Qubits: Physical platforms and applications

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Outline

Lesson 1: QC Overview - What is the mathematical language of qubits?

Lesson 2: How do we evaluate physical qubits' performance?

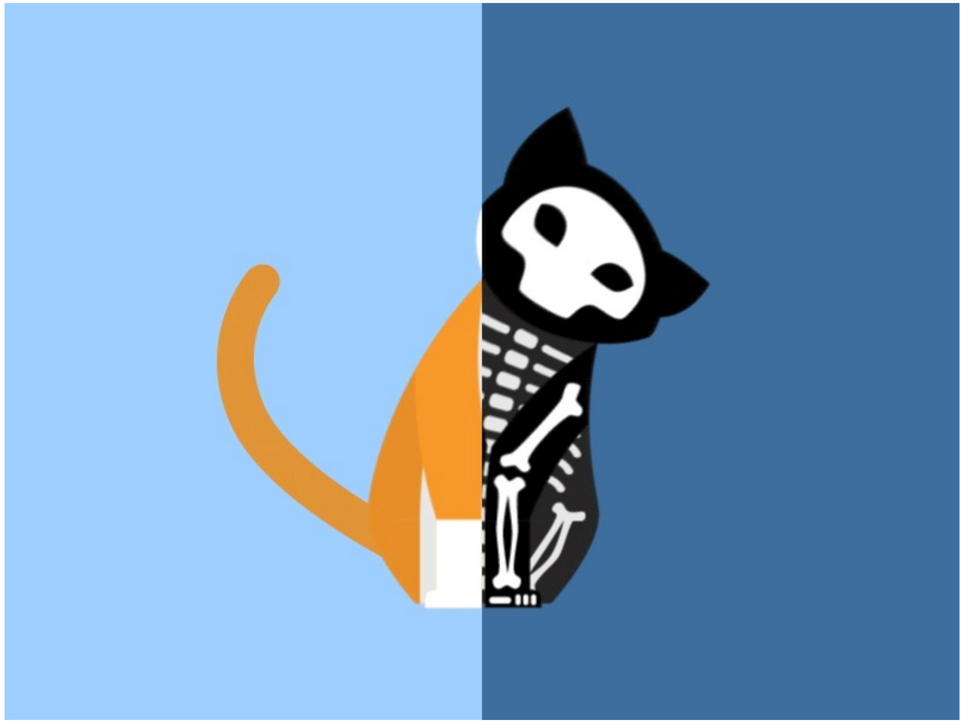
Lesson 3: How do different platforms realize qubits?

Lesson 4: Qubits as a sensor
Overview of the quantum markets and talent development

Outline

We now move from abstract qubits and performance metrics to physical hardware platforms.

Different platforms implement the same operations (initialize, control, couple, measure, reset, scale) using different physics.

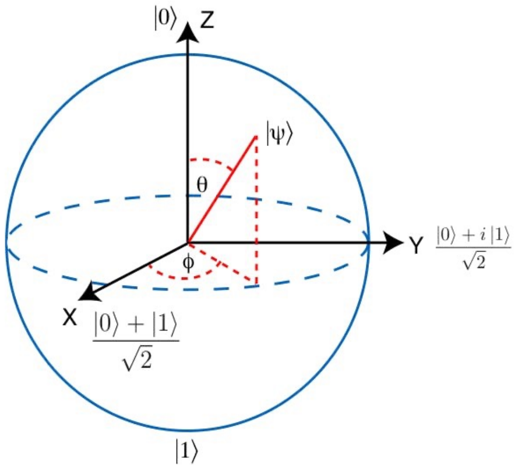


Credits: Kayla Mahoney

1. Qubits
1. Pauli Matrices
2. Multi–qubits
3. Qubits manipulation
4. Benchmarking

Noise

At the single-qubit level, noise changes either the populations, the coherences, or the validity of the two-level approximation.



Qubit-State metrics

Metrics that quantify whether a physical qubit preserves quantum information.

Metric	Meaning	Main experimental question
T_1	Energy relaxation time	How long does the excited-state population survive?
T_2^*	Inhomogeneous dephasing time	How long does a freely evolving superposition keep phase coherence?
$T_{2,}^{echo}$	Echo coherence time	How much slow dephasing noise can be refocused?
p_{leak}	Leakage probability	How often does the system leave the computational subspace?

State quality: populations, coherences, and confinement to the computational subspace

What makes a good qubit platform?

long T_1, T_2
fast and accurate gates
high readout fidelity
low leakage and crosstalk
stable calibration
scalable control architecture

A good qubit is not defined by one number.
It is a balance between coherence, controllability, measurement quality, and scalability.

What makes a good qubit platform?

SPEQC Mock Report

IBM Corporation - ibm_brisbane
Brisbane 1.1.17
(Eagle r3, 127 qubits)

IR Language suppor	OpenQASM 3	**Test Date:**	Jan-2024
Test Sponsor:	IBM Corporation	**Hardware Availability:**	Dec-2023
Tested by:	UPV/EHU	**Software Availability:**	Nov-2023

Hardware

Processor Name:	Eagle r3
Native gates:	ECR, ID, RZ, SX, X
Median T1:	222.12 us
Median T2:	144.5 us
Calibration time required:	3 h

Software

Transpiler:	Qiskit v1.0.1
Compiler:	-
Parallel:	No
System State:	Run level 3 (multi-user)

Results Table

Test suite	Base			Peak		
	Executions	Mean execution time (us)	Median execution time (us)	Executions	Mean execution time (us)	Median execution time (us)
qLinpack	1000	986	881	1275	881	767
QASMBench	250	564	445	174	447	174
SupermarQ suite	557	161	170	161	123	150
QPack	971	559	524	559	524	558
QED-C Benchmark	221	296	884	297	270	881
		SPEQC_rate_base	682			
		SPEQC-rate_peak	736			
Results appear in the order in which they were run.						

Transpiler notes

```
The Qiskit transpiler is available at
https://github.com/Qiskit/qiskit
```

Submit Notes

```
The config file option 'submit' was used.
Device was recalibrated before execution each of the benchmarks. See the configuration file for details.
```

What makes a good qubit platform?

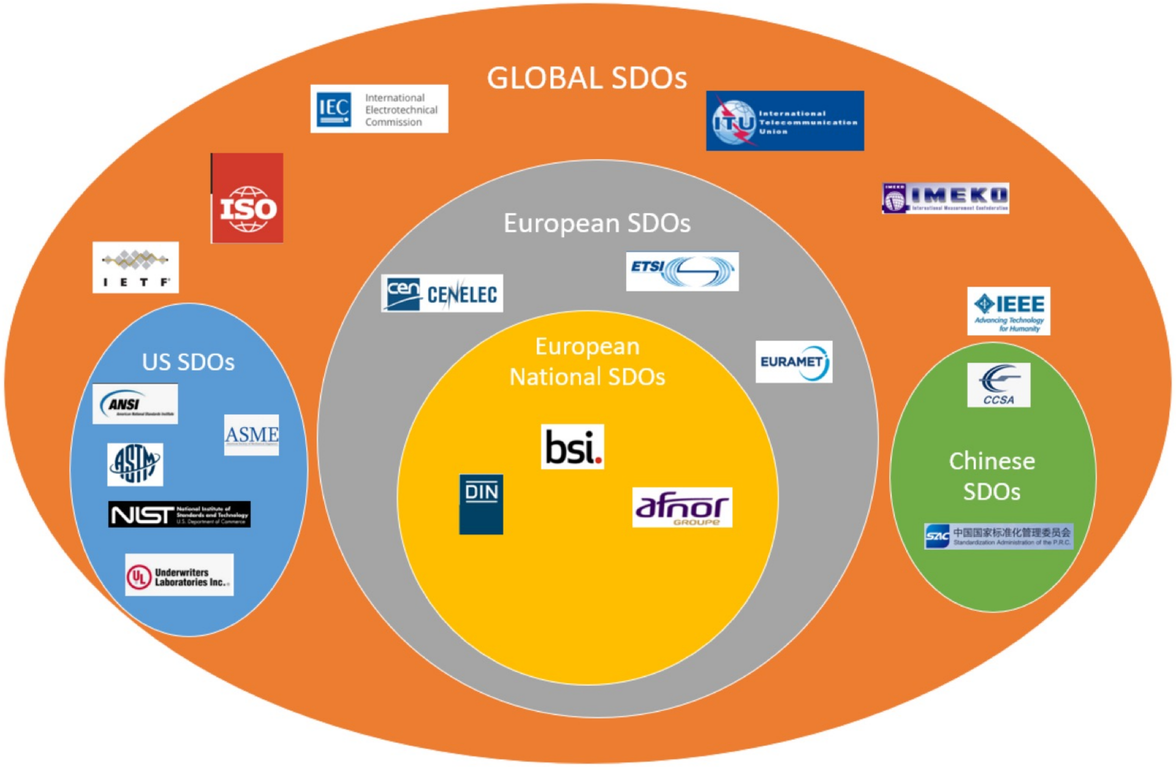


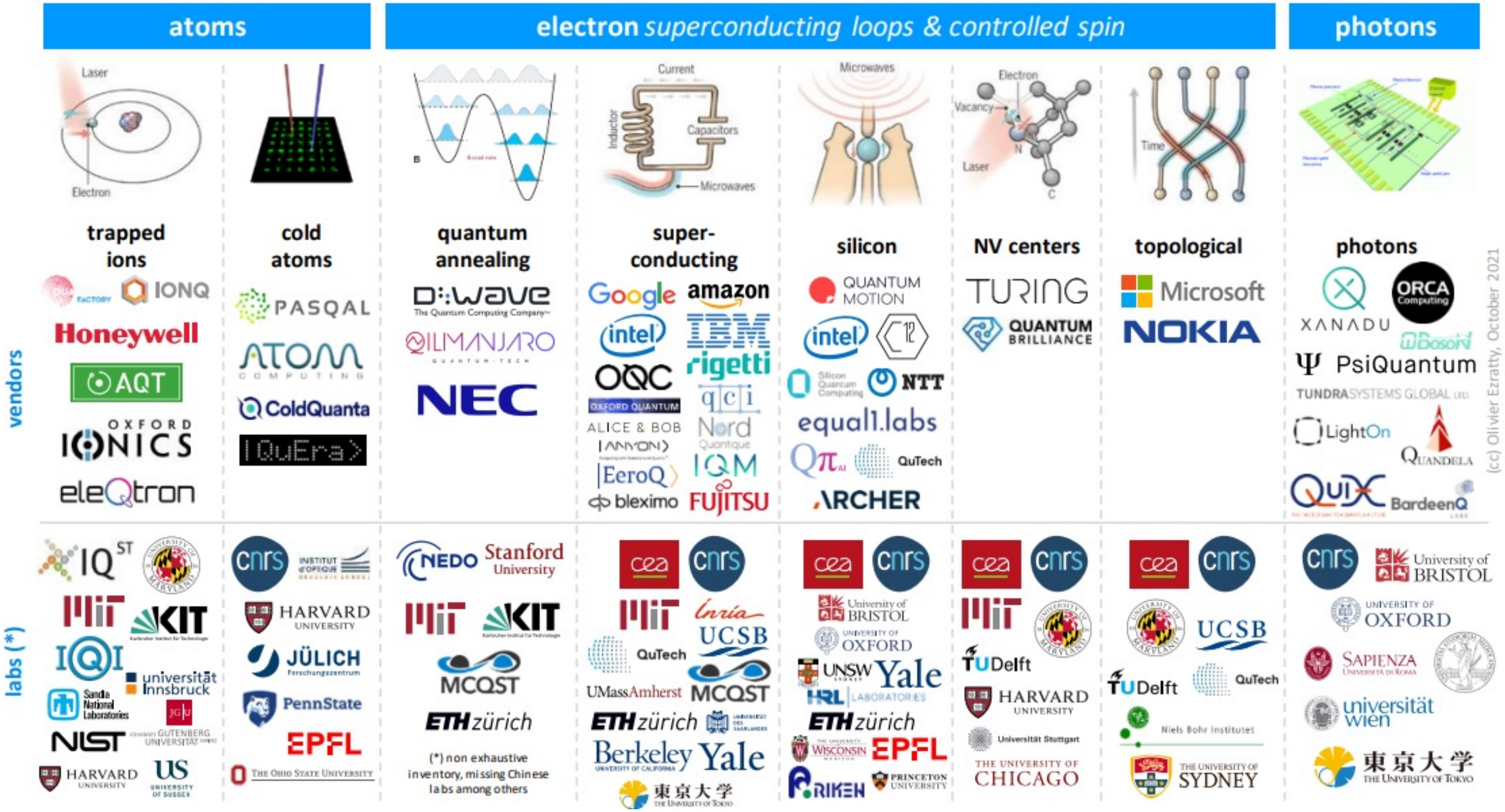
Figure 0-1: The standardisation ecosystem for QTs

Now we generalize the hardware picture:

different physical platforms implement the same abstract operations using very different physics.

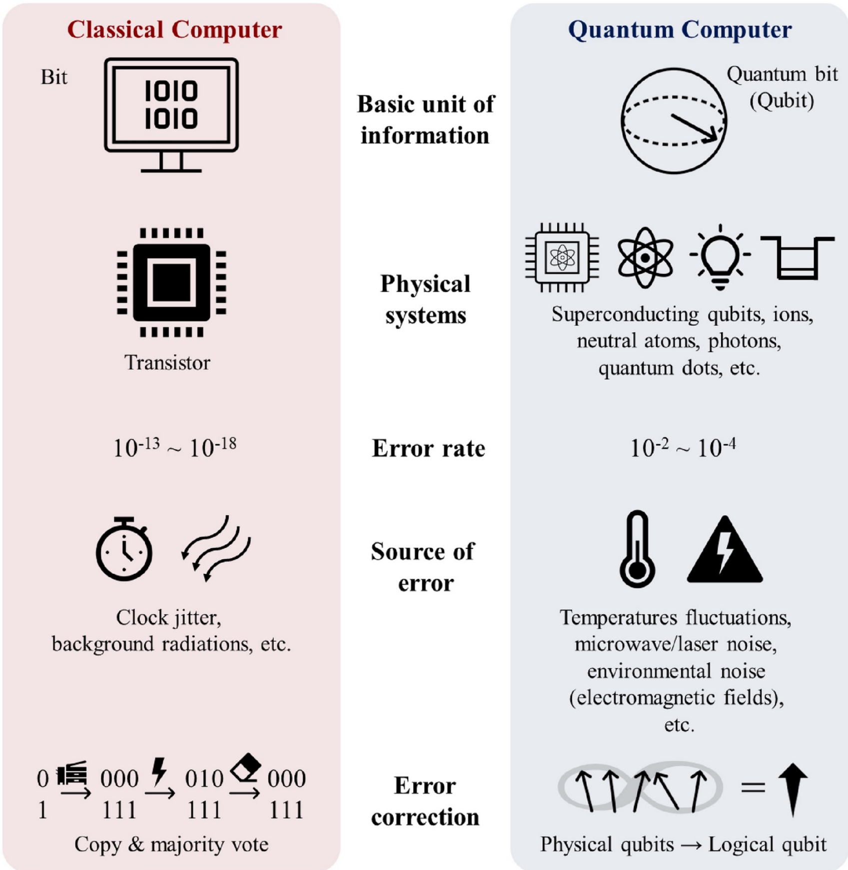
Qubits: physical platforms

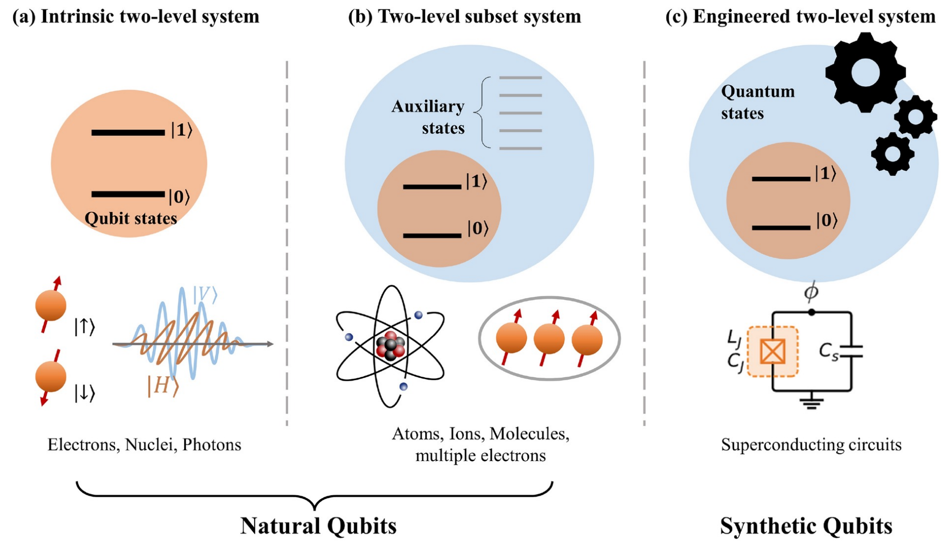
Qubits



Credit: Hanhee Paik, IBM

Bits vs Qubits





Chae, E., et al..
Nano Convergence **11**, 11 (2024)

Superconducting qubits

Superconducting qubits are artificial atoms built from electrical circuits.

Their quantized energy levels are engineered using circuit elements rather than naturally occurring atomic orbitals.

Basic ingredients:

Josephson junctions → capacitors and inductors → microwave resonators → cryogenic control

This makes superconducting circuits highly designable quantum systems.

Frequencies, couplings, nonlinearities, readout channels, and control pulses can be engineered lithographically and electrically.

Superconducting qubits turn quantum mechanics into an electrical-circuit engineering problem.

Superconducting qubits

Nobel Prize in Physics 2025

John Clarke

Prize share: 1/3

Michel H. Devoret

Prize share: 1/3

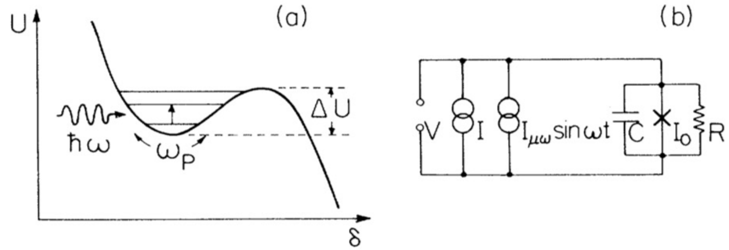
John M. Martinis

Prize share: 1/3

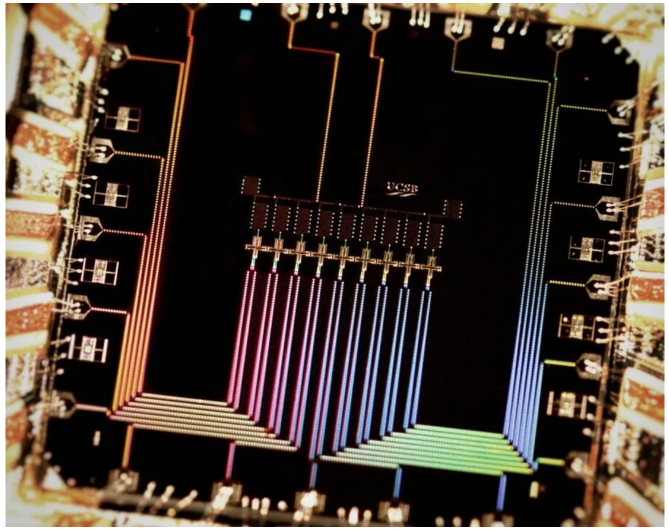
"for the discovery of macroscopic quantum mechanical tunnelling and energy quantization in an electric circuit"

Superconducting qubits

INTERNATIONAL YEAR OF
Quantum Science
and Technology



1.M. H. Devoret *et al.*, “Resonant activation from the zero-voltage state of a current-biased Josephson Junction,” **Phys. Rev. Lett. 53, 1260 (1984)**.
2.J. M. Martinis *et al.*, “Energy-level quantization in the zero-voltage state of a current-biased Josephson Junction,” **Phys. Rev. Lett. 55, 1543 (1985)**.
3.M. H. Devoret *et al.*, “Measurements of macroscopic quantum tunneling out of the zero-voltage state of a current-biased Josephson Junction,” **Phys. Rev. Lett. 55, 1908 (1985)**.



Credits: J. Kelly/University of California, Santa Barbara

Pioneering experiments in the **mid-1980s showed tunneling and other quantum behaviors in superconducting circuits.** This work set the stage for developments in superconducting quantum bits (qubits). The photo shows a nine-qubit array built in 2015 by John Martinis and his colleagues.

Why superconducting qubits?

Superconducting qubits are electrical circuits operated in the quantum regime.

Unlike natural atoms, their parameters are not fixed by nature.

They can be:

fabricated on chip
engineered by circuit design
tuned during the experiment

For this reason, superconducting qubits are often called: **artificial atoms**

Their parameters are engineered by circuit design rather than fixed by nature.

Superconducting circuits provide a highly engineerable platform for building and controlling quantum two-level systems.

Why superconducting qubits?

Superconducting qubits satisfy the basic requirements for gate-based quantum computation (DiVincenzo criteria):

fabrication of multiple qubits
initialization
single- and two-qubit gates
readout
coherence long enough for many gates

A major advantage is speed: $\mathrm{t_{Gate}} \sim 10 - 100\mathrm{ns}$

while coherence times can reach: $T_1, T_2 \sim 10 - 100\mu s$
or longer in selected devices.

Superconducting qubits combine fast gates, chip-based fabrication, microwave control, and increasingly long coherence times.

Why superconducting qubits?

A qubit superposition is fragile.
Resistive losses destroy coherence.

Superconducting materials are used because, below their critical temperature,

$$T < T_c$$

the circuit has no DC resistance.

This suppresses one major source of dissipation.
But superconductivity alone is not enough.

A superconducting circuit must also contain a **nonlinear element** to behave as a qubit.

superconductivity reduces losses; nonlinearity creates addressable qubit levels.

Superconducting qubits

Superconducting circuits are one of the leading quantum computing platforms because they combine:

strong qubit–qubit and qubit–resonator coupling, fast single- and two-qubit gates, chip-based fabrication, local addressability, a mature microwave-control toolbox, compatibility with circuit-QED readout and scalable processor architectures

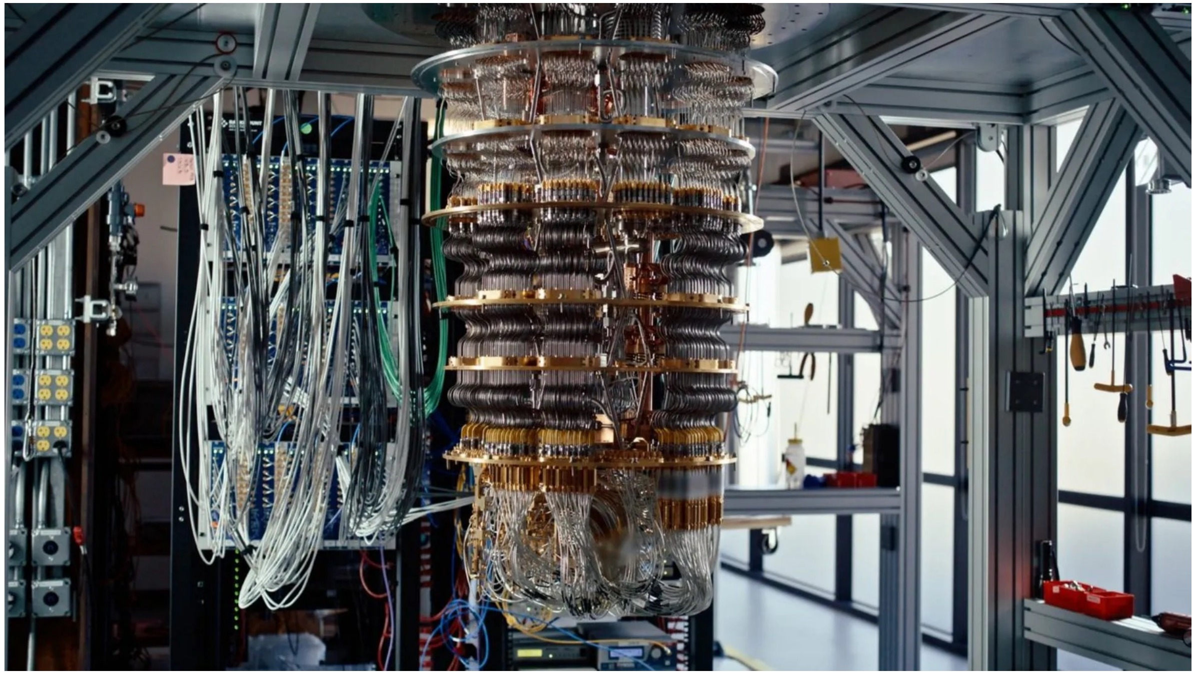
At the same time, the platform remains technically demanding.

Major challenges include:
surface and interface defects, crosstalk, packaging and wiring, cryogenic infrastructure, scaling control electronics

The strength of superconducting circuits is engineering flexibility.

The challenge is preserving quantum coherence while scaling a complex microwave-controlled hardware stack

Superconducting qubits



Superconducting qubits

Superconducting qubits are engineered quantum systems: fast and highly controllable, but experimentally demanding.

Advantages

Fast gates

Lithographic fabrication

Strong microwave coupling

Flexible circuit design

Compatibility with chip engineering

Large industrial ecosystem

Challenges

Millikelvin operation in dilution refrigerators

Wiring density and cryogenic heat load

Dielectric loss and surface/interface defects

Frequency crowding and crosstalk

Leakage outside the computational subspace

Calibration overhead and drift

From LC oscillator to quantum oscillator

A classical LC circuit is an electrical oscillator.

Its resonance frequency is:

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

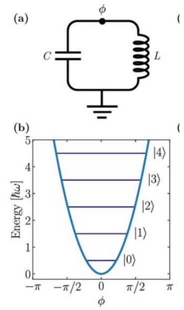
After quantization, the LC circuit becomes a harmonic oscillator.
Its energy levels are:

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

This looks promising: the circuit has quantized energy levels.
<u>However, a harmonic oscillator is not yet a qubit.</u>

The problem is that all neighboring transitions have the same frequency.

Classical



Quantum

Harmonic oscillators are not qubits

For a harmonic oscillator, the energy levels are equally spaced.
Therefore:

$$\omega_{01} = \omega_{12} = \omega_{23} = \cdots$$

This is not suitable for a qubit because the neighboring transitions have the same frequency.

Therefore, a drive resonant with $|0\rangle \leftrightarrow |1\rangle$

can also excite $|1\rangle \leftrightarrow |2\rangle$

The system cannot be cleanly restricted to the computational subspace $\{|0\rangle, |1\rangle\}$

Anharmonicity

For a harmonic oscillator, all neighboring transitions have the same frequency:

$$\omega_{01} = \omega_{12} = \omega_{23} = \cdots$$

This is not suitable for a qubit.

A pulse resonant with $|0\rangle \leftrightarrow |1\rangle$ would also drive higher transitions.

For a qubit, the transition frequencies must be different: $\boldsymbol{\omega_{01} \neq \omega_{12}}$

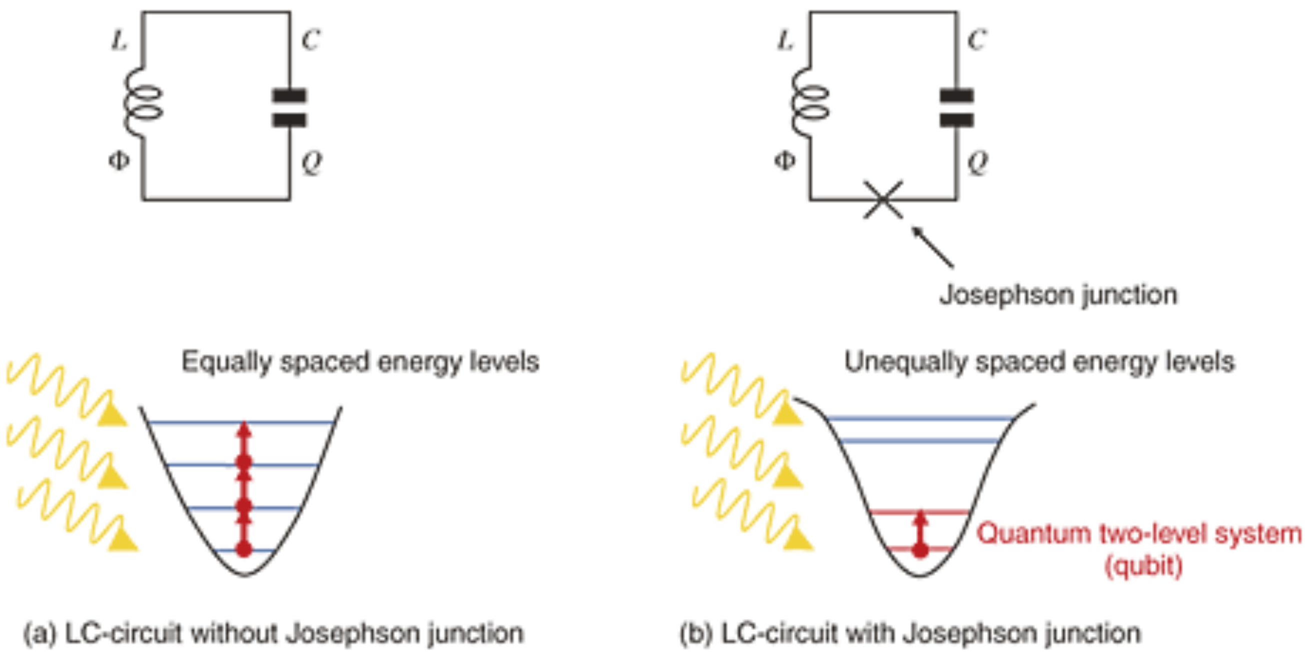
The *anharmonicity* is defined as: $\alpha = \omega_{12} - \omega_{01}$

Anharmonicity allows selective control of the $|0\rangle \leftrightarrow |1\rangle$ transition without strongly populating $|2\rangle$.

The Josephson junction provides this nonlinearity without introducing strong dissipation.

Josephson junction

Quantization is not enough; anharmonicity is required.



Credits: Kouichi Semba NTT Japan

Josephson junction

A Josephson junction consists of two superconductors separated by a thin insulating barrier.
It supports a supercurrent without a voltage drop.

The current-phase (I - ϕ) relation is:

$$I = I_c \sin\phi$$

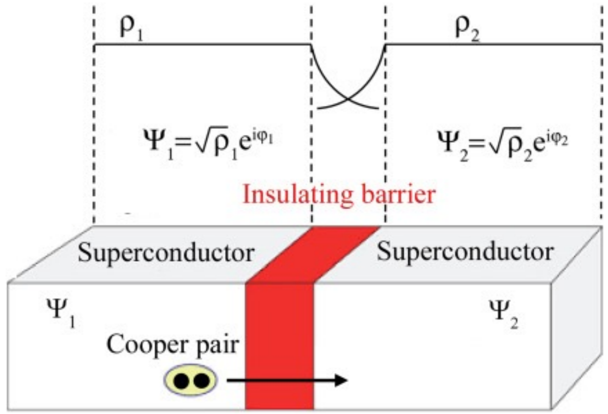
ϕ is the superconducting phase difference across the junction.

The voltage-phase relation is:

$$V = \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

with: $\Phi_0 = \frac{h}{2e}$

The phase difference ϕ becomes a dynamical circuit variable.



Why are Josephson junctions so special?

The Josephson junction is special because it gives **nonlinearity without ordinary resistance**.

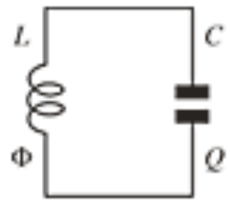
It behaves like a **nonlinear inductance**:

$$L_J(\phi) \sim \frac{\Phi_0}{2\pi I_c \cos\phi}$$

To achieve the nonlinearity I can also use non superconductor elements.

However, unlike a normal resistor or semiconductor nonlinear device, JJ can support a supercurrent through tunneling of Cooper pairs.

That means it gives you both:
nonlinearity
and
low dissipation
This combination is rare and extremely useful.



Josephson junction

On a physics level, the Josephson Junction introduces a current-phase relationship that is nonlinear.

The current through the junction is not proportional to the applied voltage but instead depends on the sine of the phase difference across the junction $I = I_c \sin\phi$

This nonlinearity causes the energy levels of the system to be unequally spaced.

The Josephson energy is: $E_J = \frac{\Phi_0 I_C}{2\pi}$

The key contribution is the nonlinear potential: $-E_J \cos\phi$

A linear inductor gives a quadratic potential.
A Josephson junction gives a cosine potential.

quadratic potential → harmonic oscillator
cosine potential → anharmonic spectrum

Josephson junction

Josephson-junction qubits typically operate in the microwave regime:

$$f_{01} = \frac{\omega_{01}}{2\pi} \sim 1 - 10\text{GHz}$$

This range is useful because it is below the junction plasma frequency ω_p and compatible with microwave electronics.

To suppress thermal excitation, the qubit energy must exceed thermal energy: $\hbar\omega_{01} \gg k_B T$

The operating temperature is typically: $T_{op} \approx 10\ mK$

This is not the superconducting transition temperature.

$$T_{op} \ll T_\mathrm{C}$$

Superconducting qubits operate at mK to remain superconducting and to keep thermal excitations low.

Josephson junction plasma frequency

Josephson-junction qubits typically operate in the microwave regime:

$$f_{01} = \frac{\omega_{01}}{2\pi} \sim 1 - 10\mathrm{GHz}$$

This range is useful because it is **below the junction plasma frequency $\boldsymbol{\omega_{\mathrm{p}}}$**

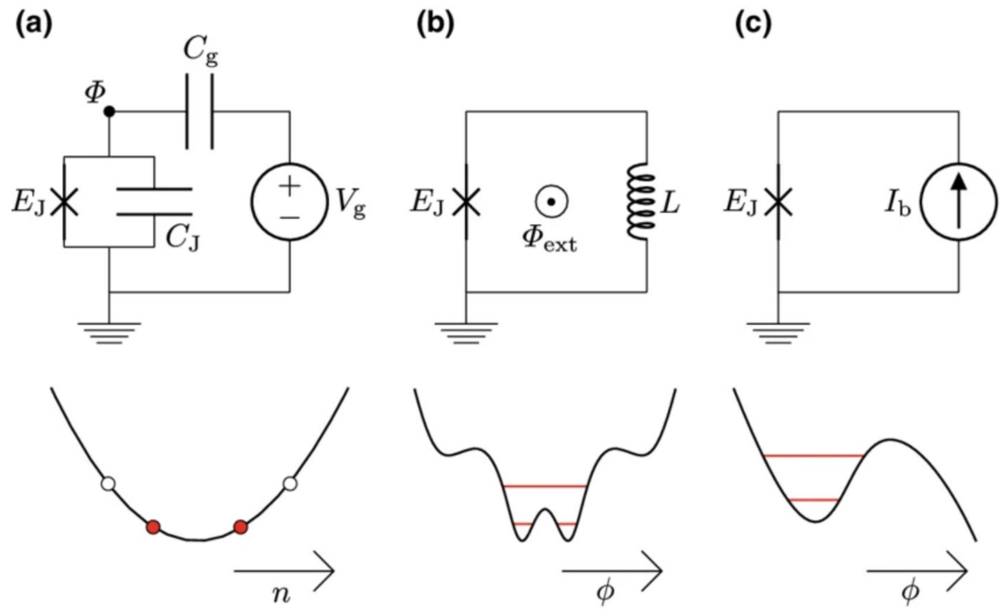
Typical **Josephson junction plasma frequencies** are usually in the **tens of GHz**, but the exact value depends strongly on the junction. Typically, $\omega_p/2\pi \sim 10 - 100\mathrm{GHz}$

If the frequency is too close to the plasma frequency, several problems can appear:

Poor two-level approximation
More leakage
Less selective control
More sensitivity to circuit details

Josephson junction qubit circuits

Historically, three basic Josephson-junction qubit designs are:



4 The three basic Josephson-junction qubit circuits and their potential-energy landscapes, with the two lowest energy levels marked in red. The details of each qubit are given in the following subsections. a Charge qubit. b Flux qubit. c Phase qubit. For simplicity, the capacitance C J is only shown in panel (a), although it is also present in the circuits in panels (b) and (c) (Color figure online)

a) Charge Qubit

b) Flux Qubit

c) Phase Qubit

Kockum, A.F., Nori, F. (2019). Quantum Bits with Josephson Junctions. Springer

Josephson junction qubit circuits

	Main control variable	Physical degree of freedom	Physical idea
Charge qubit	Gate voltage V_g	Cooper-pair number n	Charge on a superconducting island
Flux qubit	Φ_{ext}	Magnetic flux / persistent current	Current circulating clockwise or anticlockwise
Phase qubit	Bias current I_b	Phase difference \Φ	Phase in a tilted Josephson potential

The charge qubit is controlled by an external voltage, the flux qubit by an external magnetic flux, and the phase qubit by a bias current.

Phase and charge as conjugate variables

In Josephson-junction circuits, a natural coordinate is the phase difference: $\boldsymbol{\phi}$

Its conjugate variable is the number of Cooper pairs: n

These variables obey an uncertainty relation:

$$\boldsymbol{\Delta\phi, \Delta n \gtrsim 1}$$

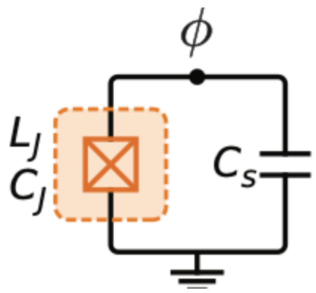
The design of a superconducting qubit depends strongly on the balance between E_J and E_C where E_J is the Josephson energy and E_C is the charging energy.

Josephson qubits are designed by choosing how much the circuit behaves like a phase-like or charge-like quantum system.

if the circuit has a very well-defined charge n, the phase $\boldsymbol{\phi}$ fluctuates strongly.
If the circuit has a very well-defined phase $\boldsymbol{\phi}$ the charge n fluctuates strongly.

Transmons

A **transmon** is a superconducting qubit made from a Josephson junction shunted by a large capacitance.



It can be seen as a weakly anharmonic oscillator.
The Josephson junction provides the nonlinearity needed to make the energy levels unequally spaced:

$$\omega_{01} \neq \omega_{12}$$

The large capacitance reduces the charging energy: $E_C = \frac{e^2}{2C_\Sigma}$
so the transmon operates in the regime:

$$E_J \gg E_C$$

This makes the qubit much less sensitive to charge noise.

Transmons

The charging energy is:

$$E_C = \frac{e^2}{2C_\Sigma}$$

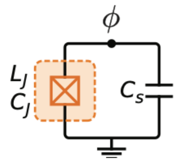
C_Σ total capacitance seen by the Josephson junction

The transmon operates in the regime: $\boldsymbol{E_J \gg E_C}$ E_J Josephson energy and E_C charging energy.

This makes the qubit much less sensitive to charge noise. The price is reduced anharmonicity.

E_C large $\Rightarrow$ charge matters a lot

$E_J \gg E_C$ $\Rightarrow$ phase is more stable; charge fluctuations matter less}

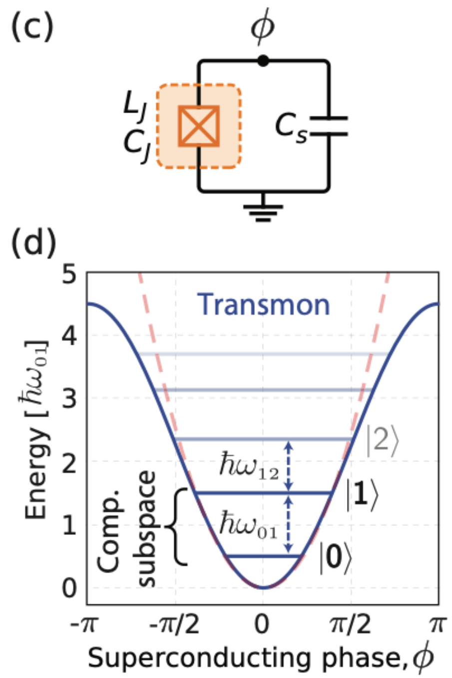


The transmon improves coherence by suppressing charge-noise sensitivity while keeping enough anharmonicity to define a qubit.

Transmons

The goal is to make the qubit much less sensitive to charge noise.
But there is a trade-off: less charge noise ↔ less anharmonicity

The transmon improves coherence by reducing charge-noise sensitivity, while keeping enough anharmonicity to function as a qubit.



Effective two-level system

A transmon is not fundamentally a two-level system.
It is a weakly anharmonic oscillator with many energy levels.

For quantum computing, we choose the two lowest levels as the computational basis: $|0\rangle$, $|1\rangle$

These two states define the qubit subspace.
However, higher levels also exist: $|2\rangle$, $|3\rangle$, ...

This means that the qubit approximation is only valid if the dynamics remain inside the computational subspace.

Strong or poorly shaped control pulses can drive population into higher levels.

This is leakage.

A transmon behaves as a qubit only when control pulses selectively address $|\mathbf{0}\rangle$ and $|\mathbf{1}\rangle$ without populating higher levels.

Anharmonicity

Transmons can be seen as a weakly anharmonic oscillator

The anharmonicity is defined as: $\alpha = \omega_{12} - \omega_{01}$

In a transmon, the anharmonicity is finite but relatively small.

This is why pulse shaping and calibration are essential.

Anharmonicity allows selective control of the $|0\rangle \leftrightarrow |1\rangle$ transition without strongly populating $|2\rangle$.

Transmon compromise

In the transmon regime, the approximate qubit transition frequency is:

$$\hbar\omega_{01} \approx \sqrt{8E_J E_C} - E_C$$

The anharmonicity is approximately:

$$\alpha = \omega_{12} - \omega_{01} \approx -\frac{E_C}{\hbar}$$

Increasing the ratio E_J/E_C reduces sensitivity to charge noise.
However, it also reduces anharmonicity.

This means that the transmon becomes more coherent, but less strongly nonlinear.

The transmon is not optimized for maximum anharmonicity.

It is optimized for reduced charge-noise sensitivity while keeping enough anharmonicity for qubit control.

Transmon compromise

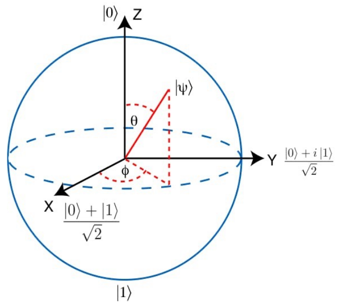
Design Choice	Consequence	Physical meaning
Large E_J/E_C	Better protection from charge noise	The qubit frequency becomes less sensitive to offset-charge fluctuations.
Small E_C	Smaller anharmonicity	The transition frequencies become closer together.
Smaller anharmonicity	Higher leakage risk	Pulses addressing $\|0\rangle \leftrightarrow \|1\rangle$may also populate $\|2\rangle$.
Larger anharmonicity	Easier spectral selectivity	The qubit transition is better separated from higher transitions.
Very strong driving	Faster gates, but more leakage and spectral spillover	Short pulses have broader spectral content and can drive unwanted transitions.

The transmon deliberately sacrifices some anharmonicity to gain strong protection from charge noise.

Microwave pulses as a gate

In many quantum computing platforms, qubit transitions lie in the microwave-frequency range.
This is especially important for superconducting qubits.

Microwaves allow us to drive transitions between the qubit states:



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

A microwave pulse is not just a signal.
It is the physical implementation of a quantum gate.

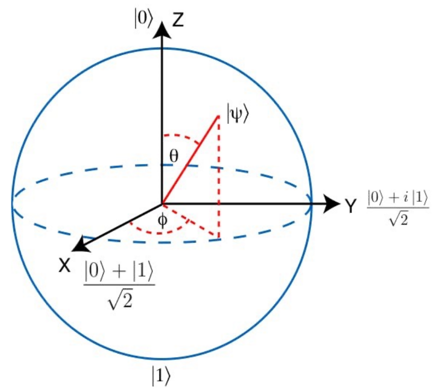
By controlling the frequency, amplitude, phase, duration, and shape of the pulse, we control the motion of the qubit on the Bloch sphere.

In superconducting circuits, quantum gates are engineered microwave rotations.

Microwave control

Single-qubit gates are implemented by microwave pulses.

In the rotating frame, **a resonant drive produces rotations such as**:



$$R_x(\theta) = e^{-i\frac{\theta}{2}X}, \qquad R_y(\theta) = e^{-i\frac{\theta}{2}Y}$$

The rotation angle is determined by the pulse area:

$$\theta \propto \int \Omega(t), dt$$

<u>The microwave phase determines the rotation axis in the equatorial plane of the Bloch sphere.</u>

Experimentally, a gate is calibrated through four pulse parameters:

amplitude **duration** **phase** **envelope**

In superconducting qubits, gates are microwave-engineered rotations.

Two-qubits gates

Two-qubit gates require an interaction between qubits.

At the effective Hamiltonian level, useful interaction terms include:

$$JX_1X_2, \qquad JY_1Y_2, \qquad JZ_1Z_2$$

These terms describe different ways in which the state of one qubit affects the dynamics of another.

Coupling can be implemented in several ways:
fixed coupling
tunable coupling
direct coupling
resonator-mediated coupling
coupler-mediated coupling

A two-qubit gate is not only a logical operation. It is a controlled physical interaction engineered between two quantum systems.

Superconducting circuits

In superconducting circuits, coupling may be fixed, tunable, direct, resonator-mediated, or coupler-mediated.

Common gates include:

CZ, iSWAP, cross-resonance CNOT-like gates

Two-qubit gates make the hardware architecture visible: connectivity, frequency allocation, couplers, crosstalk, and leakage all matter.

2 Qubits Gates

Gate	Physical idea	Main action
CZ	Controlled phase interaction	Adds a phase to $\|11\rangle$
iSWAP	Exchange interaction	Swaps $\|01\rangle$and $\|10\rangle$ with phase i
Cross-resonance	Microwave-driven conditional rotation	Produces an effective ZX interaction, calibrated into a CNOT-like gate

Gates

CZ gate

A controlled-phase gate.

It leaves the computational basis states unchanged, except that $|11\rangle$ acquires a phase.

Main effect: $|11\rangle \rightarrow -|11\rangle$

It is widely used because it naturally arises from conditional frequency shifts or avoided crossings.

iSWAP gate

An exchange-type gate.

It swaps the single-excitation states with an additional phase: $|01\rangle \rightarrow i|10\rangle$ $|10\rangle \rightarrow i|01\rangle$

It is associated with XY-type coupling between qubits.

Cross-resonance CNOT-like gate

A microwave-driven entangling gate.

One qubit is driven at the transition frequency of another qubit. This produces an effective conditional rotation, often described as a ZX-type interaction. With calibration and additional single-qubit rotations, it can implement a CNOT-like operation.

Connectivity as a metrics

Superconducting processors usually have local connectivity.

Each qubit can interact directly only with selected neighboring qubits.

When a circuit requires an interaction between distant qubits, the compiler must introduce routing operations.

These are often implemented using SWAP gates.

limited connectivity → routing overhead → extra gates → extra errors

Common design approaches include: nearest-neighbor lattices, heavy-hex-like layouts, square or rectangular grids, tunable coupler networks, modular chiplets or multi-chip architectures…

Connectivity is a hardware metric.

A processor with many qubits but poor routing efficiency may perform worse than a smaller processor with better effective circuit execution.

Dispersive qubit readout

Modern superconducting qubits are often read out dispersively.

Superconducting qubits are often measured through a microwave resonator.

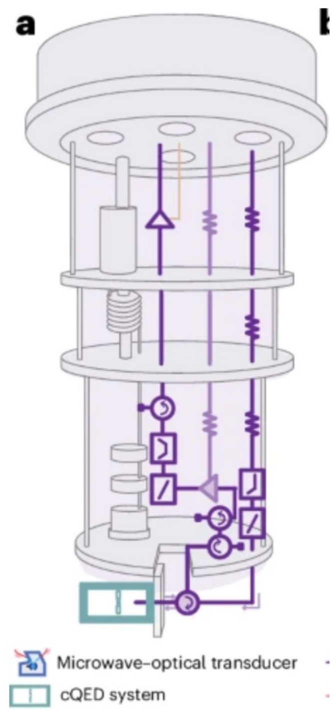
The qubit is coupled to a resonator with frequency: ω_r

When the qubit and resonator are far detuned, $|\omega_r - \omega_{01}| \gg g$
the system is in the dispersive regime.

No excitation is directly exchanged.

Instead, **the qubit state shifts the resonator frequency.**

By probing the resonator, the qubit state is inferred indirectly.



Superconducting-qubit readout converts qubit-state information into a microwave-resonator response.

Microwave readout chain

A simplified superconducting-qubit readout chain is:

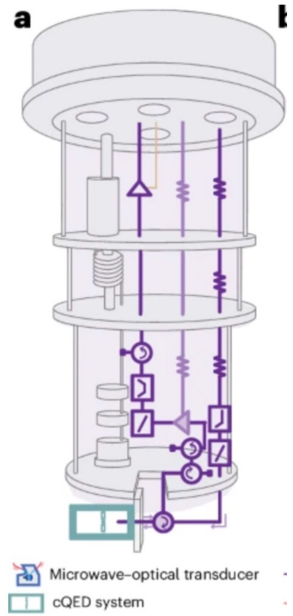
qubit → readout resonator → feedline → parametric amplifier → HEMT amplifier → digitizer → classifier

Each stage affects the final readout fidelity.

Important factors include: resonator design, measurement time, amplifier noise, signal-to-noise ratio, crosstalk…

Readout fidelity is not only a property of the qubit.

It depends on the full microwave measurement chain.



Why mK?

Thermal excitation must be strongly suppressed.

The excitation probability scales approximately as:

$$P_{exc} \sim e^{-\frac{\hbar\omega_q}{k_B T}}$$

For a typical 5 GHz superconducting qubit:

$$\boxed{\frac{\hbar\omega_q}{k_B} \approx 240, mK}$$

This means that the qubit transition energy is comparable to the thermal energy at a few hundred mK

To keep the qubit near its ground state, the device must operate at much lower temperature.
Superconducting quantum processors therefore operate in dilution refrigerators, typically around 10–20 mK.

<u>Millikelvin temperatures are required so that thermal energy is much smaller than the qubit transition energy.</u>

Cryogenic and control stack

A superconducting quantum processor is not only a qubit chip.

It requires a full hardware and software stack.

Main components:
dilution refrigerator operating at millikelvin temperatures
microwave input and output lines
attenuation, filtering, isolation, and amplification
room-temperature waveform generation and digitization
calibration software and pulse compilation
packaging, shielding, multiplexing, and thermal engineering
Common mistake to avoid:

The cryogenic wiring, control electronics, packaging, calibration, and software stack are part of the machine.

Calibration drift and stability

Superconducting devices require frequent calibration because parameters drift over time.

Examples of drift:
qubit frequency drift
readout resonator frequency drift
pulse amplitude drift
two-qubit gate calibration drift
changes in crosstalk and residual couplings
amplifier and measurement-chain drift

High performance is not static.

A reported high fidelity is not a permanent property of a device.

It is the result of a maintained calibration ecosystem.

Superconducting qubits

Dimension	Strength	Challenge
Gate speed	Very fast microwave control	Leakage, pulse distortion, crosstalk
Fabrication	Chip-based lithography	Materials defects, variability, yield
Readout	Fast dispersive readout	Amplifier noise, measurement crosstalk
Scaling	Compatible with integrated engineering	Wiring, cryogenic heat load, packaging
Ecosystem	Strong industrial and academic ecosystem	Complex calibration stack
Error correction	Leading demonstrations in surface-code experiments	Physical-to-logical overhead still large

Superconducting qubits offer fast, engineerable control, but scaling requires solving system-level challenges in materials, packaging, wiring, calibration, and error correction.

Superconducting qubits

Commercial product claims and roadmaps changes quickly

Superconducting qubits processors: examples 2026

Provider	Example system / chip	Qubit count
IBM Quantum	Heron; Nighthawk roadmap	Heron: 133 / 156 qubits; Nighthawk: 120-qubit modules
Google Quantum AI	Willow	105 qubits
Rigetti	Novera; Cepheus-1-108Q	Novera: 9 qubits; Cepheus-1-108Q: 108 qubits
IQM	Spark; Radiance	Spark: 5 qubits; Radiance: 54 / 150 qubits
OQC	Toshiko	32 qubits
Alice & Bob	Boson / cat-qubit systems	Boson 4: 4 cat qubits

The market now includes cloud-accessible and on-premises superconducting systems, but these remain NISQ or early error-correction-era devices, not general-purpose fault-tolerant quantum computers.

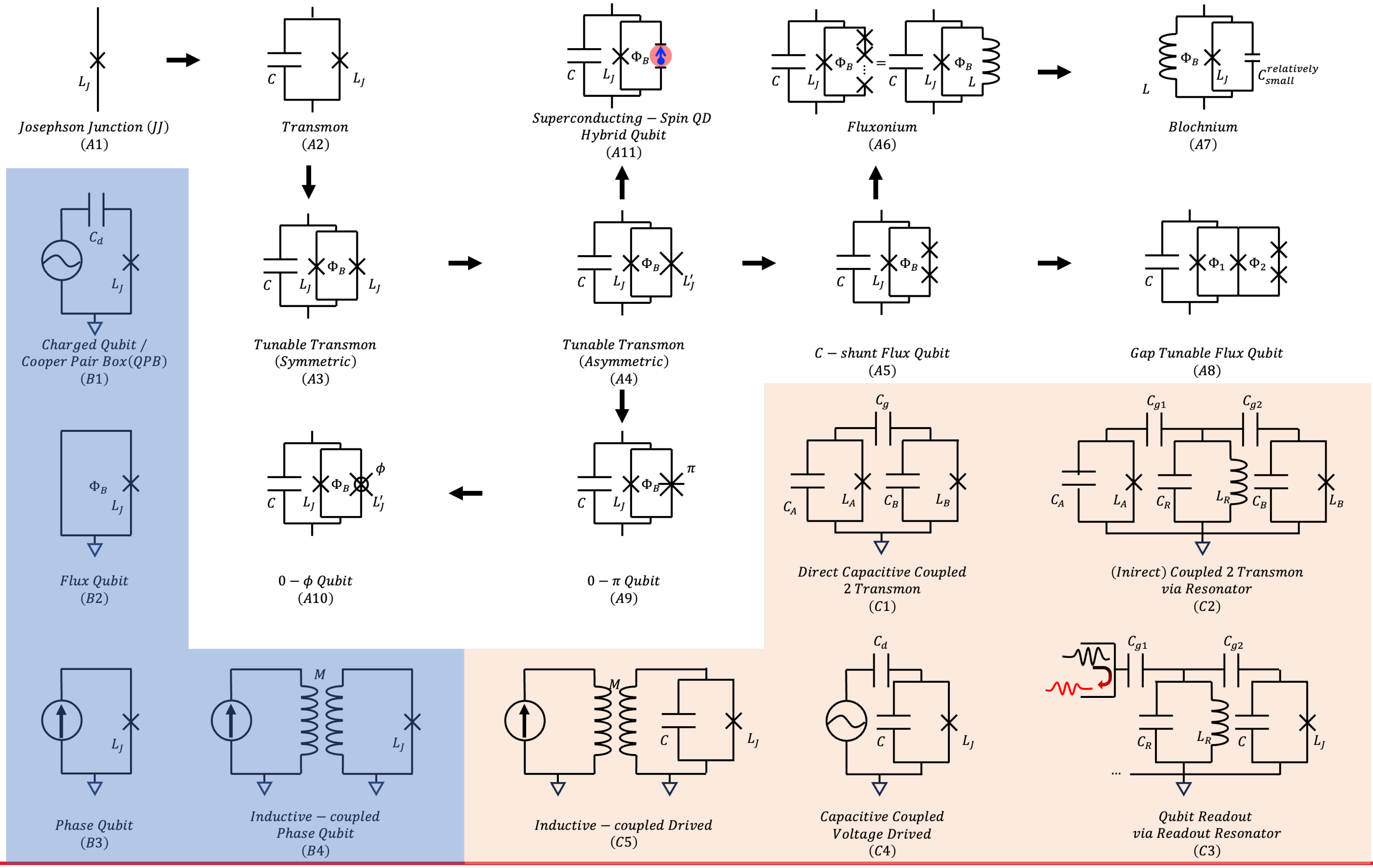
Qubits

The frontier is no longer only “How many physical qubits?”

It is:

How efficiently can physical hardware be converted into logical computation?

Superconducting qubits



Superconducting qubits

Design	**Main idea**
Transmon	reduce charge-noise sensitivity
Xmon	improve connectivity
Gmon	tunable coupling
Fluxonium	improve protection and anharmonicity
3-junction flux qubit	reduce flux noise
C-shunt flux qubit	reduce charge-noise sensitivity

Superconducting qubits: Frontiers

The field is moving from “more physical qubits” to better logical performance per physical resource.

Key directions: Better coherence T_1, T_2. cleaner interfaces, quasiparticle mitigation…

Better two-qubit gates $F_{2\%q} \rightarrow 99.9\%$ and beyond, lower leakage, lower crosstalk, better calibration stability

Scalable architectures wiring, packaging, heat load, multiplexing, yield, connectivity, modularity

Quantum error correction

cat qubits, bosonic encodings, fluxonium, tunable couplers, modular chiplets, biased-noise qubits

The frontier is no longer only the number of physical qubits.
It is how much logical performance can be extracted from each physical resource.

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From superconducting platform to others

From superconducting platform to others

Superconducting circuits are one solution to the general problem of building a controlled quantum many-body system.

Other platforms use:
ions
neutral atoms
spins
photons…

A quantum processor is not defined by the material system alone.

It is defined by whether the physical system can implement the full operational stack:

initialize → control → couple → measure → reset → scale

Different platforms use different physics, but they must all solve the same operational problem.

From abstract to physical circuits

An abstract quantum circuit is written as a sequence of gates:

$$|0\rangle^{\otimes n} \to U_1 \to U_2 \to \cdots \to measurement$$

A physical processor must realize this sequence using real laboratory operations:

Hamiltonians, pulses, fields, resonators, lasers, voltages, detectors, optical modes

The same gate symbol can correspond to very different physical operations.

For example, an X_π gate may be implemented as: microwave pulse in a transmon, laser or microwave pulse in an ion, ESR or EDSR pulse in a spin qubit, wave-plate or interferometer operation in photonics

The circuit model is platform-independent.

Its physical implementation is deeply platform-dependent.

Spin qubits

We used superconducting circuits to show how an abstract qubit becomes a controlled laboratory system.

A superconducting qubit uses collective circuit variables and microwave engineering.

A semiconductor spin qubit uses a microscopic spin degree of freedom confined in a nanoscale semiconductor device.

The physical implementation is different, but the operational problem is the same:

initialize → control → couple → measure → reset → scale

<u>Different platforms use different physical degrees of freedom, but they must all implement the same quantum-processing stack.</u>

NCCR SPIN: Loss - DiVincenzo Qubit

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

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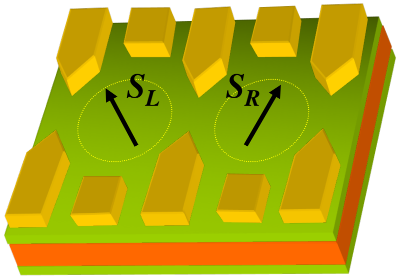
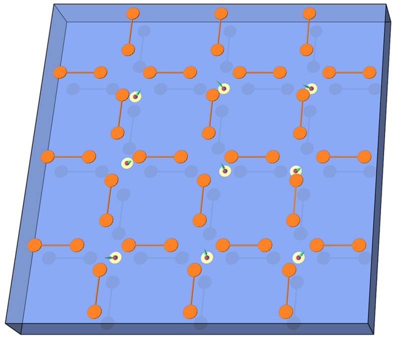




Daniel Loss and David P. DiVincenzo have been selected as a Clarivate Citation Laureate 2025 for proposing the Loss-DiVincenzo model for quantum computing, using electron spins in quantum dots as qubits

Advantages

- **CMOS compatibility**
- Scalable architectures
- Tight cryo-CMOS integration
- Microelectronics know-how
- Wafer-scale integration
- Low energy consumption
- Fast gate operations
- Modular design potential

Challenges

- Cryogenic operation
- **Uniform qubit performance**
- High coherence & fidelity
- Interface disorder and material defects
- Sensitivity to charge noise
- Classical–quantum integration

Technology Opportunities

- Industrial supply chains
- CMOS infrastructure
- National innovation priorities
- Public–private partnerships
- Hybrid quantum–classical systems
- **Industry engagement (Intel, TSMC, etc.)**

Global Collaboration Opportunities

- Cross-border foundry access
- Shared R&D infrastructure
- **Standardization efforts**
- Co-funded international projects
- Scientific mobility & exchange
- Joint education & training programs
- Academic–industry–government consortia

Qubits

Spin qubits aim to combine three properties that are rarely available together:

small physical size (10-100 nm)
long intrinsic spin coherence
compatibility with semiconductor fabrication

This makes spin qubits attractive for dense integration.
However, the same small scale also makes the platform highly sensitive *to device details*.

Central scientific challenges include:
device variability, tuning complexity, charge disorder, interfaces, cryogenic control

<u>Spin qubits are promising because they are compact and semiconductor-compatible, but scaling them requires solving device-level variability and control (clean room fabrication)</u>

Semiconductors vs spin qubits

	Superconducting circuits	**Semiconductor spin qubits**
Physical variable	Circuit phase, charge, flux	Electron or hole spin in a quantum dot
Typical control	Microwave pulses on circuit modes	ESR, EDSR, exchange pulses, voltage gates
Qubit size	Mesoscopic circuits	Nanoscale quantum dots
Two-qubit coupling	Capacitive/inductive coupling, resonators, tunable couplers	Exchange, capacitive coupling, resonators, floating gates, shuttling
Main advantage	Fast gates and mature microwave toolbox	Small size, semiconductor compatibility, long spin-coherence potential
Main challenge	Wiring, packaging, materials loss, crosstalk	Fabrication, tuning, disorder, valley/orbit physics, charge noise, readout and coupling

Spin qubits

Spin qubits are compelling because of density and materials integration.

Their challenge is to turn microscopic devices into reproducible, calibrated, many-qubit processors.

Spin qubits

A semiconductor quantum dot confines one or a few charge carriers in all spatial directions. The two-level system is not the orbital state itself, but the spin of the confined electron or hole.

<u>The confinement can be produced by:</u>
electrostatic gates
nanowire geometry
heterostructure design
transistor-like fin architectures

A quantum dot is often called an artificial atom. Like an atom, it has a discrete energy spectrum.

Unlike a natural atom, its charge occupation, confinement potential, tunnel barriers, and coupling to nearby dots can be engineered electrically.

Semiconductor quantum dots

Spin qubits are a broad family of platforms.

The qubit is encoded in the spin state of a confined electron or hole.

The quantum dot is the nanoscale region where one or a few carriers are trapped.
This confinement can be realized in different material systems and device architectures:

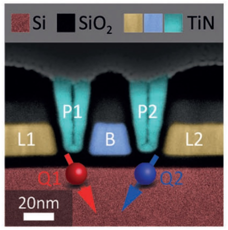
Si MOS quantum dots
Si/SiGe quantum dots
Si/Ge nanostructures
FinFET-like silicon devices
planar Ge hole quantum dots

They are a family of semiconductor implementations in which a confined carrier spin becomes the qubit.

NCCR SPIN: Qubits portfolio

Silicon

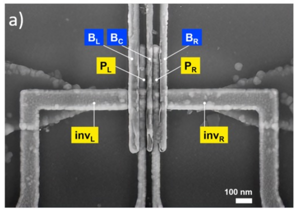
MOS FinFET



1Q gates, up to 150 MHz
T_2^* 500 ns, 99 % fidelity
1.5 K - 5 K operation
2Q gate 24 ns
anisotropic ex., phase drive

large SOI (1D/DR-SOI)

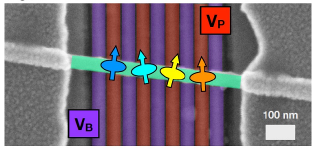
FD-SOI



integrated Co gates
optimized nanomagnets
Coulomb blockade observed
qubit devices ready
multi-qubit devices

Germanium

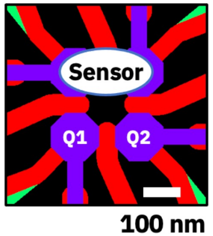
nanowires



1Q gates, up to 440 MHz
T_2^* 10 ns, echo 250 ns
1.5 K operation
2Q gate 18 ns
sweet spot: speed & coherence

large SOI (1D/DR-SOI)

planar Ge



1Q gates 50 MHz, 99% fidelity 1 K
T_2^* up to 17 μs, echo to 1.3 ms
1 K operation
sweet spot operation
heavy-hole spin, anisotropic g

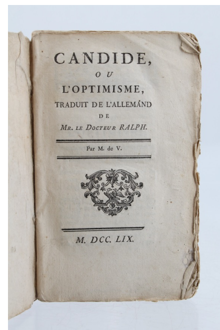
Minimal Hamiltonian

A confined carrier in a semiconductor quantum dot is affected by orbital, spin, material, and disorder terms.

A useful schematic Hamiltonian is:

$$H = \frac{(\mathbf{p}+q\mathbf{A})^2}{2m^*} + V_{conf}(\mathbf{r}) + H_Z + H_{SO} + H_{valley} + H_{hf} + H_{disorder}$$

V_{conf} defines the quantum dot.
H_Z is the Zeeman term.
H_{SO} describes spin-orbit coupling.
H_{valley} is important in silicon.
H_{hf} describes hyperfine coupling to nuclear spins.
$H_{disorder}$ describes interface disorder, charge disorder, and device imperfections.

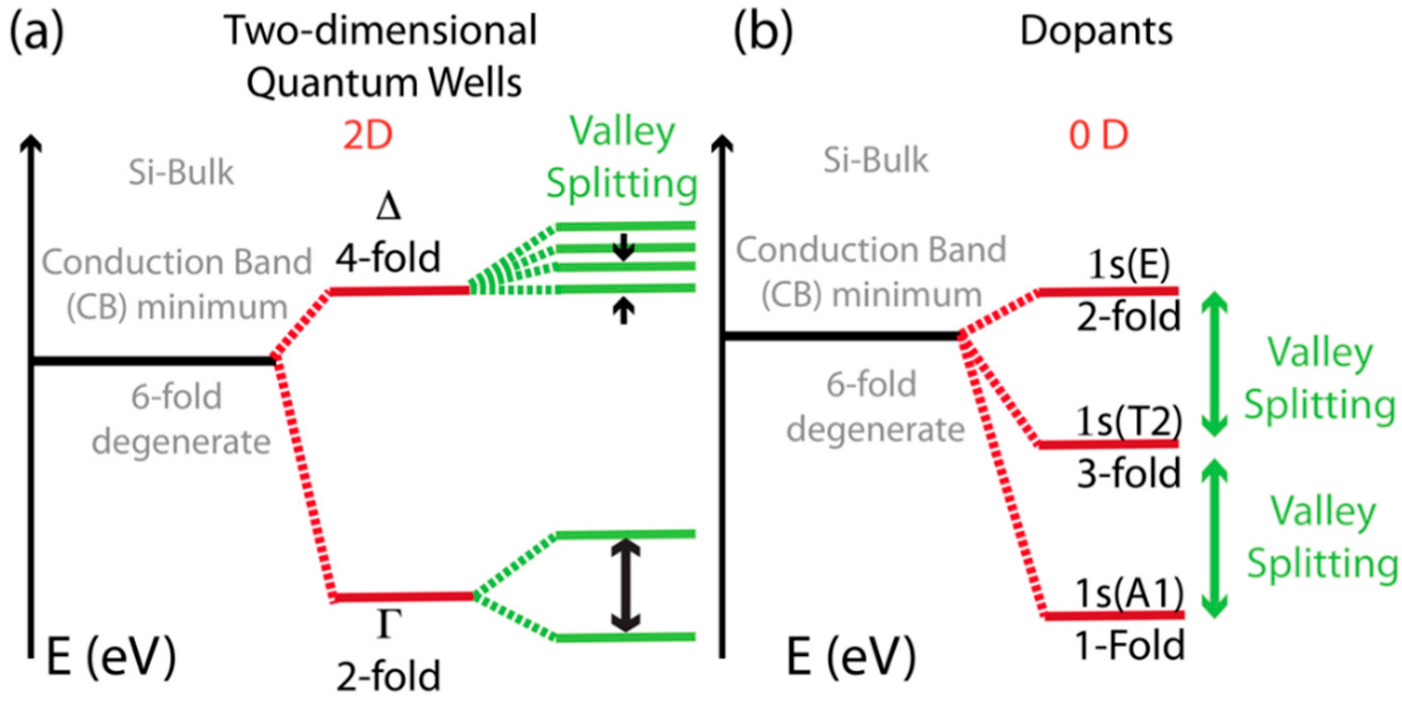


A real spin qubit is not only a spin.
It is a spin embedded in a real semiconductor environment.

Useful ingredients

Ingredient	What it does	Why it is useful
Coulomb blockade	Makes electron number discrete and controllable	Allows single-electron occupation and charge-state identification
Valley splitting	Separates valley ground/excited states	Helps isolate the spin qubit and reduce leakage
Sweet spots	Reduce first-order sensitivity to noise	Improve coherence and gate stability
Spin-orbit coupling	Couples spin to electric fields	Enables fast electrical control, especially for holes
Pauli spin blockade	Converts spin information into charge motion	Enables spin-to-charge readout

Valley splitting



H_{valley}

Silicon has multiple conduction-band minima, called valleys.
Valleys are useful when they are well separated

Valley splitting

Valley splitting is very useful, and often essential, for spin qubits in silicon.

In silicon quantum dots, the electron does not only have spin:

$$|\uparrow\rangle, \quad |\downarrow\rangle$$

It can also occupy different **valley states**, because silicon has multiple conduction-band valleys.

So the physical electron states are more like: $|\text{spin}\rangle \otimes |\text{valley}\rangle$

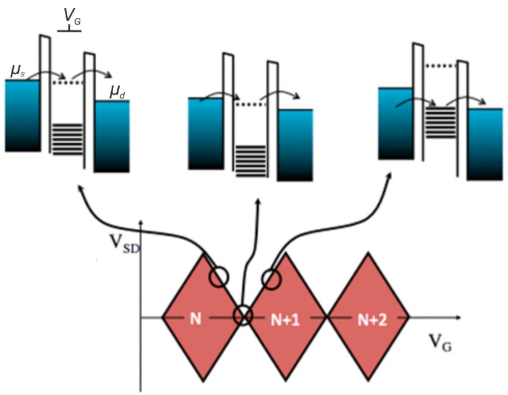
If E_V valley splitting is large (well separated):
the qubit behaves more like a clean spin two-level system.

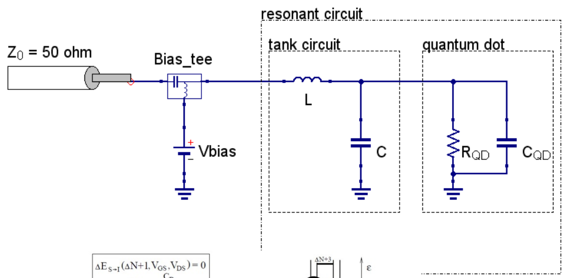
If E_V valley splitting is too small:
valley states can mix with spin states, create leakage, give readout errors, or device variability and make gate operation less reproducible.

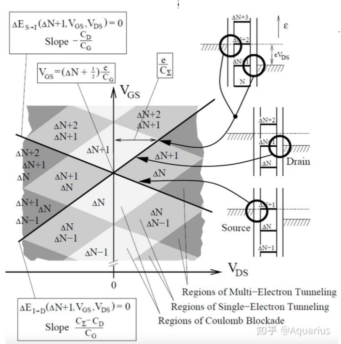
Coulomb blockade

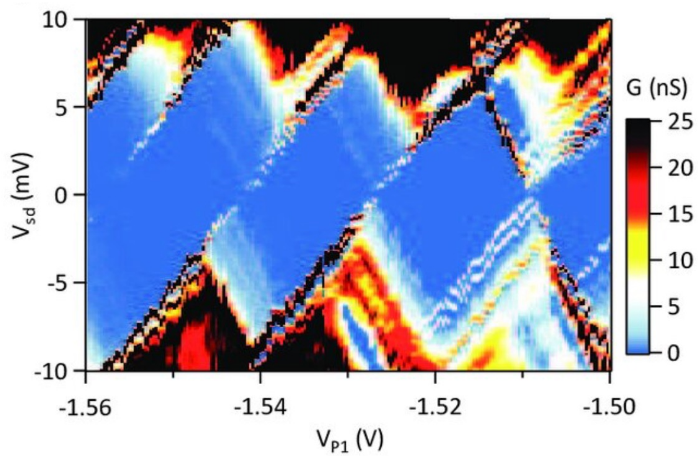
Coulomb blockade is extremely useful for quantum dots and spin qubits.

It is not just an obstacle; it is the mechanism that lets us **control electrons one by one**.

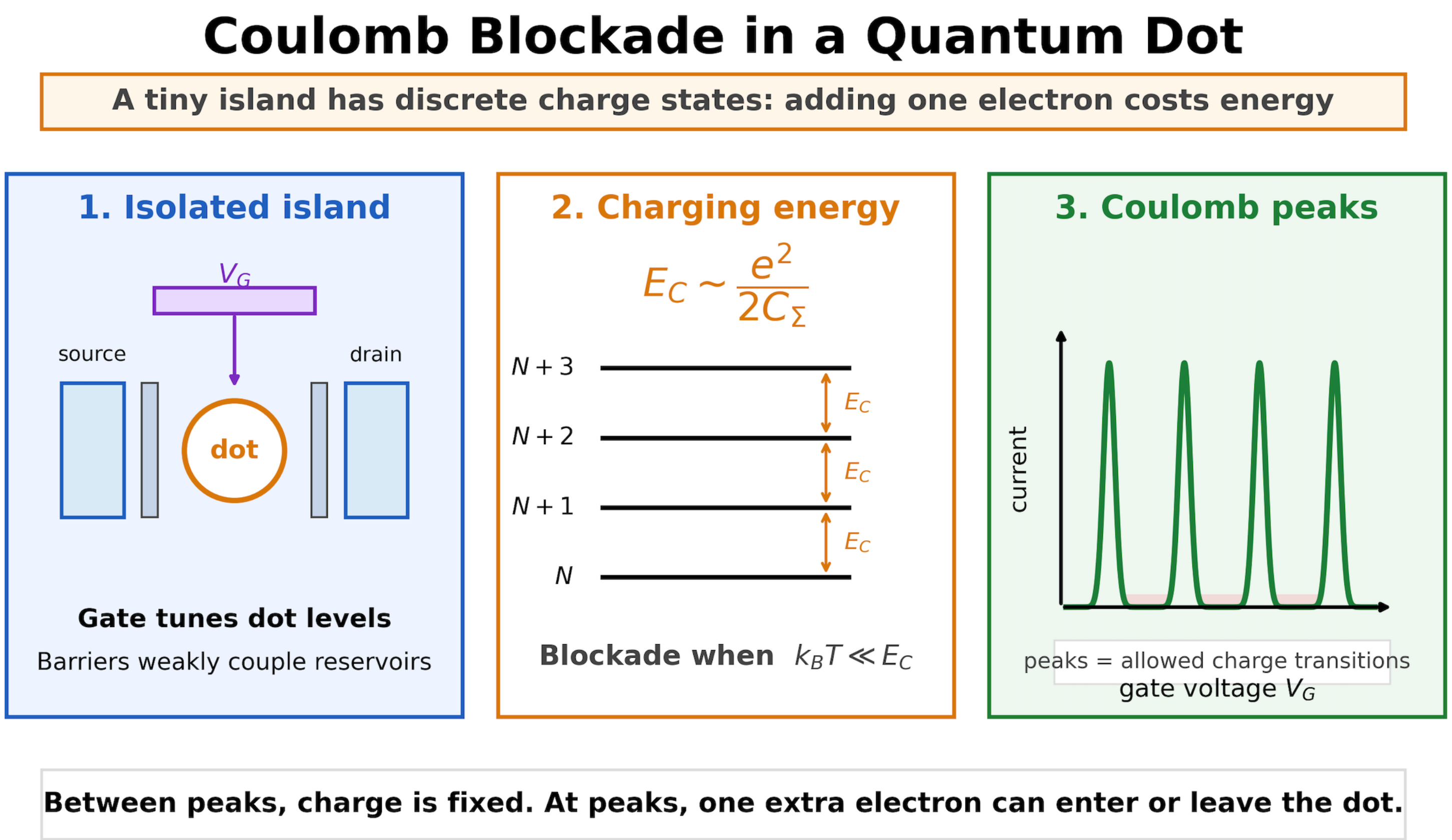








Coulomb blockade



Coulomb blockade

A quantum dot behaves like a tiny electrically isolated island, and because it is so small, adding even one extra electron costs a measurable amount of energy.

Adding one electron costs the charging energy: $E_C \sim \frac{e^2}{2C_\Sigma}$

At low temperature, if

$$k_B T \ll E_C$$

thermal fluctuations cannot randomly add electrons to the dot.

If the tunnel coupling to the reservoirs is weak, electrons cannot freely flow through.

<u>So current is blocked except at special gate voltages where adding one electron becomes energetically allowed</u>.

This is Coulomb blockade. At low temperature and weak reservoir coupling, this produces Coulomb blockade.

Sweet spots

Sweet spots protect the qubit from charge noise while preserving electrical control.

The goal is to operate where: **strong electrical control and reduced first-order sensitivity to charge noise coexist.**

These operating points are called sweet spots.

At a sweet spot, the qubit frequency is locally insensitive to a noisy control parameter:

$$\frac{\partial \omega_q}{\partial \delta} = 0$$

where δ (detuning) can be a noisy control parameter, such as detuning, gate voltage, or magnetic-field orientation.

Examples: $\delta = 0$ (detuning usually means the energy difference between two relevant charge configurations or dot levels) or selected magnetic-field orientations

Sweet spots

Spin-orbit coupling enables fast electrical spin control, but also makes the spin sensitive to electric-field noise.

Sweet spots are operating points where this noise sensitivity is reduced while the qubit can still be driven electrically.

Electric fields are easy and fast to apply on a chip, but a spin typically couples primarily to magnetic fields, not electric fields.

Spin-orbit coupling creates a bridge between them.

Spin-orbit coupling enables fast electrical control of the spin.
But it also converts electric-field noise into fluctuations of the qubit frequency.

electric noise → fluctuating qubit frequency → dephasing

Pauli spin blockade

Pauli spin blockade occurs in a double quantum dot.

A charge transition is allowed for a singlet configuration but blocked for a triplet configuration.

Typical transition:

$\mathrm{S}(1,1) \rightarrow S(0,2)$

A spin state itself is hard to measure directly.
A charge movement is much easier to measure.

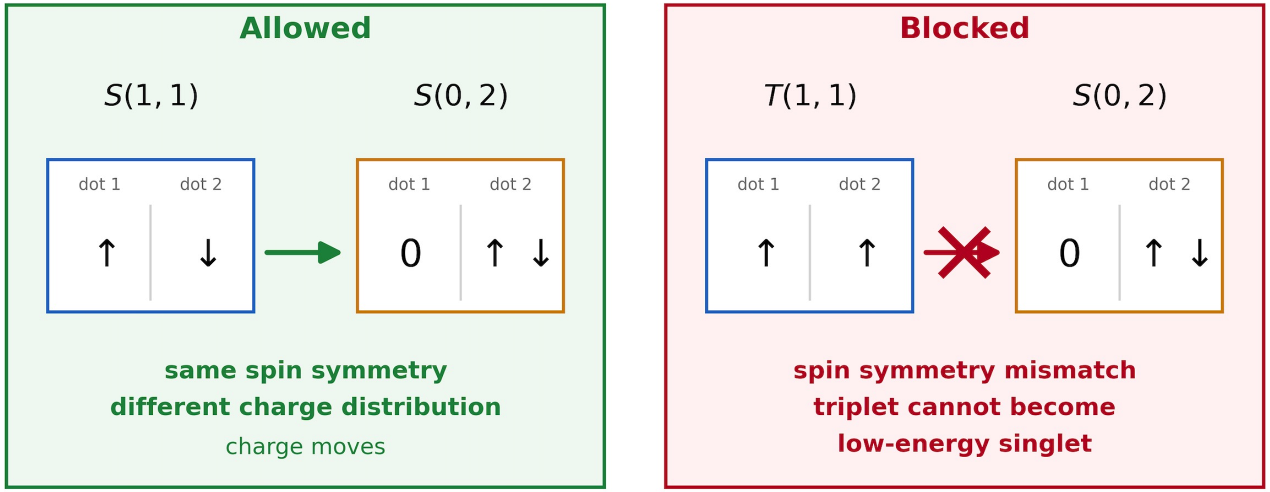
Pauli spin blockade maps spin symmetry onto charge motion.
S(1,1) → S(0,2) allowed: charge moves
T(1,1) → S(0,2) blocked: charge stays

If the two-spin state is triplet-like, charge motion is blocked by spin selection rules.

<u>Spin symmetry is therefore converted into a measurable charge or current signal.</u>

This makes Pauli spin blockade a central readout mechanism for singlet-triplet and two-spin devices.

Pauli spin blockade for readout

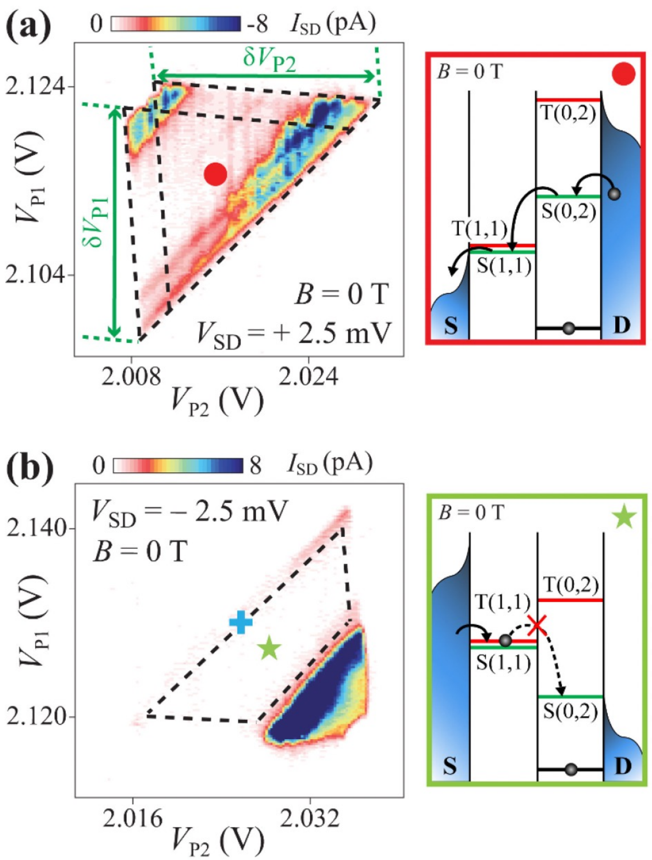


Pauli spin blockade maps spin symmetry onto charge motion.

S(1,1) → S(0,2) allowed: charge moves

T(1,1) → S(0,2) blocked: charge stays

Pauli spin blockade



Pauli spin blockade in the weakly coupled regime.
Current ISD as a function of VP1 and VP2 for B50 T. The lead and barrier gate voltages were fixed at VL15VL253.2 V, VB150.656 V, VB25 1.176 V and VB35 0.940 V throughout the experiment. (a) For VSD512.5 mV, the ground state and excited states of a full bias triangle are shown. The current flows freely at the S(0,2)–S(1,1) transition as illustrated in the box marked by red dot. (b) The same configuration at VSD522.5 mV, the current between the singlet and triplet states is fully suppressed by spin blockade (green star box) except on the bottom of the bias triangle marked by the blue cross.
The blue cross marks the region of leakage current in the Pauli spin blockade region due to spin-flip cotunneling

SCIENTIFIC REPORTS -1 : 110 –
DOI: 10.1038/srep00110

Stability diagrams

A **stability diagram** shows where current can flow as you change gate voltages.

Single dot: charge-transition lines
For one quantum dot, charge changes one electron at a time:

$$N \ \rightarrow N + 1$$

In a stability diagram, these appear as **charge-transition lines**.
Each line marks where two charge states have equal energy, for example:

$$N \ \leftrightarrow N + 1$$

Double dot: honeycomb pattern

Finite bias: bias triangles
If you apply a source-drain voltage, current can flow over a finite energy window.
In a double dot, the points where current is allowed expand into triangular regions.
These are called **bias triangles**.

They are important because they reveal: tunnel coupling, energy-level alignment, orbital or valley excited states, spin blockade

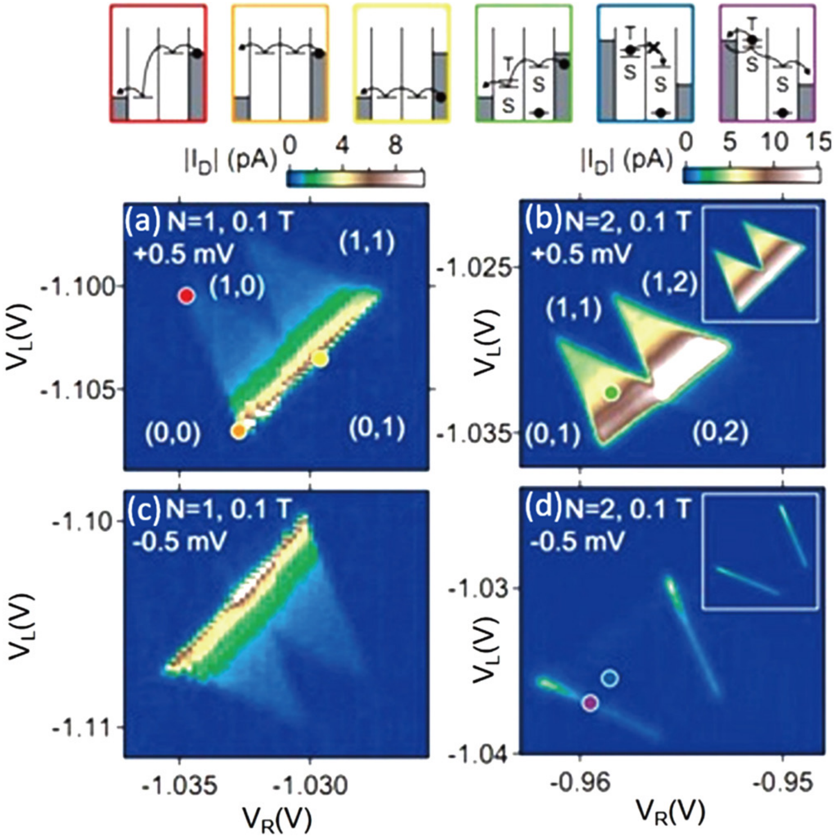
Pauli spin blockade protocol

Pauli spin blockade then maps this spin information onto a charge/current signal

1)Tune the double dot in the few-charge **Coulomb-blockade regime**.
The occupation is well defined, for example (1,1), (0,2), or (2,0).
2) **Initialize** into a known charge/spin configuration.
For example, load one hole in each dot.
3) **Apply control pulses** or microwave/electric drive.
This rotates the spin state or changes the singlet/triplet probability.
4) **Pulse to the readout** point near the spin-blockade transition.
This is where (1,1)→(0,2) or (1,1)→(2,0) is energetically allowed for a singlet but blocked for a triplet.
5) **Measure current**.
If charge moves, the state was singlet-like. If charge is blocked, the state was triplet-like.
6) **Convert** the signal into a singlet/triplet or spin-state probability.

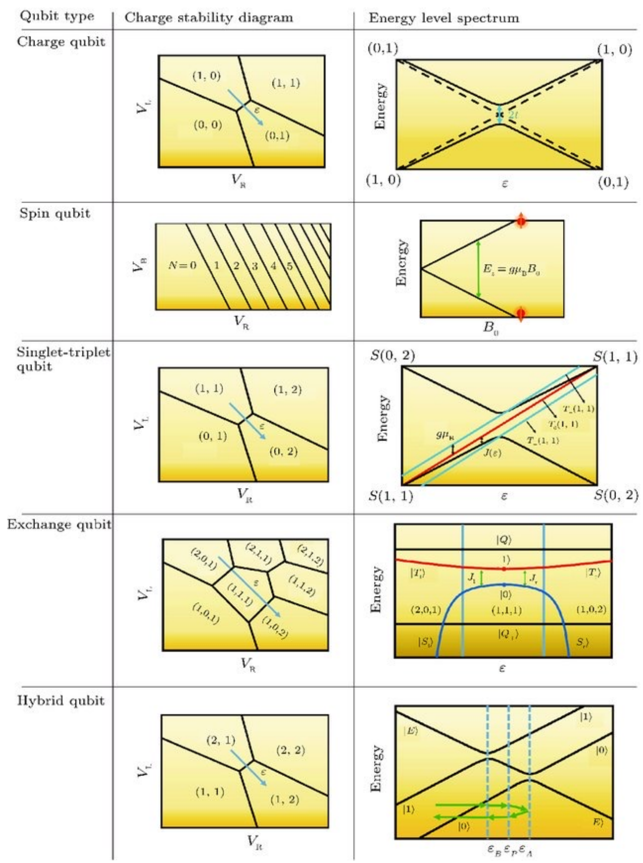
charge transition observed → singlet-like state
charge transition blocked → triplet-like state

Pauli spin blockade protocol

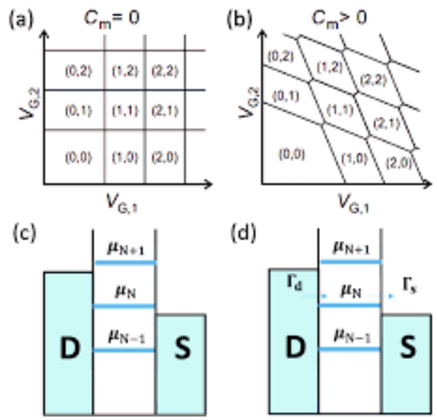


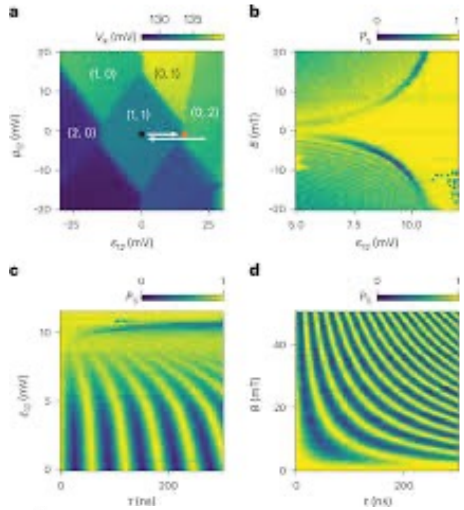
Petta et al 2005 *Phys. Rev.* **72** 165308

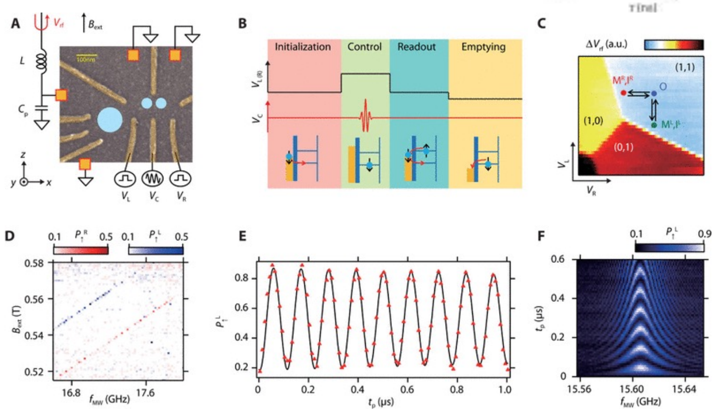
Stability diagrams



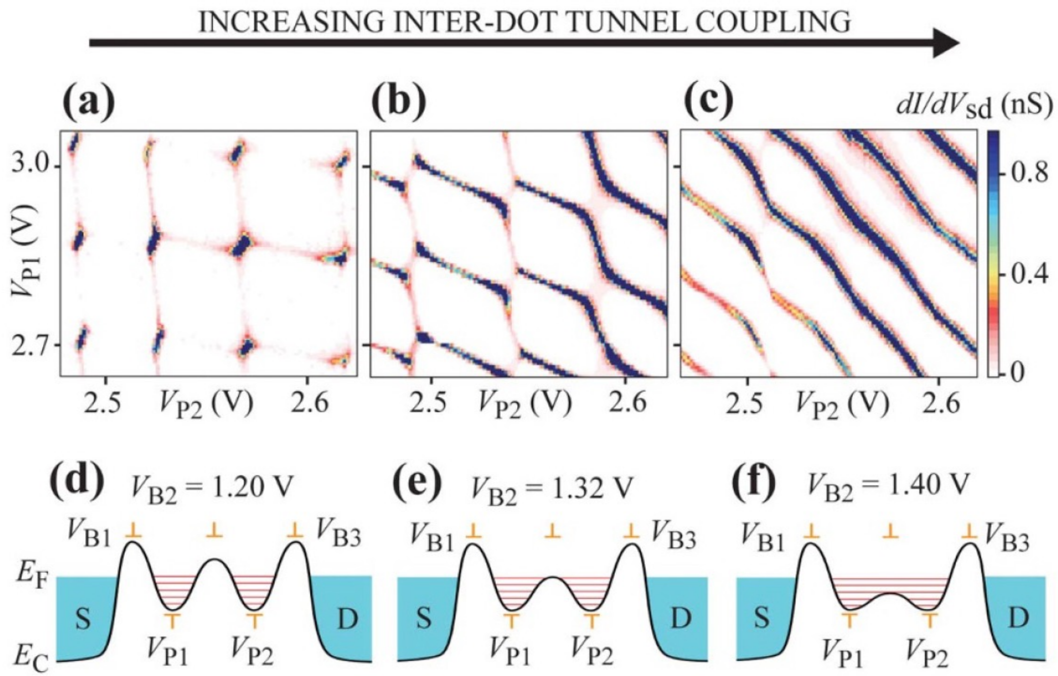
Credits Hai-Ou Li







Stability diagrams



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DOI: 10.1038/srep00110

Charge stability diagrams at different inter-dot tunnel coupling. *Measured stability diagrams and energy landscape of the double dot system ranging from weak to strong inter-dot tunnel coupling (a)–(c) and (d)–(f) respectively, for VL1 5 VL2 5 3.0 V, VB1 5 0.76 V, VB3 5 1.0 V and VSD 5 0. From lower to higher VB2, the tunnel barrier height decreases resulting in stronger inter-dot tunnel coupling. (a) A checker box pattern, (b) honeycomb pattern and (c) diagonal parallel lines indicate that the two dots merge into a single dot as the coupling is increased*

Single spin qubit

A single-spin qubit uses one spin-1/2 degree of freedom and has two basis states

The logical basis is often written as: $|0\rangle = |\downarrow\rangle, \qquad |1\rangle = |\uparrow\rangle$

Without magnetic field, these two spin states can be energetically degenerate. When you apply a magnetic field, the two spin orientations have different energies. This is the **Zeeman splitting**.

In a magnetic field, the spin states are split by the Zeeman interaction:

$$H_Z = \frac{1}{2} g \mu_{B\mathbf{B}} \cdot \boldsymbol{\sigma}$$

Choosing z as the quantization axis:

$$g = \text{g}-\text{factor}$$
$$\mu_B = \text{Bohr magneton}$$
$$\mathbf{B} = \text{magnetic field}$$
$$\boldsymbol{\sigma} = (X, Y, Z) = \text{Pauli matrices}$$

$$H_Z = \frac{1}{2} \hbar \omega_Z Z$$

$$\omega_Z = \frac{g \mu_B B_z}{\hbar}$$

is the **Larmor frequency**
or **spin transition frequency**.

Single spin qubit

A single-spin qubit is conceptually simple.

The difficulty is experimental control.

Local addressability:
control one spin without unintentionally driving neighboring spins

Readout:
convert a weak spin signal into a measurable electrical or optical signal

In quantum dots, this often requires spin-to-charge conversion.

The spin is the information carrier.

Charge motion, reservoirs, sensors, or resonators provide the measurement handle.

Spin qubits

	Electron spin qubits	Hole spin qubits
Typical material focus	Silicon, especially enriched ^{28}Si	Germanium, silicon/germanium
Spin-orbit coupling	Weak	Strong
Coherence potential	Very high	Strong, but more noise-sensitive
Electrical control	Often requires assistance	Naturally strong
Control mechanisms	ESR, EDSR, micromagnets	EDSR, g-tensor modulation
Main challenge	Fast local control and scaling	Charge-noise sensitivity and anisotropy
Goal	Preserve coherence while improving control	Find sweet spots for fast but noise-protected control

Electron spin vs Hole spin

Electron spin qubits in silicon:

weak spin-orbit coupling
low nuclear-spin noise in isotopically enriched ^{28}Si
long coherence potential

electrical control may be slower unless assisted by:
micromagnet gradients
spin-orbit mechanisms

excellent coherence potential
weaker direct electrical control

Hole spin qubits, especially in germanium:

stronger spin-orbit coupling
highly anisotropic g-tensor

fast all-electrical control through:
electric-dipole spin resonance
g-tensor modulation

fast electrical control
stronger coupling to electric fields
sweet spots are important

Singlet-triplet qubit

A singlet-triplet qubit uses two spins in a double quantum dot.

The logical basis is commonly chosen as:

$$|S\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$

An effective Hamiltonian is:

$$H_{ST} = \frac{1}{2}J(\epsilon)Z + \frac{1}{2}\Delta E_Z X$$

$J(\epsilon)$ is the exchange splitting, controlled electrically by detuning and tunnel coupling.
ΔE_Z is the Zeeman-energy difference between the two dots.

Exchange control can be fast, but it is often sensitive to charge noise.

Singlet-triplet operation is therefore a balance between fast electrical control and noise protection.

Multi-spin qubits

Multi-spin qubits encode logical information in a subspace of three or more spins.

<u>Instead of using one physical spin as one qubit, the qubit is encoded collectively.</u>

Main advantage:
operations can, in principle, be implemented using exchange interactions only
This reduces the need for local magnetic control.

Main challenges:
more physical dots per logical qubit
larger calibration space
more control parameters
more possible leakage channels

<u>Leakage is especially important because the state can leave the encoded logical subspace.</u>

Multi-spin qubits trade simpler interaction physics for greater device and calibration complexity.

Spin qubits

	Physical system	Main control	Main challenge
Single electron spin	One electron in one quantum dot	ESR, EDSR, micromagnet gradient	Local addressability, valley splitting, readout
Single hole spin	One hole in one quantum dot	Spin-orbit-mediated electrical drive	Charge-noise sensitivity, anisotropic g-tensor
Singlet-triplet	Two spins in a double quantum dot	Exchange and Zeeman gradient	Charge-noise-sensitive exchange, leakage to T_\pm
Exchange-only	Three or more spins	Exchange pulses	Complex calibration, encoded leakage

Control mechanisms

Magnetic resonance control (single qubit rotation)

A transverse oscillating field drives coherent spin rotations.

In the rotating frame:

$$H_{rot} = \frac{\hbar\Delta}{2} Z + \frac{\hbar\Omega_R}{2} (\cos\phi\,, X + \sin\phi\,, Y)$$

$\Delta = \omega_d - \omega_{01}$ detuning
Ω_R Rabi frequency
ϕ drive phase

On resonance, $\Delta = 0$, the spin rotates in the equatorial plane.

The drive phase ϕ selects the rotation axis.

The pulse area sets the rotation angle: $\theta = \int \Omega_R(t), dt$

Therefore magnetic resonance turns a physical drive pulse into a calibrated single-qubit rotation.

Magnetic resonance control

On resonance, the pulse implements:

$$R_{\hat{n}}(\theta) = \exp\left[-i\frac{\theta}{2}(\cos\phi\,, X + \sin\phi\,, Y)\right]$$

with:

$$\hat{n} = (\cos\phi\,, \sin\phi\,, 0)$$

$$\theta = \int \Omega_R(t), dt$$

Changing the phase changes the rotation axis.
Changing the pulse area changes the rotation angle.

This is the spin-qubit analogue of microwave rotations in superconducting qubits.
The physics is the same at the circuit level: controlled rotations.

ESR: magnetic resonance control

Electron Spin Resonance (ESR) uses an oscillating transverse drive at the spin transition frequency.

A simple driven-spin Hamiltonian is:

$$H(t) = \frac{1}{2}\hbar\omega_Z Z + \hbar\Omega_R \cos(\omega_d t + \phi)\, X$$

ω_Z is the spin transition frequency
ω_d is the drive frequency
Ω_R is the Rabi frequency

ϕ is the drive phase

On resonance, the drive produces coherent spin rotations.

Spin rotations

In the rotating-wave approximation, a resonant drive produces rotations in the equatorial plane of the Bloch sphere:

$$R_{\hat{n}}(\theta) = \exp\left[-i\frac{\theta}{2}(\cos\phi\,,X + \sin\phi\,,Y)\right]$$

The rotation angle is set by the pulse area:

$$\theta = \int \Omega_R(t), dt$$

The drive phase ϕ selects the rotation axis.

This is the spin-qubit analogue of microwave rotations in superconducting qubits.
The physics is the same at the circuit level: controlled rotations.

The hardware implementation is different.

Oscillating drive

The oscillating drive can be delivered through:

microwave antenna
on-chip stripline
gate line
nearby control electrode

The drive may act magnetically or electrically, depending on the device.

ESR:
direct magnetic driving of the spin

EDSR:
electric driving converted into spin rotations through spin-orbit coupling or a micromagnet gradient

Practical control parameters:
drive frequency

EDSR: Electric-Dipole Spin Resonance

In semiconductor spin qubit arrays, purely magnetic driving is hard to scale because local microwave magnetic fields are difficult to generate in dense arrays.

Electrical control is therefore crucial.

Electric-dipole spin resonance (EDSR) converts an electric field into spin rotation through spin-orbit coupling or through a magnetic-field gradient:

A schematic EDSR Hamiltonian is:

$$H_{EDSR} \sim eE_{ac}x + \frac{1}{2}g\mu_{B\mathbf{B_{eff}}}(x) \cdot \boldsymbol{\sigma}$$

The first term describes electric driving of the carrier position.
The second term describes the effective spin drive.
The electric field moves the carrier wave function.

Spin-orbit coupling or a micromagnet gradient converts this motion into an effective time-

EDSR: Electric-Dipole Spin Resonance

Spin-orbit coupling or a micromagnet gradient converts this motion into an effective time-dependent magnetic field.

Physical chain:

electric field → wave-function displacement → effective magnetic field → spin rotation

EDSR is attractive because local electric gates are easier to integrate densely than local microwave magnetic antennas.

Effective EDSR drive

A schematic effective drive Hamiltonian is:

$$H_{drive}(t) = \frac{1}{2}\hbar\Omega_{EDSR}(t)[\cos\phi\,, X + \sin\phi\,, Y]$$

$\Omega_{EDSR}(t)$ is the electrically driven Rabi rate.
ϕ is the drive phase.

The phase selects the rotation axis in the equatorial plane.

For hole spins, Ω_{EDSR} can be large because intrinsic spin-orbit coupling is strong.

For electron spins in silicon, synthetic spin-orbit coupling can be generated using micromagnets.

Exchange control

For two neighboring spins, the exchange interaction is:

$$H_{ex} = J(t)\mathbf{S_1} \cdot \mathbf{S_2}$$

Exchange separates singlet and triplet states.

Pulsing $J(t)$ enables two-qubit gates, singlet-triplet rotations, and exchange-only operations.

The advantage is fast electrical control.

The drawback is sensitivity to charge noise, because J depends on detuning and barrier voltages:

$$\delta J \simeq \frac{\partial J}{\partial \epsilon}\delta\epsilon + \frac{\partial J}{\partial V_b}\delta V_b$$

Sweet-spot operation reduces these derivatives while preserving controllability.

Spin qubits

Measurement and practical experimental protocols

Spin readout is indirect

Spin is not directly measured by a current meter.

Most spin-qubit readout first converts spin information into charge information.
This is called spin-to-charge conversion.

Then the charge state is detected electrically.

Possible charge detectors include:
quantum point contact
single-electron transistor
gate-based rf sensor
microwave resonator

The measurement chain is therefore:
spin state → charge configuration → electrical signal

Energy-selective tunneling readout

Energy-selective tunneling uses a reservoir as a spin filter.

One spin state has an electrochemical potential above the reservoir Fermi level.

The other spin state remains below it.
Therefore, only one spin state can tunnel.
Observing a tunneling event reveals the spin state.

Pulse sequence:

initialize → manipulate spin → pulse to readout point → detect tunneling event

The readout window must balance:
spin splitting
tunnel rate
thermal broadening
spin relaxation time

Measurements

Practical Tuning and Characterization Workflow

Before a spin qubit can be measured as a qubit, the device must first be tuned as a quantum-dot system.

Typical workflow:

charge stability → dot occupation → tunnel barriers → readout point → qubit operating point

Spin qubits

	What is measured	Why it matters
Charge stability map	Sensor current, RF reflectometry, or dispersive response versus gate voltages	Identifies dot occupation and charge transitions
Barrier tuning	Transition linewidths, tunnel rates, charge-sensor response	Sets coupling to reservoirs and between dots
Readout calibration	Histograms or time traces for known prepared states	Determines assignment fidelity and measurement time
Qubit spectroscopy	Spin resonance or electric-dipole spin resonance response	Finds ω_{01} and local g-factor
Coherent control	Rabi, Ramsey, echo sequences	Extracts gate rates and coherence times
Benchmarking	Repeated calibrated gates or randomized sequences	Estimates operational error rates

Identify the transition frequency

For a single-spin qubit:

$$\omega_d \simeq \omega_{01} = \frac{g\mu_B B}{\hbar}$$

A drive frequency is scanned while the experiment measures the final spin-state probability.

The drive can be:
microwave magnetic field
electric drive converted by spin-orbit coupling
electric drive in a micromagnet gradient

Minimal spectroscopy sequence:
initialize → drive at ω_d for fixed time → spin-to-charge readout

At resonance, the final spin population changes.

The goal is the same as in superconducting qubits:

find ω_{01}

But the signal is different:

superconducting qubits → microwave response of a circuit

spin qubits → spin-dependent charge or sensor response

Calibrating rotating spin: Rabi oscillations

Once the transition frequency is known, the next step is coherent control.

Pulse sequence:

initialize $|0\rangle$→ resonant drive of duration τ→ readout

For resonant driving, the excited-state probability oscillates as:

$$P_1(\tau) = A\sin^2\left(\frac{\Omega_R \tau}{2}\right) + B$$

Ω_R is the Rabi frequency.

The fitted oscillation determines the pulse durations for: $\pi/2$ rotations π rotations 2π rotations

This converts a physical drive pulse into calibrated single-qubit gates.

Calibrating rotating spin: Rabi oscillations

Quantity	Experimental knob	Interpretation
Ω_R	Drive amplitude	Rotation rate on the Bloch sphere
$\boldsymbol{\pi\ pulse}$	Duration satisfying $\Omega_R \tau = \pi$	Population inversion
$\pi/2$ **pulse**	Duration satisfying $\Omega_R \tau = \pi/2$	Creates an equatorial superposition
Drive phase	Phase of microwave, RF, or electrical tone	Selects X-like or Y-like rotation axis

Rabi oscillations calibrate how pulse amplitude, duration, and phase become controlled rotations on the Bloch sphere.

Spin relaxation: T_1 measurement

Measure how long the excited spin state survives.

Pulse sequence:

$$X_\pi \rightarrow wait\ t \rightarrow readout$$

Fit

$$P_1(t) = P_1(0)e^{-\frac{t}{T_1}} + P_{1,\infty}$$

The offset $P_{1,\infty}$ accounts for residual excited-state population, imperfect initialization, or readout offset.

In spin qubits, T_1 is affected by magnetic field, spin-orbit coupling, phonons, reservoir coupling, and electrical noise.

A long T_1 is necessary for memory, but it does not guarantee a long T_2^*

Free induction dephasing: Ramsey measurement

Measure how long a freely evolving superposition keeps phase coherence.

Pulse sequence:

$$X_{\pi/2} \rightarrow wait\ t \rightarrow X_{\pi/2} \rightarrow readout$$

Typical fit:

$$P_1(t) = \frac{1}{2}\left[1 + Ce^{-\frac{t}{T_2^*}} \cos(\Delta\omega t + \phi_0)\right]$$

For quasi-static noise:

$$P_1(t) = \frac{1}{2}\left[1 + Ce^{-\left(\frac{t}{T_2^*}\right)^2} \cos(\Delta\omega t + \phi_0)\right]$$

Ramsey decay is sensitive to slow fluctuations in the spin transition frequency:
magnetic noise, nuclear noise, detuning noise, exchange noise, and electric-field noise converted through spin-orbit or g-tensor effects.

Dynamical decoupling and Hahn Echo

Separate irreversible decoherence from slow, refocusable dephasing noise.

Pulse sequence:

$$X_{\pi/2} \rightarrow wait\ \frac{t}{2} \rightarrow X_{\pi} \rightarrow wait\ \frac{t}{2} \rightarrow X_{\pi/2} \rightarrow readout$$

Typical fit:

$$P_1(t) = \frac{1}{2}\left[1 + Ce^{-\left(\frac{t}{T_{2,echo}}\right)^n}\right]$$

If $T_{2,echo} \gg T_2^*$, a significant part of the Ramsey dephasing comes from slow fluctuations can be refocused.

More advanced dynamical-decoupling sequences, like CPMG and XY sequences, add multiple refocusing pulses to extend coherence and probe the noise spectrum.

Exchange oscillations

Calibrate coherent two-spin dynamics for entangling gates.

Minimal sequence:

$$prepare|\uparrow\downarrow\rangle \rightarrow pulse\ exchange\ J\ for\ time\ \tau \rightarrow spin\ readout$$

Exchange Hamiltonian:

$$H_{ex} = J\mathbf{S_1} \cdot \mathbf{S_2}$$

Ideal effect:

$|\uparrow\downarrow\rangle \leftrightarrow |\downarrow\uparrow\rangle$ with an oscillation rate set by J.

Real devices may include magnetic-field gradients, spin-orbit terms, anisotropic exchange, leakage, and charge-noise fluctuations in J.

A two-qubit gate is calibrated by measuring coherent exchange dynamics, identifying the interaction axis,and choosing pulse parameters that realize the target unitary while suppressing leakage and dephasing.

Readout fidelity

Practical spin readout is a chain:

spin state → charge configuration → sensor or resonator response → voltage trace → classifier → assigned bit.

Each step contributes to the readout fidelity.

Gate-based dispersive readout

In gate-based dispersive readout, an RF or microwave resonator is connected to a gate electrode.

The quantum dot modifies the resonator response through:
state-dependent admittance
quantum capacitance
tunnel-rate-dependent damping

The measured signal is a reflected amplitude and phase, not a direct spin projection.

When combined with spin-to-charge conversion or Pauli spin blockade, dispersive sensing provides a scalable route to multiplexed spin readout.

Readout chain:

spin state → charge configuration → resonator response → voltage trace → classifier → assigned bit

Each step contributes to the final readout fidelity.

Performance metrics for spin qubits

Metric	How it is measured in spin qubits	Main limitation probed
T_1	Prepare excited spin, wait, read out	Spin relaxation via spin-orbit coupling, phonons, reservoirs, or electrical noise
T_2^*	Ramsey free induction	Slow magnetic, nuclear, charge, or g-factor noise
T_2,echo	Hahn echo or dynamical decoupling	Refocusable low-frequency noise
ΩR	Rabi oscillations	Control speed and drive calibration
F_1q	Gate benchmarking or tomography-like calibration	Drive errors, detuning, phase noise, leakage
F_2q	Exchange-gate calibration and benchmarking	Charge-noise sensitivity of J, leakage, anisotropic terms
FRO	Assignment matrix from prepared states	Sensor noise, relaxation during readout, blockade lifting
p_leak	Population outside chosen spin/charge subspace	Orbital, valley, triplet, or higher-state excitation

Spin qubits

For spin qubits, high performance means more than long coherence.

It means fast calibrated control, robust operating points, reliable spin-to-charge conversion, automated tuning, and reproducible fabrication.

Why do spin qubits need cryogenic operations?

Spin qubits are operated at mK to make quantum-dot energy scales resolvable and stable.

Thermal energy must be smaller than the relevant energies:

$$kBT \ll EC, EV, EZ, Delta_{\mathrm{orb}}$$

E_C = charging energy
E_V = valley splitting
E_Z = Zeeman splitting
Delta$_{_\mathrm{orb}}$ = orbital level spacing

Low temperature is needed to: stabilize single-electron occupation, enable Coulomb blockade, suppress thermal excitation, improve initialization and readout fidelity

Typical operation: T = 10–100 mK (Some devices are also explored around 1–4 K).

Cryogenic operation keeps electrons in well-defined quantum-dot states and prevents thermal energy from washing out spin, charge, valley, and orbital energy splittings.

Thank you
for your attention

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