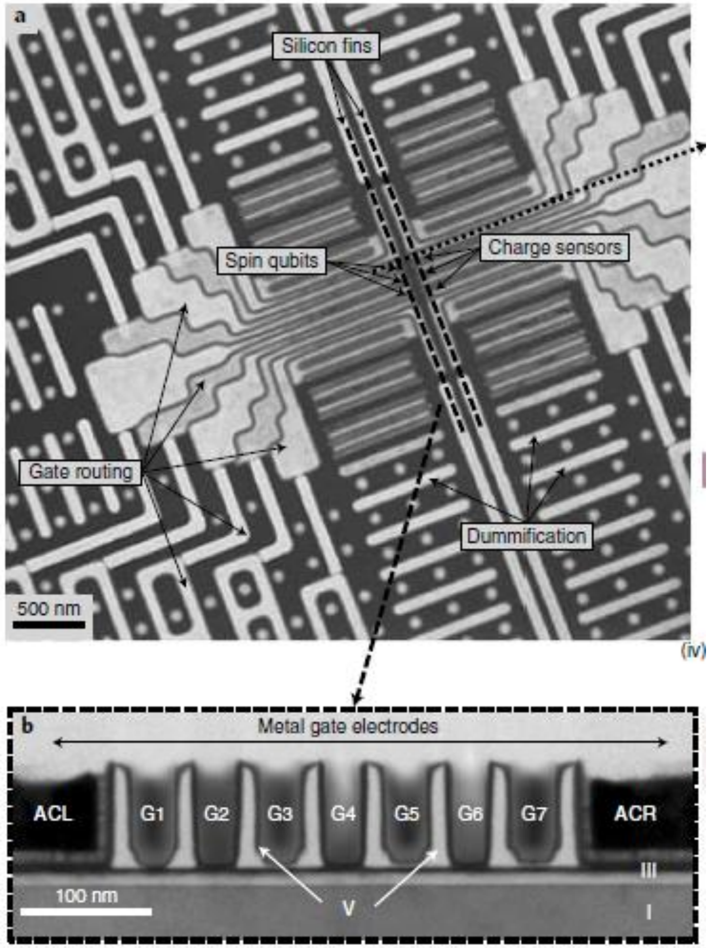
'Now that the 99% barrier for the two-qubit gate fidelity has been surpassed, semiconductor qubits have gained credibility as a leading platform, not only for scaling but also for high-fidelity control.'

State of the art of spin qubits

INTEL- TU Delft

Qubits made by advanced semiconductor manufacturing

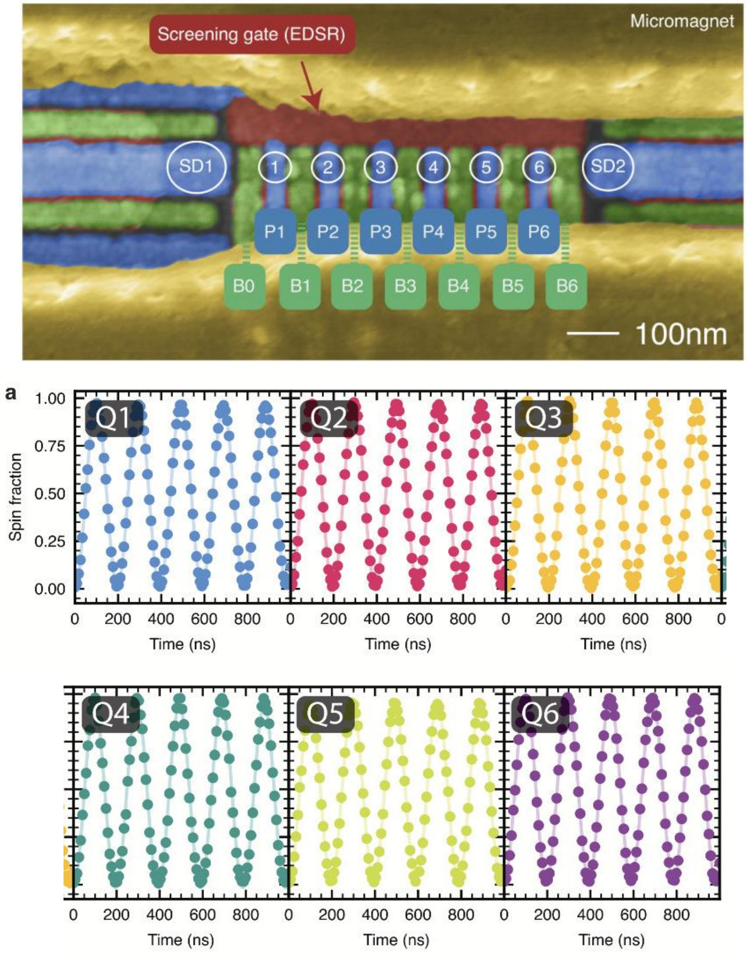
A. M. J. Zwerver, et al., *Nat. Electronics* **5**, 184 (2022)



TU Delft

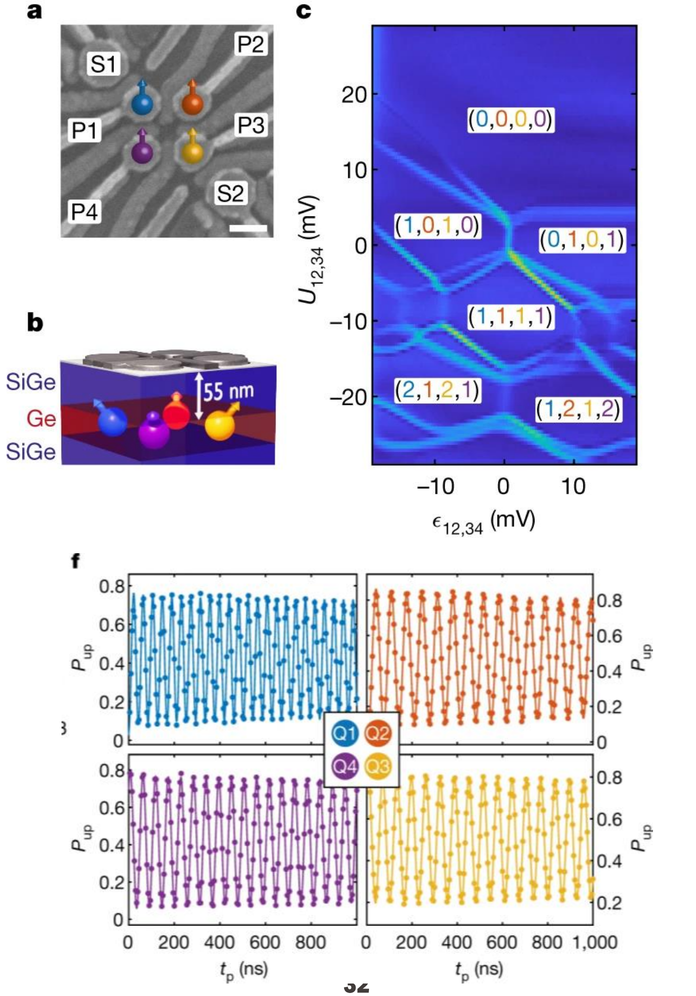
Universal control of a six-qubit quantum processor in silicon

S. G.J. Philips, et al., *Nature* **609**, 919–924 (2022)



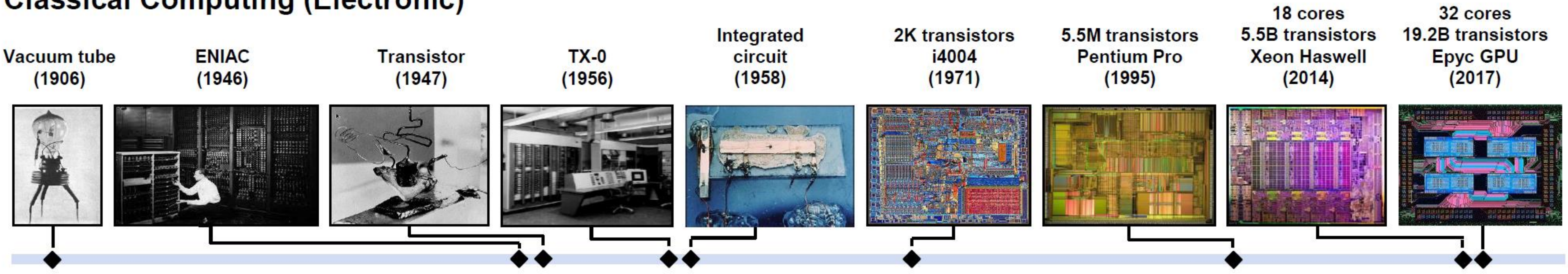
A four-qubit germanium quantum processor

N.W. Hendrickx et al., *Nature* **591**, 580–585 (2021)



Computing Development over Time

Classical Computing (Electronic)



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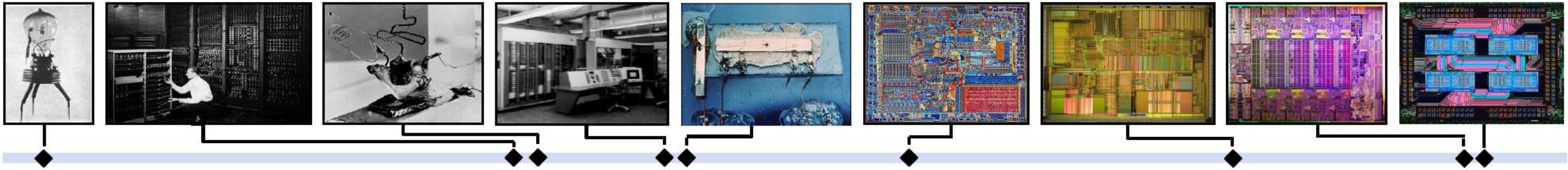
Computing Development over Time

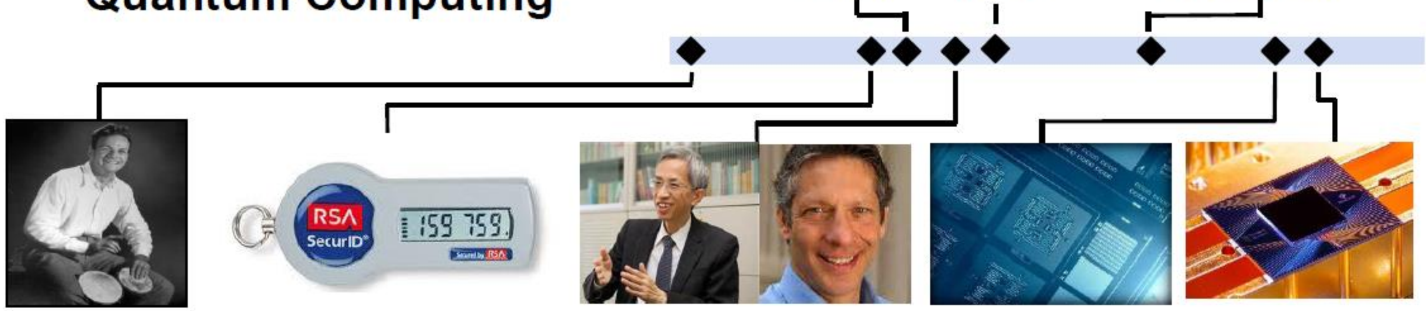
Classical Computing (Electronic)

Vacuum tube (1906) | ENIAC (1946) | Transistor (1947) | TX-0 (1956) | Integrated circuit (1958) | 2K transistors i4004 (1971) | 5.5M transistors Pentium Pro (1995) | 18 cores 5.5B transistors Xeon Haswell (2014) | 32 cores 19.2B transistors Epyc GPU (2017)



Quantum Computing

Grover (1996) | Factor 15 (2002) | Few-qubit processors (2010-2016)



Quantum simulator proposed (1981) | Shor's algorithm & CSS error correction (1994-95) | Quantum annealing & adiabatic QC (1998-2000) | Cloud-based QCs (2017) | Quantum Advantage 53-qubit QCs

Quantum computing is transitioning from scientific curiosity to technical reality.

Advancing from discovery to useful machines takes time & engineering

You must be in the game to play

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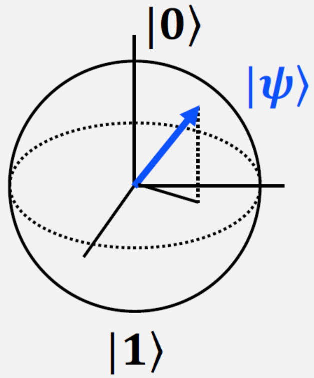
How is Quantum Computing Different?

	Classical Computer	Quantum Computer
Fundamental logic element	**“Bit” : classical bit** (transistor, spin in magnetic memory, …)	**“Qubit” : quantum bit** (any coherent two-level system)
State	**0 “Or” 1**	 **Superposition:** $\alpha\|0\rangle + \beta\|1\rangle$ $\|0\rangle$ **“And”** $\|1\rangle$ $\|\psi\rangle = \alpha \begin{bmatrix}1\\0\end{bmatrix} + \beta \begin{bmatrix}0\\1\end{bmatrix}$
Measurement	• ***Discrete*** **states** • **Deterministic measurement:** **Ex: Set as 1, measure as 1**	• ***Superposition*** **states** • **Probabilistic measurement:** **Ex: If** $\|\alpha\| = \|\beta\|$, **50%** $\|0\rangle$, **50%** $\|1\rangle$

Quantum computers rely on encoding information in a fundamentally different way than classical computers

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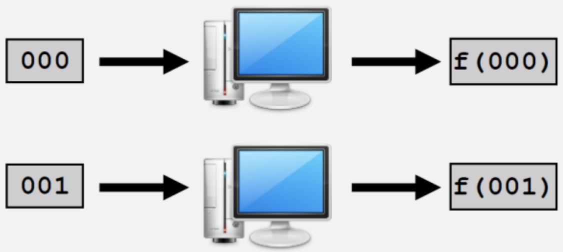
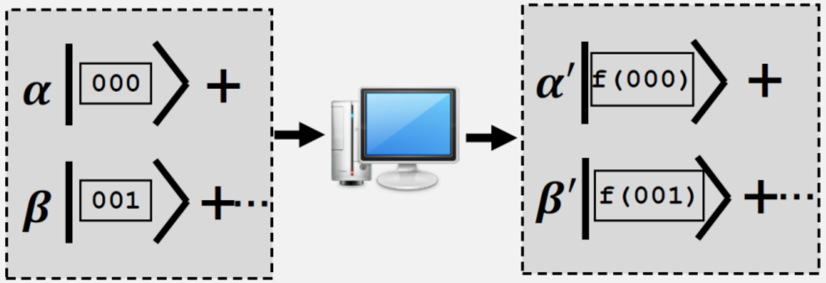
How is Quantum Computing Different?

	Classical Computer	Quantum Computer
Fundamental logic element	**"Bit" : classical bit** (transistor, spin in magnetic memory, …)	**"Qubit" : quantum bit** (any coherent two-level system)
Computing	• N bits: One N-bit state 000, 001, …, 111 (N = 3) • Change a bit: new calculation (classical parallelism)	• N qubits: 2^N components to one state $\alpha\|000\rangle + \beta\|001\rangle + \cdots + \gamma\|111\rangle$ (N = 3) • Quantum parallelism & interference





Quantum computers rely on encoding information in a fundamentally different way than classical computers

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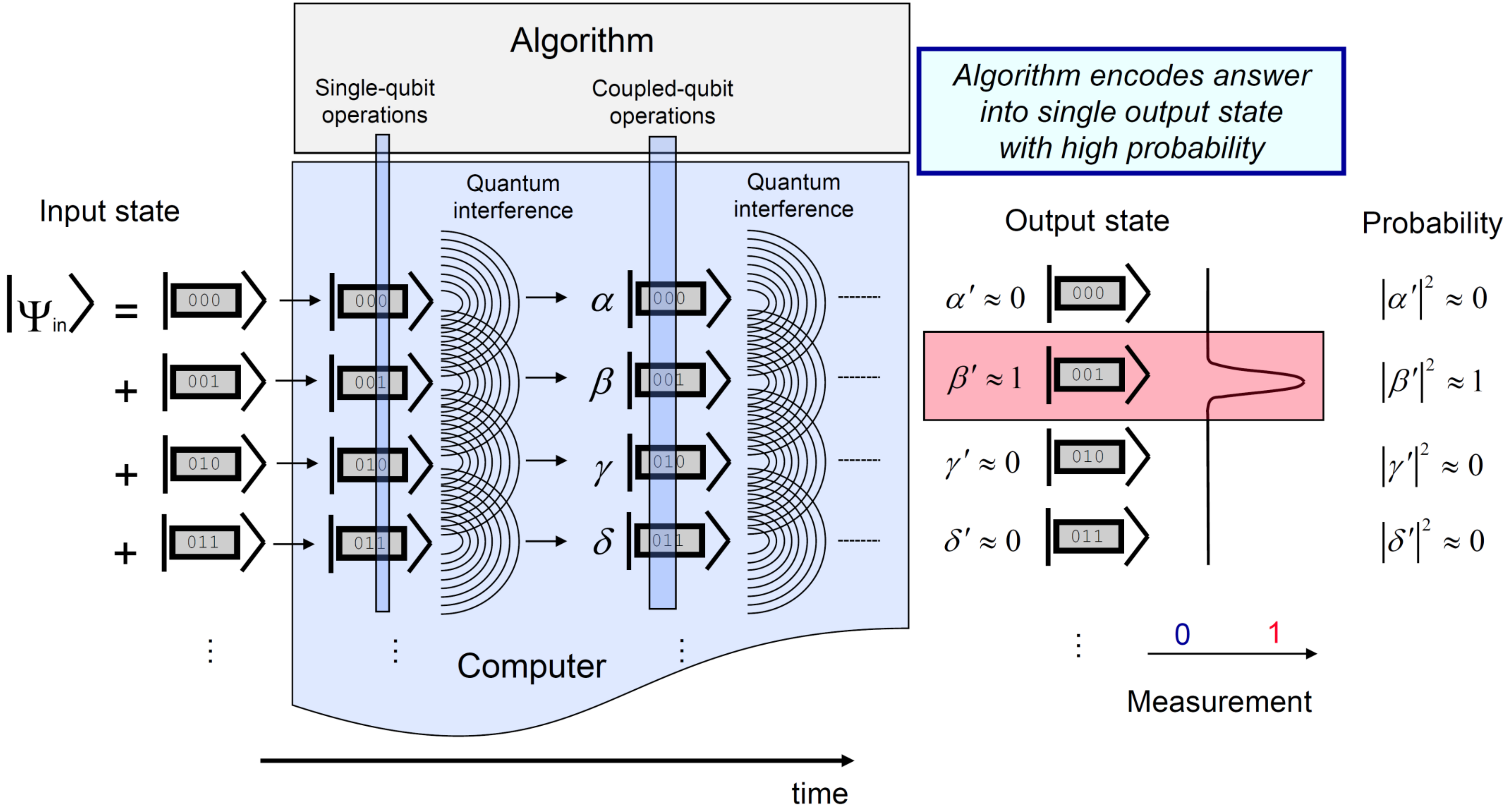
Quantum Algorithm (Universal)



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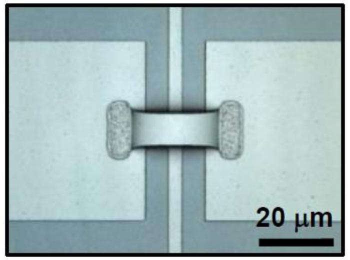
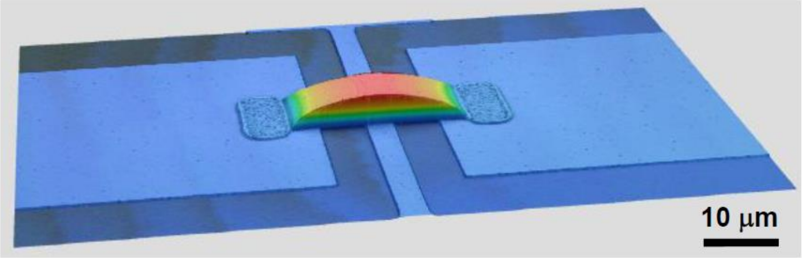
Fabrication Engineering

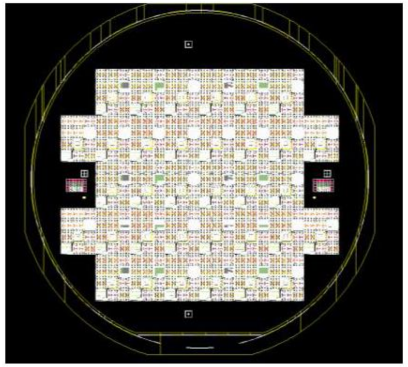
- **Manufactured/designed qubits**
- **Lithographic scalability (silicon)**

High-coherence air-gap cross-overs (optical microscope and confocal images)

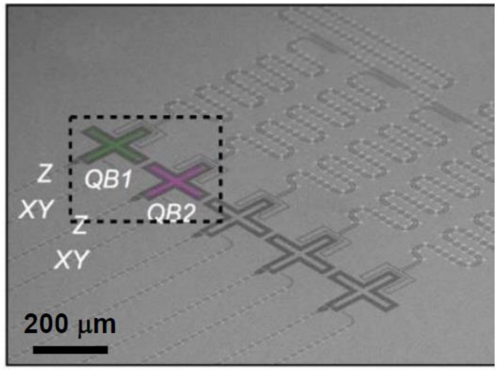




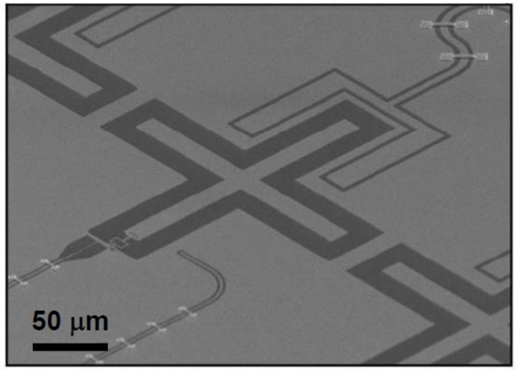
200-mm wafers (49 Reticles × 16 chips)



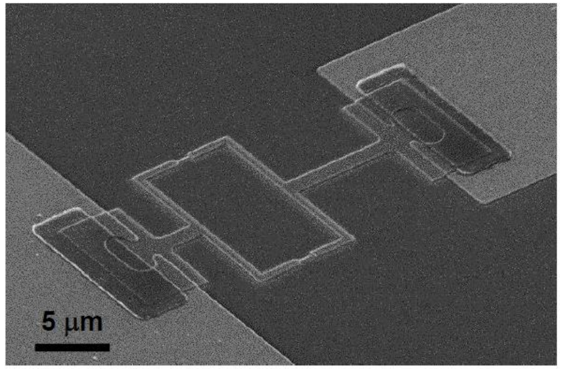
5-Transmon chip with readout resonators



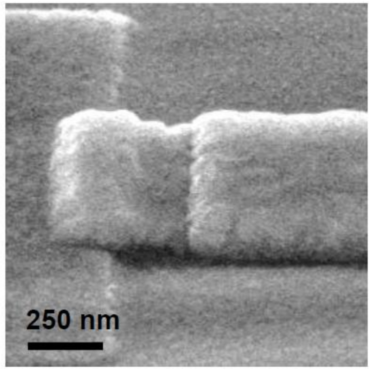
Transmon capacitor and control lines



Tunable transmon qubit loop with junctions



Josephson junctions (aluminum)



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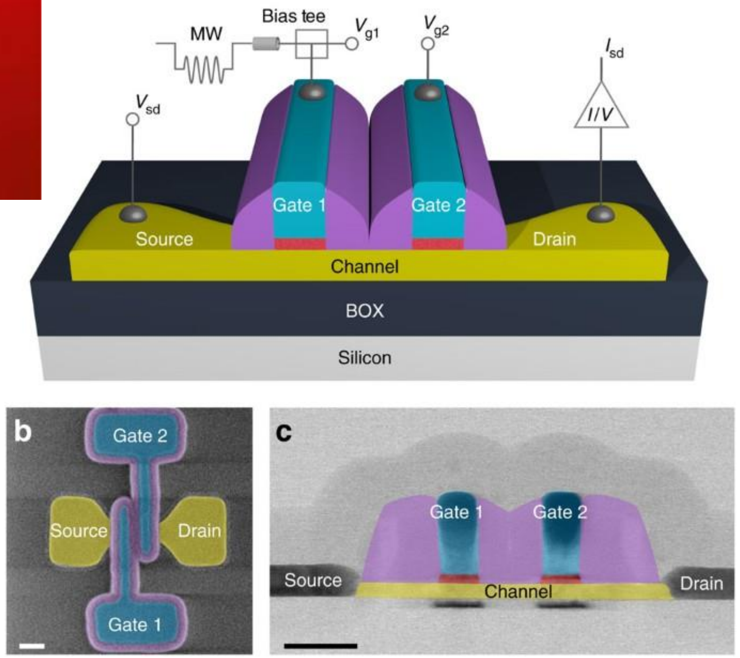
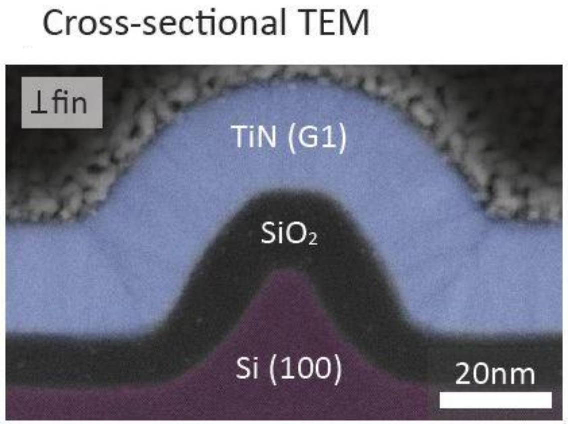
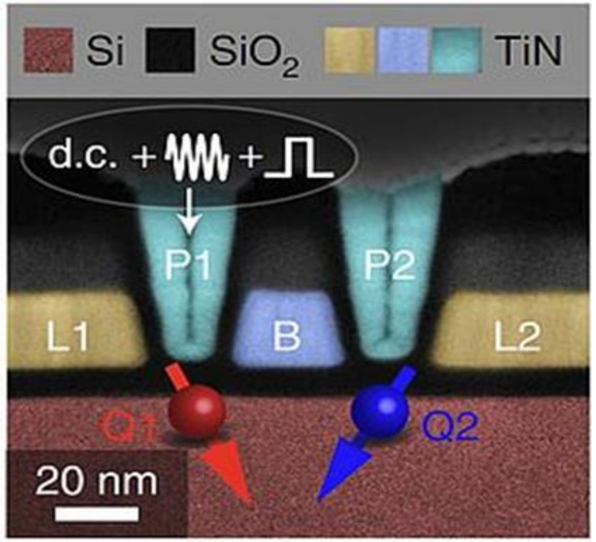
Leverage CMOS platform to design quantum bits

Silicon quantum bit (qubit) devices made with an industry-standard fabrication process

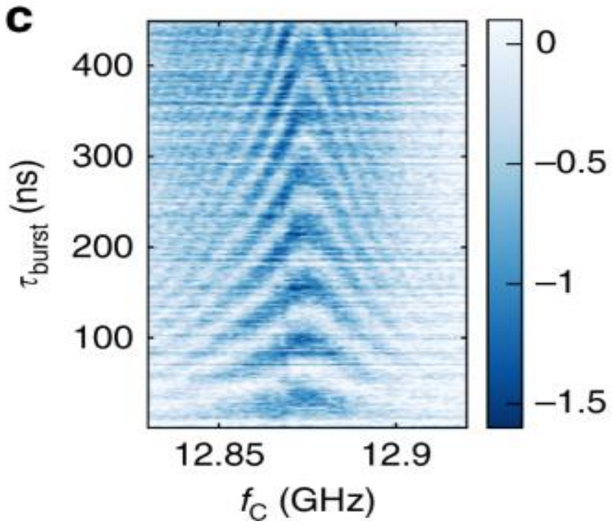




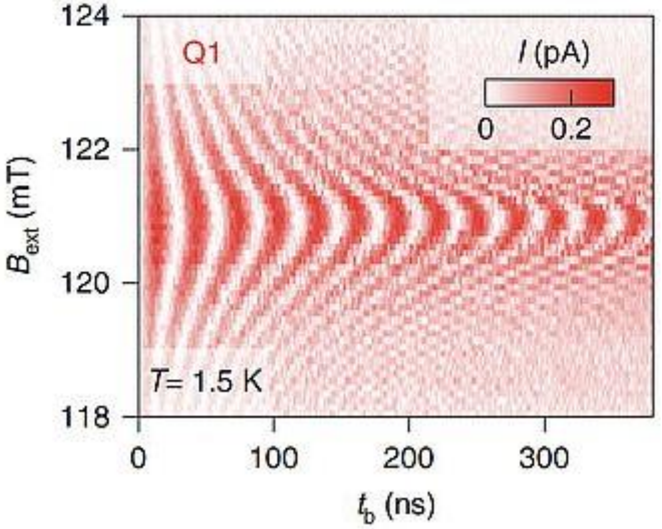
IBM Research | Zurich



NCCR SPIN

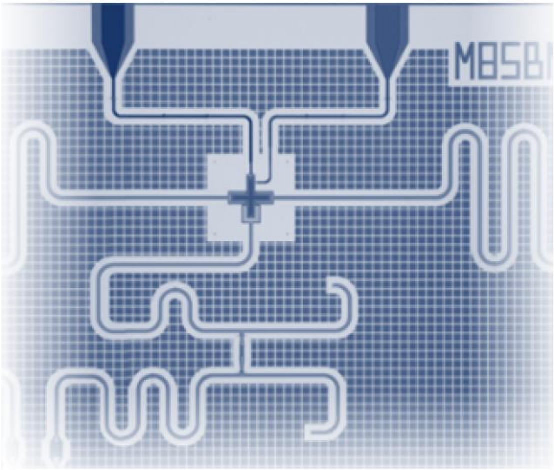


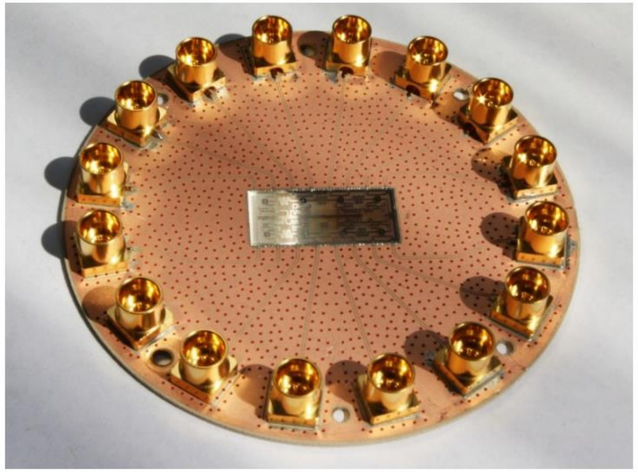
Leveraging the well-established complementary metal–oxide–semiconductor (CMOS) technology would be a clear asset to the development of scalable quantum computing architectures and to their co-integration with classical control hardware.

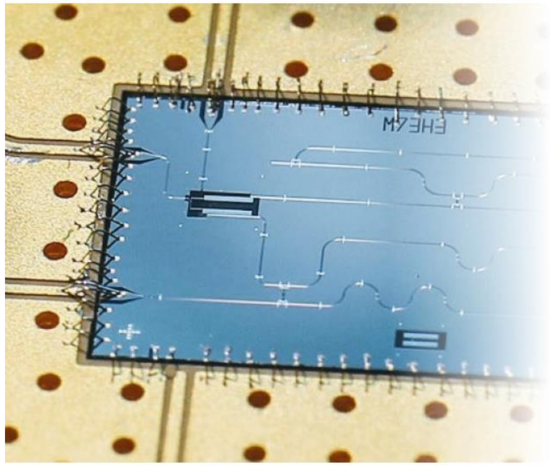


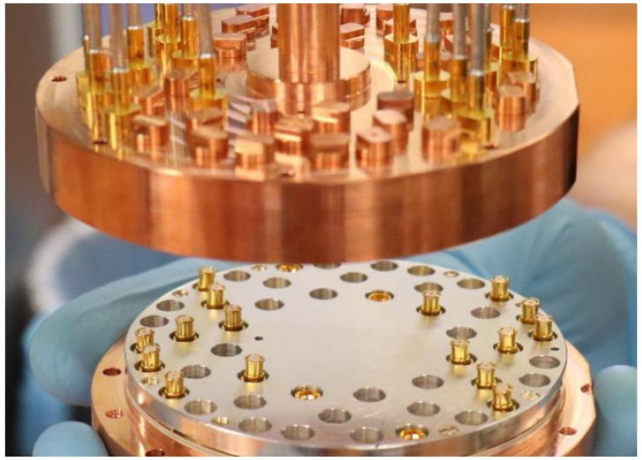
Rabi oscillations of a single spin qubit implemented in a transistor!!!

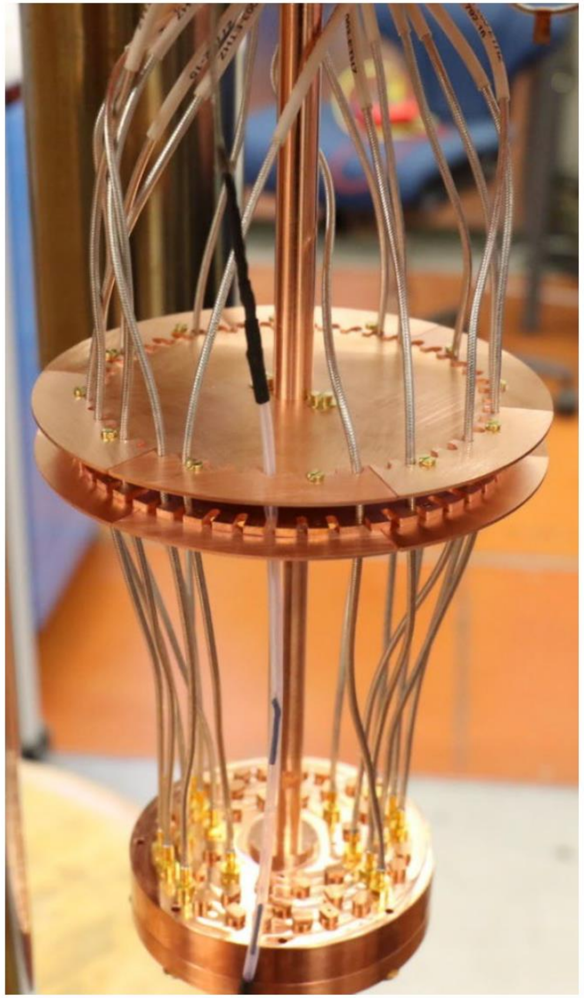
Control and Characterization of solid-state qubits

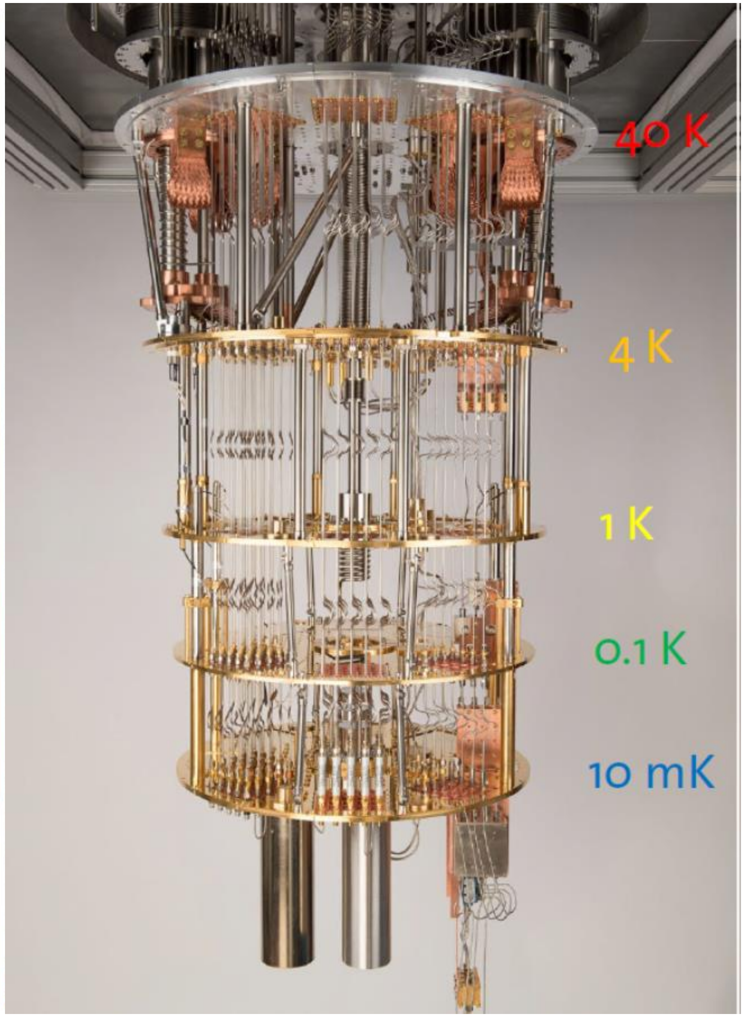










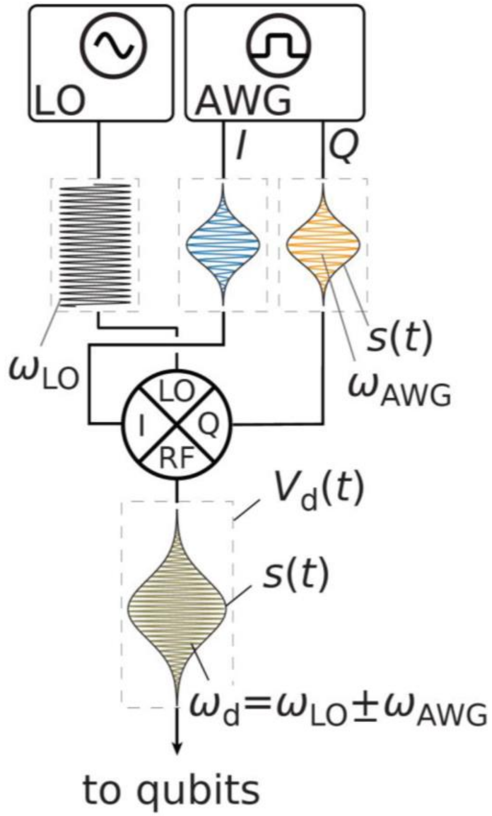


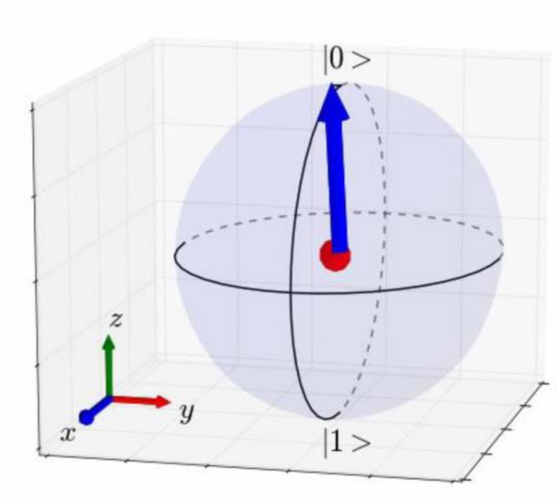
Microwave Engineering and Control

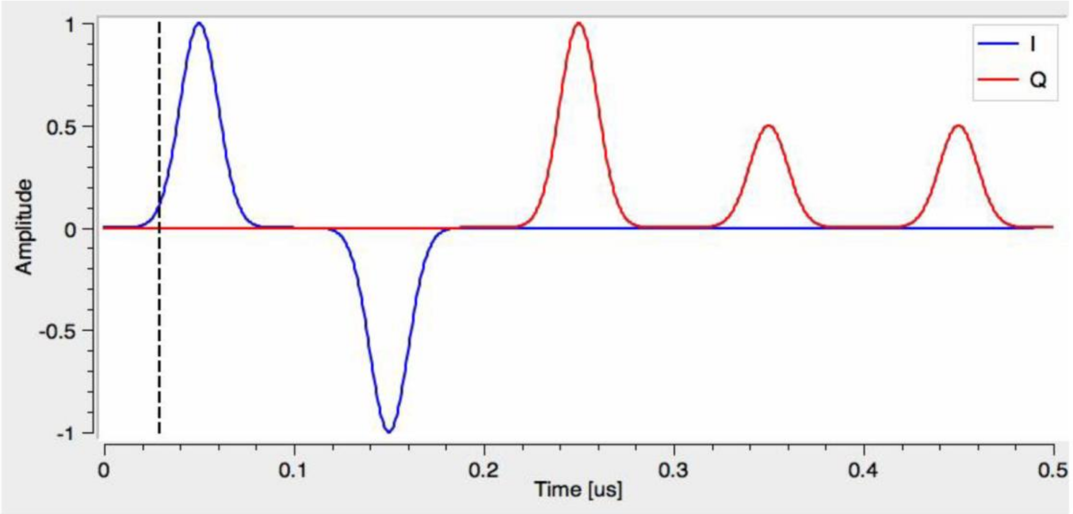
- RF and microwave control
- 100 MHz gate operations

Dual-Channel, 2GS/s, 14-bit AWG

Qubit Control via Microwave Pulses







I: in-phase (0^0) → x axis

Q: quadrature (90^0) → y axis

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