Qubits:
Physical platforms and applications

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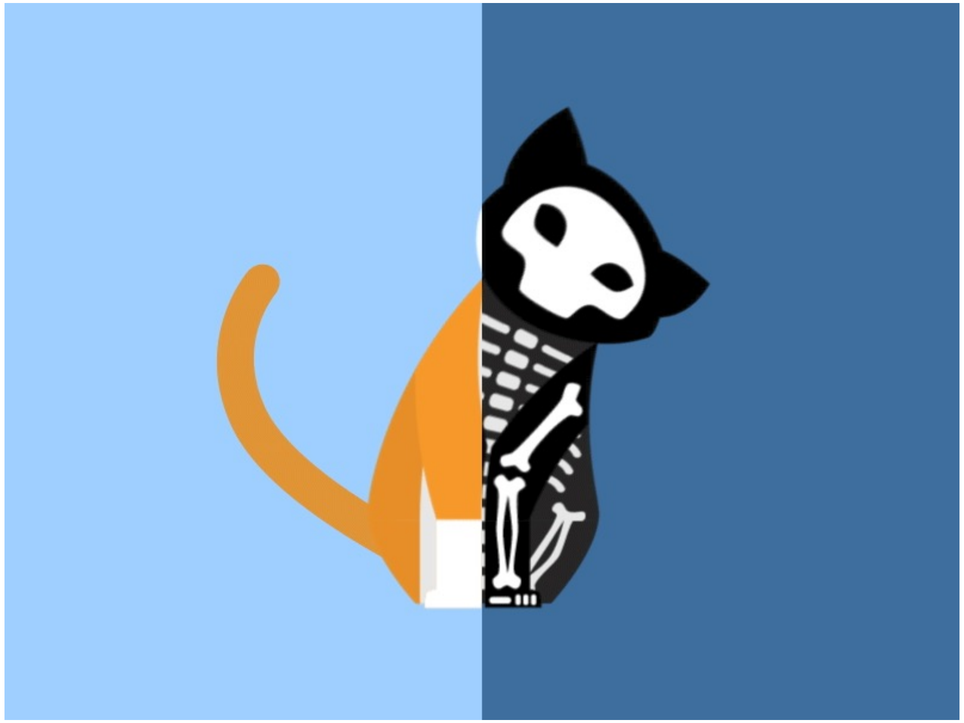
Outline

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



Credits: Kayla Mahoney

Qubits as vectors in the complex Hilbert space

Pauli Matrices

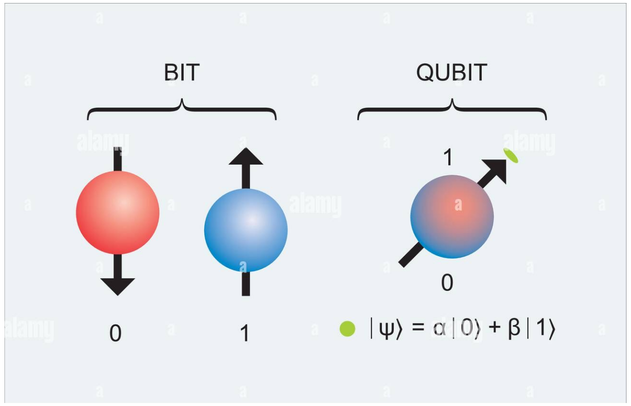
Multi–qubits

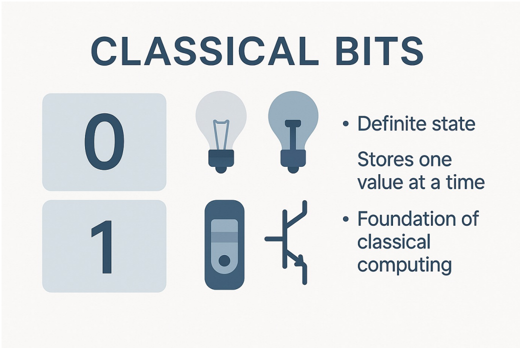
Bits vs Qubits

Classical bit: one of two states, 0 or 1.

Qubit: quantum two-level system with basis states
$|0\rangle$ and $|1\rangle$

and superpositions $\alpha|0\rangle + \beta|1\rangle$.





From bits to qubits

From the classical bit to the qubit.

A classical bit has a definite value: 0 or 1.
A qubit is different: it is described by a vector in a two-dimensional Hilbert space.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \qquad |\alpha|^2 + |\beta|^2 = 1$$

The numbers $\alpha$and β are complex amplitudes, containing two kinds of information:

amplitude magnitude → measurement probability
relative phase → quantum interference

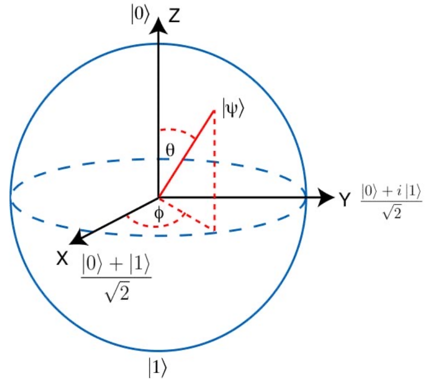
This distinction is essential: quantum computation is not based on reading out many amplitudes directly, but on controlling them before measurement.

Bloch sphere

A single pure qubit state can be represented on the Bloch sphere.

Spherical coordinates

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



Bloch Sphere

The polar angle $\boldsymbol{\theta}$ **controls the population balance between $|\mathbf{0}\rangle$ and $|\mathbf{1}\rangle$**.
The azimuthal angle $\boldsymbol{\phi}$ **is the relative phase.**

Measurement converts the quantum state into a classical outcome.

$P(0) = |\alpha|^2, \quad P(1) = |\beta|^2$

The Bloch sphere is therefore not just a picture of “superposition”.

It is a compact way to visualize amplitudes, phase, and measurement axes.

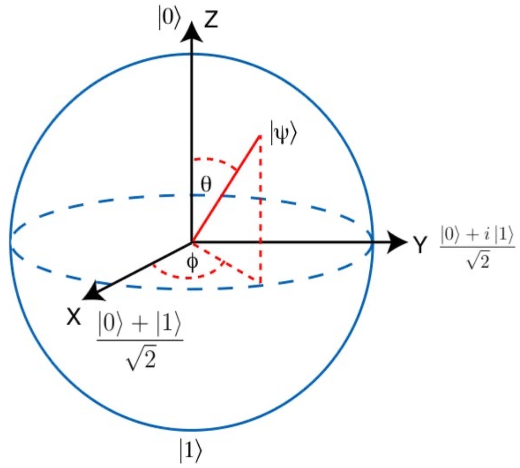
Equatorial states

Equatorial states have equal populations:

$$P(0) = P(1) = 1/2$$

Therefore **their information is carried by the relative phase $\boldsymbol{\varphi}$:**

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{e^{i\phi}}{\sqrt{2}}|1\rangle.$$



<u>They are central for phase-sensitive experiments.</u>

A π/2 pulse prepares an equatorial state (superposition)
During free evolution, the state accumulates phase around the equator.
Loss of phase coherence appears as decay of the equatorial Bloch vector.

<u>This is why Ramsey and dephasing measurements are naturally described using equatorial states.</u>

Real qubits

For an ideal pure qubit, the state can be represented by a state vector:

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

not exchange energy or information with the environment

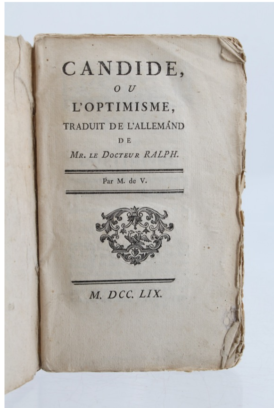
relative phase between $|0\rangle$ and $|1\rangle$ is well defined

This description is sufficient when the qubit is perfectly isolated and fully coherent.

In a real device, the qubit is affected by noise and interactions with its environment.

The state is therefore often better represented by a density matrix:

$$\rho = \begin{pmatrix} \rho_{00} & \rho_{01} \\ \rho_{10} & \rho_{11} \end{pmatrix}$$



The **density matrix** contains both populations and coherences.

Pauli Matrices

The three Pauli matrices are:

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

They are Hermitian (observable):

$$X = X^{\dagger}, \qquad Y = Y^{\dagger}, \qquad Z = Z^{\dagger}$$

They are also unitary (reversible):

$$X^{\dagger} X = I, \qquad Y^{\dagger} Y = I, \qquad Z^{\dagger} Z = I$$

Hermitian means they can represent **observables**.

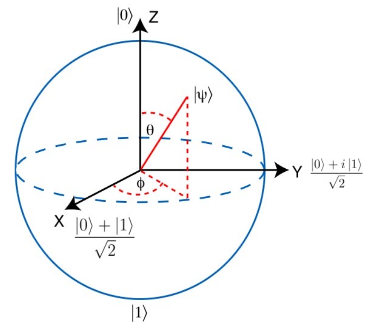
Unitary means they can also act as **reversible quantum gates.**

As observables, they correspond to measurements.

As gates, they implement specific reversible qubit transformations.

Single qubit control

A qubit is useful for computation only if its quantum state can be controlled.



The Bloch sphere gives a geometric description of single-qubit states.

The Pauli operators define the three fundamental control axes:

$$X\colon bit - flip\ axis \qquad Y\colon bit - flip\ with\ phase \qquad Z\colon phase\ axis$$

Equivalently, they define measurements and rotations around the x, y, and z axes.

The Bloch vector connects the abstract state to measurable quantities:

$$r = (< X >, < Y >, < Z >)$$

Single-qubit physics is the physics of controlled rotations, phases, and measurements.

Qubits

Time evolution is generated by a Hamiltonian:

$$U(t) = e^{-i\frac{Ht}{\hbar}}$$

Single-qubit gates are controlled unitary rotations:

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

For many qubits, the state space grows exponentially:

$$|\psi\rangle = \Sigma_x c_x |x\rangle, \qquad \Sigma_x |c_x|^2 = 1$$

The useful resources are not just “many states”.

They are coherent amplitudes, phase, interference, and entanglement.

Superposition, interference and entanglement

Superposition

The state can contain amplitudes over many basis states.

$$|\psi\rangle = \sum_x c_x |x\rangle$$

Interference

Gates reshape amplitudes to enhance useful outcomes and suppress others.

$$P(x) = |c_x|^2$$

Entanglement

The state may be genuinely multi-qubit, not a product of independent qubits.

$$|\psi\rangle \neq |\psi_1\rangle \otimes \cdots \otimes |\psi_n\rangle$$

Measurement

Only one classical bit string is observed.

$$x \in \{0,1\}^n$$

Qubits

We have seen the language of ideal qubits: states, phases, rotations, gates, and measurements.

We now ask how these concepts survive in the laboratory.
A real qubit is an open quantum system.

It interacts with control electronics, measurement apparatus, materials, electromagnetic modes, and its environment.

So the first question is not yet:

Which platform is best?

The first question is:

How do we measure whether a qubit is reliable?

Real Qubits

Real qubits are noisy systems

The ideal qubit is described as a controllable two-level quantum system.

A real qubit is never perfectly isolated.

Its state is affected by several physical and technical mechanisms:

energy relaxation, dephasing, control errors, readout errors, crosstalk, leakage, drift

These mechanisms determine whether quantum information can be preserved, manipulated, and measured reliably.

A qubit is not only a two-level quantum system.

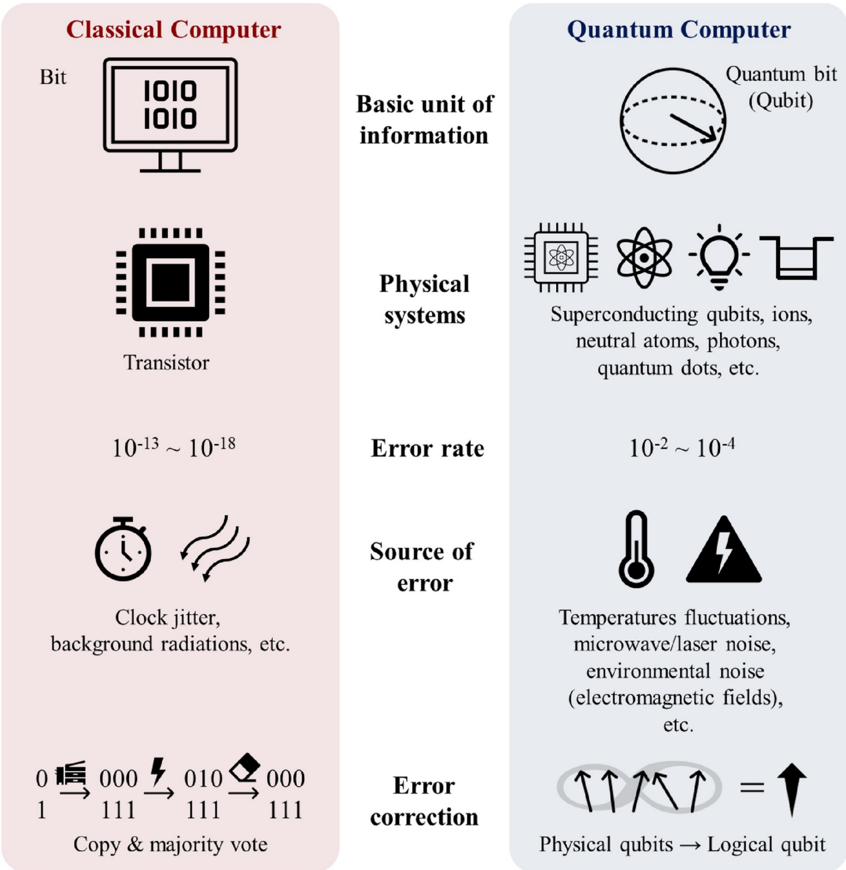
A useful physical qubit must be controllable:

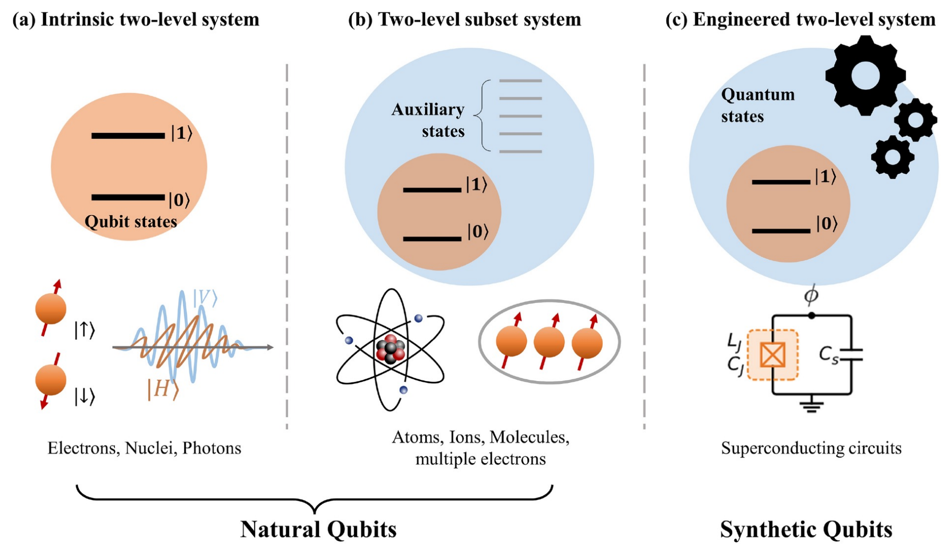
we must be able to prepare it, preserve coherence, apply gates, and measure it.

In Hamiltonian language, control means being able to engineer rotations around the Bloch sphere.

Without controllable rotations, a two-level system cannot function as a practical qubit for quantum computing.

Bits vs Qubits





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

We now move from the mathematical description of qubits to the performance criteria used to evaluate real devices.

Qubits

For quantum hardware, it is useful to distinguish three levels.

State-level description
Describes the quantum state itself.

state vector or density matrix

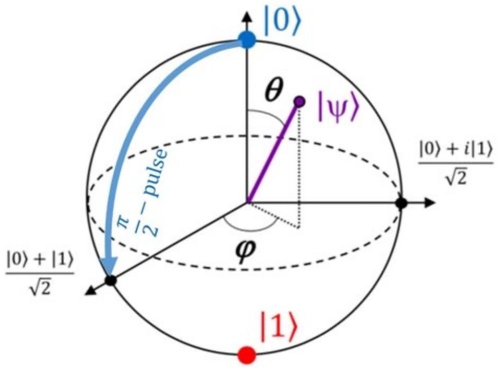
Process-level description
Describes the physical operation applied to the state.

unitary gate noisy channel measurement process

Device-level description
Describes the full experimental system.

qubit chip calibration wiring cryogenics control electronics software compilation

A physical quantum processor must be understood across all three levels.



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

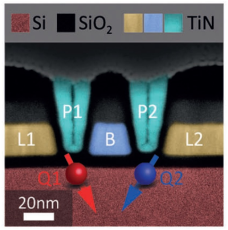
Real Qubits

Noise channels
and benchmark metrics

NCCR SPIN: Qubits portfolio

Silicon

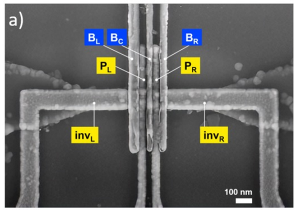
MOS FinFET



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)

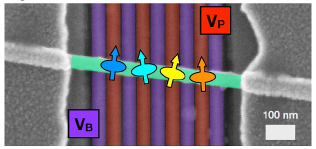
FD-SOI



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

Germanium

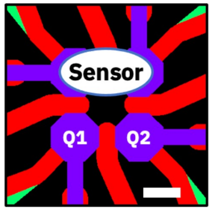
nanowires



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



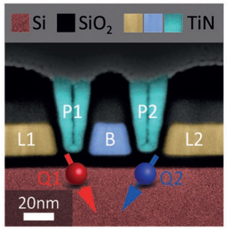
100 nm

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

NCCR SPIN: Qubits portfolio

Silicon

MOS FinFET



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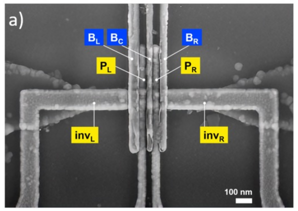

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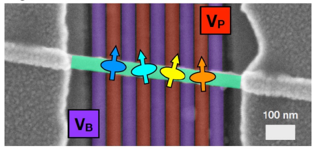

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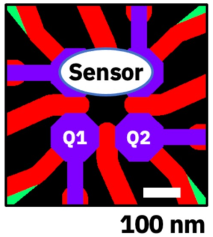

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Benchmarking

Initiative	Region / year	Main focus	Why it matters
BACQ	France, 2022	Application-oriented, multi-criteria benchmarking	Combines accuracy, time, energy, problem size
EuroQHPC / Open QBench	Europe, 2023	Quantum-HPC integration and application benchmarks	Important for hybrid quantum-classical computing
DARPA Quantum Benchmarking Initiative — QBI	US, 2024	Utility-scale quantum computing by 2033	Evaluates whether different hardware approaches can realistically deliver industrially useful quantum computation.
BenchQC	Germany, 2025	Industrial application benchmarking	Focuses on simulation, optimization, and machine-learning use

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Initiative	Region / year	Main focus	Why it matters
QED-C benchmarking suite	US, 2019	Application-oriented benchmarks	Provides benchmark circuits and workflows for comparing quantum systems on practical tasks.
Quantum Energy Initiative — QEI	International, 2022	Energy/resource footprint of quantum technologies	Adds sustainability and physical resource consumption to the benchmarking discussion.
Metriq	US / open platform, 2022	Collaborative database of benchmarks, datasets, and visualizations	Helps collect and compare benchmarking results in a transparent way.

Benchmarking

DARPA Quantum Benchmarking Initiative — QBI

in **November 2025**, DARPA selected **11 companies** for Stage B, where they must provide detailed R&D plans, risk mitigation, and prototype milestones.

DARPA explicitly says the initiative is not meant to select one winner, but to evaluate different architectures on their own merits.

In **March 2026**, DARPA expanded QBI with a new Stage A solicitation to include additional approaches not yet evaluated.

Benchmarking

Home › News › Quantum Benchmarking Initiative Expands Quest To Separate Hype From Reality

Quantum Benchmarking Initiative expands quest to separate hype from reality

New solicitation invites new entrants and approaches

March 10, 2026

As the quantum computing field accelerates, DARPA's Quantum Benchmarking Initiative (QBI) is expanding to capture its momentum.

Organizations that have not yet been funded by QBI are invited to join under a new Stage A Quantum Benchmarking Initiative Topic (QBIT), which builds on QBI's ongoing effort to rigorously determine whether any quantum computing architecture can achieve utility-scale operation — meaning its computational value exceeds its cost — by 2033.

Of particular interest are entrants with distinct approaches that have not yet been evaluated under QBI. Selected participants will enter Stage A, a six-month period in which they will describe a full system concept and provide evidence supporting its feasibility.

With this solicitation comes another shift for QBI: Micah Stoutimore is assuming the role of

Quantum Benchmarking Initiative

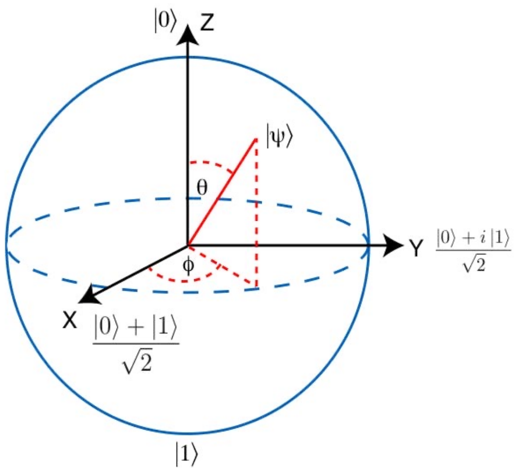
Opportunity

DARPA-PA-26-02-02

- **Published:** March 9, 2026

Noise

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



Single-Qubit noise mechanisms

Mechanism	Effect	Metric
Energy relaxation	excited state decays to ground state $\|1\rangle \rightarrow \|0\rangle$	T_1
Thermal excitation	ground state is excited by the environment $\|0\rangle \rightarrow \|1\rangle$	p_{th}
Pure dephasing	relative phase information is lost populations may remain unchanged	T_φ, T_2
Inhomogeneous dephasing	slow frequency fluctuations shot-to-shot detuning	T_2^*
Leakage	state leaves the computational subspace $\{\|0\rangle, \|1\rangle\}$	p_{leak}

Amplitude damping T_1

Amplitude damping describes **the irreversible relaxation of the qubit from the excited state to the ground state.** $|1\rangle \rightarrow |0\rangle$

Physically, the qubit loses energy to its environment.

If the qubit is prepared in $|1\rangle$, the excited-state population decays in time: (time evolution)

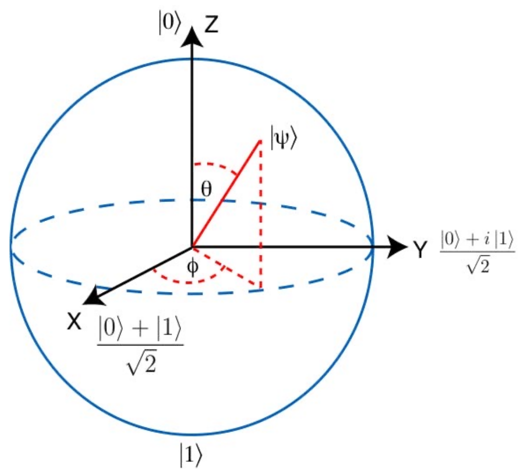
$$\rho_{11}(t) = \rho_{11}(0)e^{-\frac{t}{T_1}}$$

The characteristic **decay time is T_1.**

On the Bloch sphere, relaxation pulls the state toward the ground state.

If $|0\rangle$ is the ground state, the state moves toward the north pole.

T_1 measures how long the qubit can preserve population in the excited state.



Pure Dephasing T_ϕ and T_2

Pure **dephasing destroys the relative phase in a superposition** without necessarily changing the populations.

The state

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

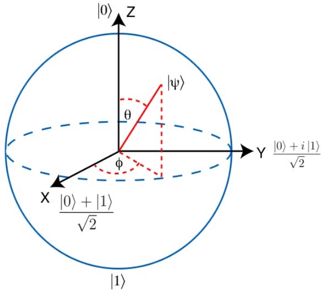
has equal populations in $|0\rangle$ and $|1\rangle$, but also a well-defined phase relation between them.

Under dephasing, this phase relation becomes uncertain.
In density-matrix language, the off-diagonal elements decay:

$$\rho_{01}(t) = \rho_{01}(0)e^{-\frac{t}{T_2}}$$

while the populations can remain approximately unchanged.

T_1: population decay
T_2: coherence decay
T_ϕ : pure dephasing



The measured coherence time is often written as: $$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

Coherence time

The measured coherence time is often written as: $\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$

T_1: population decay, diagonal density-matrix elements.

$$\rho_{11}(t) = \rho_{11}(0)e^{-\frac{t}{T_1}}$$

T_2: coherence decay, off-diagonal density-matrix elements.

$$\rho_{01}(t) = \rho_{01}(0)e^{-\frac{t}{T_2}}$$

while the populations can remain approximately unchanged.

T_ϕ : pure dephasing only, excluding the contribution from energy relaxation.

Real qubits
Density matrix

$$\rho = \begin{pmatrix} \rho_{00} & \rho_{01} \\ \rho_{10} & \rho_{11} \end{pmatrix}$$

ρ_{01}, ρ_{10},

contain the **coherences**, meaning the phase relationship between $|0\rangle$ and $|1\rangle$.

Inhomogeneous dephasing T_2^*

<u>Not all dephasing comes from fast random noise.</u>

In many experiments, the **qubit frequency fluctuates slowly from one experimental shot to the next**. This means that the **qubit does not always precess at exactly the same frequency.**

The phase accumulated during free evolution is therefore slightly different in each repetition of the experiment.

After averaging many shots, the measured coherence decays faster.

This is called inhomogeneous dephasing.

It is characterized by T_2^*.

T_2^* describes loss of phase coherence caused by slow frequency fluctuations and shot-to-shot detuning.

T_2 vs T_2*

T_2^*: free evolution; slow frequency fluctuations are not corrected

T_2: echo/refocused evolution; slow phase drift is partially cancelled

.

Tipically

$$T_2^* \leq T_2$$

The reason is that $\boldsymbol{T_2^*}$ **includes both true decoherence and reversible dephasing due to slow detuning**.

In density-matrix language:

$$\rho_{01}(t) = \rho_{01}(0)e^{-\frac{t}{T_2^*}}\rho_{01}(t) \sim \rho_{01}(0)e^{-\left(\frac{t}{T_2^*}\right)^2}$$

The off-diagonal element decays because the relative phase becomes uncertain after averaging over many experimental shots.

$\boldsymbol{T_2^*}$ is not only a property of the qubit. It also reflects the stability of the experimental environment.

Leakage

The **ideal qubit** lives in a two-dimensional computational subspace:

$$\{|0\rangle, |1\rangle\}$$

In a **real device**, the physical system may have additional energy levels. Leakage occurs when the state leaves the computational subspace.

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle$

The leakage probability is: $p_{\text{leak}} = |\gamma|^2$

It may have additional physical energy levels:

$|0\rangle, |1\rangle, |2\rangle, |3\rangle, \ldots$

Leakage is not the same as a standard bit-flip or phase error. The information is no longer encoded only in $|0\rangle\ and |1\rangle$.

Leakage reduces the validity of the qubit approximation.

A good physical qubit must keep the dynamics inside the computational subspace.

Leakage: example

For a spin qubit, the computational basis may be:

$$|0\rangle = |\uparrow\rangle, \qquad |1\rangle = |\downarrow\rangle$$

But the electron is confined in a quantum dot, and the dot can also have **orbital excited states** or unwanted charge states.

Leakage can happen if the electron is excited out of the intended spin subspace, for example into an orbital state:

$$|\uparrow, \text{ground orbital}\rangle \quad \rightarrow \quad |\uparrow, \text{excited orbital}\rangle$$

or if the charge configuration changes, for example in singlet-triplet qubits:

$$(1,1) \rightarrow (0,2)$$

depending on the encoding and operation.

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

Control and measurement metrics

Metrics that quantify whether operations and readout are reliable enough for computation.

Metric	Meaning	Main experimental question
F_1q	Single-qubit gate fidelity	How accurately do we implement one-qubit gates?
F_2q	Two-qubit gate fidelity	How accurately do we generate entangling operations?
F_{RO}	Readout fidelity	How reliably do we convert qubit states into classical bits?
ε_{SPAM}	State-preparation and measurement error	How reliable are initialization and measurement?

Operational quality: control accuracy, measurement reliability, and initialization errors

There is no single universal number that tells us whether a quantum processor is good.

A useful device requires a balanced combination of long coherence, fast and accurate gates, reliable readout, low crosstalk, low leakage, and stable calibration.

Experimental characterization and benchmarking

Pauli Matrices as gates

The Pauli matrices can also act as single-qubit gates.

The X gate **flips the computational basis states**: $X|0\rangle = |1\rangle$ $X|1\rangle = |0\rangle$

The Z gate **changes the relative phase**: $Z|0\rangle = |0\rangle$ $Z|1\rangle = -|1\rangle$

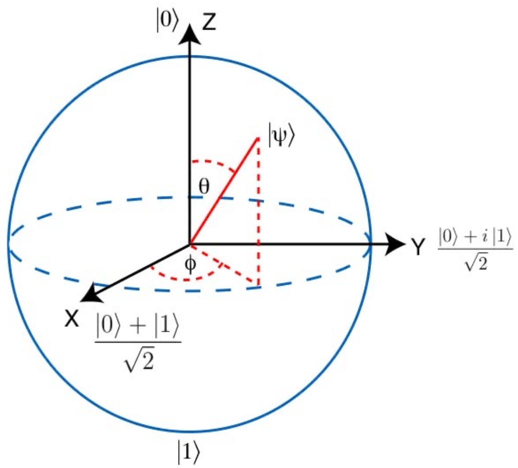
The Y gate **combines a bit flip with a phase change**:

$$Y|0\rangle = i|1\rangle, \qquad Y|1\rangle = -i|0\rangle$$

X_π: 180° rotation around the X-axis

Y_π: 180° rotation around the Y-axis

Z_π: 180° rotation around the Z-axis



T_1 Energy relaxation time

If the qubit is initialized in the excited state, the excited-state population decays approximately as:

$|\uparrow\rangle \rightarrow |0\rangle$

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

The offset term $P_{1,\infty}$ accounts for non-ideal experimental conditions, such as:

thermal population
readout offset
imperfect initialization

Physical meaning:

T_1 measures how long the qubit keeps energy before relaxing to the ground state.

T_1 measurements

Energy relaxation corresponds to decay from the excited state to the ground state:

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

through energy exchange with the environment.

X_π: 180° rotation around the X-axis (flipping)

Standard pulse sequence:

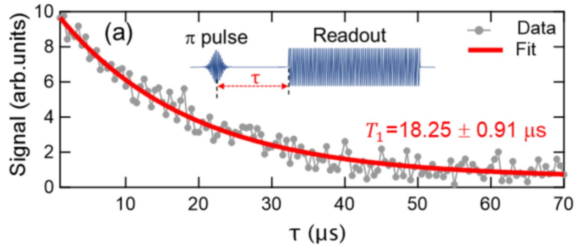
$X_\pi \rightarrow$ wait t $\rightarrow$ measure

$|0\rangle \longrightarrow X_\pi \longrightarrow |1\rangle$ wait $t \longrightarrow measure$

Experimental procedure:

1. Initialize the qubit close to $|0\rangle$
2. Apply a X_π pulse to prepare $|1\rangle$
3. Wait for a variable delay t (sweep over different t)
4. Measure the excited-state population $P1(t) = P1(0)e^{(-t/T_1)}$
5. Fit the exponential decay to extract T_1

Fig. 3: Energy relaxation time T_1 and its temporal variation.



Commun Mater **2**, 98 (2021)

A short T_1 limits circuit depth because the qubit can relax before the computation is complete.

T_1 Energy relaxation time

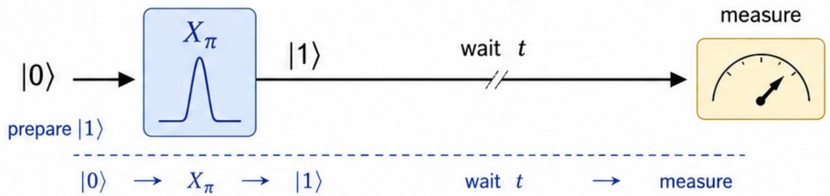
Initialize $|0\rangle \rightarrow X_\pi \rightarrow$ wait $t \rightarrow$ measure P_1

Energy relaxation corresponds to decay from the excited state to the ground state:

$$\boxed{|1\rangle \rightarrow |0\rangle}$$

through energy exchange with the environment.

Standard pulse sequence:



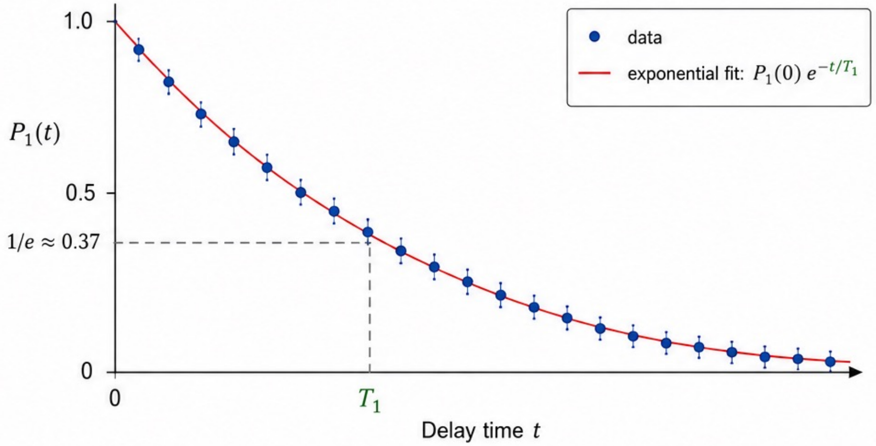
Experimental procedure:

1. Initialize the qubit close to $|0\rangle$.
2. Apply a X_π pulse to prepare $|1\rangle$.
3. Wait for a variable delay t (sweep over different t).
4. Measure the excited-state population

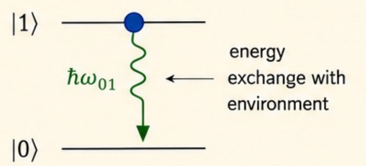
$$\boxed{P_1(t) = P_1(0)\, e^{-t/T_1}}$$

5. Fit the exponential decay to extract T_1.

Typical measurement result:



Physical picture:



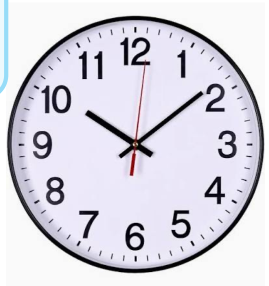
A short T_1 limits circuit depth because the qubit can relax before the computation is complete.

T_1 Energy relaxation time

Platform	Typical good T_1 scale	Key remark
Superconducting transmons	$50 - 300 \sim \mu s$	Fast gates, but shorter T_1
High-coherence superconducting qubits	$0.3 - 1 \sim \mathrm{ms}$	Best devices reach ms scale
Semiconductor spin qubits	$\mathrm{ms} - \mathrm{s}$	Long spin relaxation possible
Trapped ions	$\mathrm{s} - \mathrm{min}$	Very long-lived states
Neutral atoms	$\sim \mathrm{s}$	Long storage; Rydberg states shorter
Photonic qubits	not usually T_1-limited	Main issue is photon loss

T_2* inhomogeneous dephasing

T_2* is the characteristic decay time of phase coherence in a free-evolution experiment.
It is usually measured by Ramsey interferometry.



A useful single-qubit superposition is:

$$|\psi\rangle = \frac{|0\rangle + e^{i\phi}|1\rangle}{\sqrt{2}}$$

Dephasing randomizes the relative phase ϕ

<u>The populations may remain approximately unchanged, but the phase relation becomes uncertain.</u>

Physical meaning:

T_2* measures how long a freely evolving superposition keeps a well-defined phase.

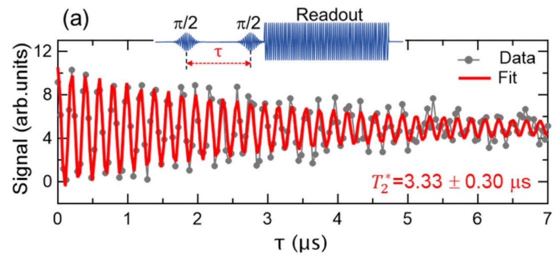
T_2* Ramsey experiments

Standard pulse sequence: $X_{\pi/2}$ →wait t → $X_{\pi/2}$ → measure

$X_{\pi/2}$: 90° rotation around the X-axis
Used to create superposition states

A typical Ramsey signal can be written as:

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



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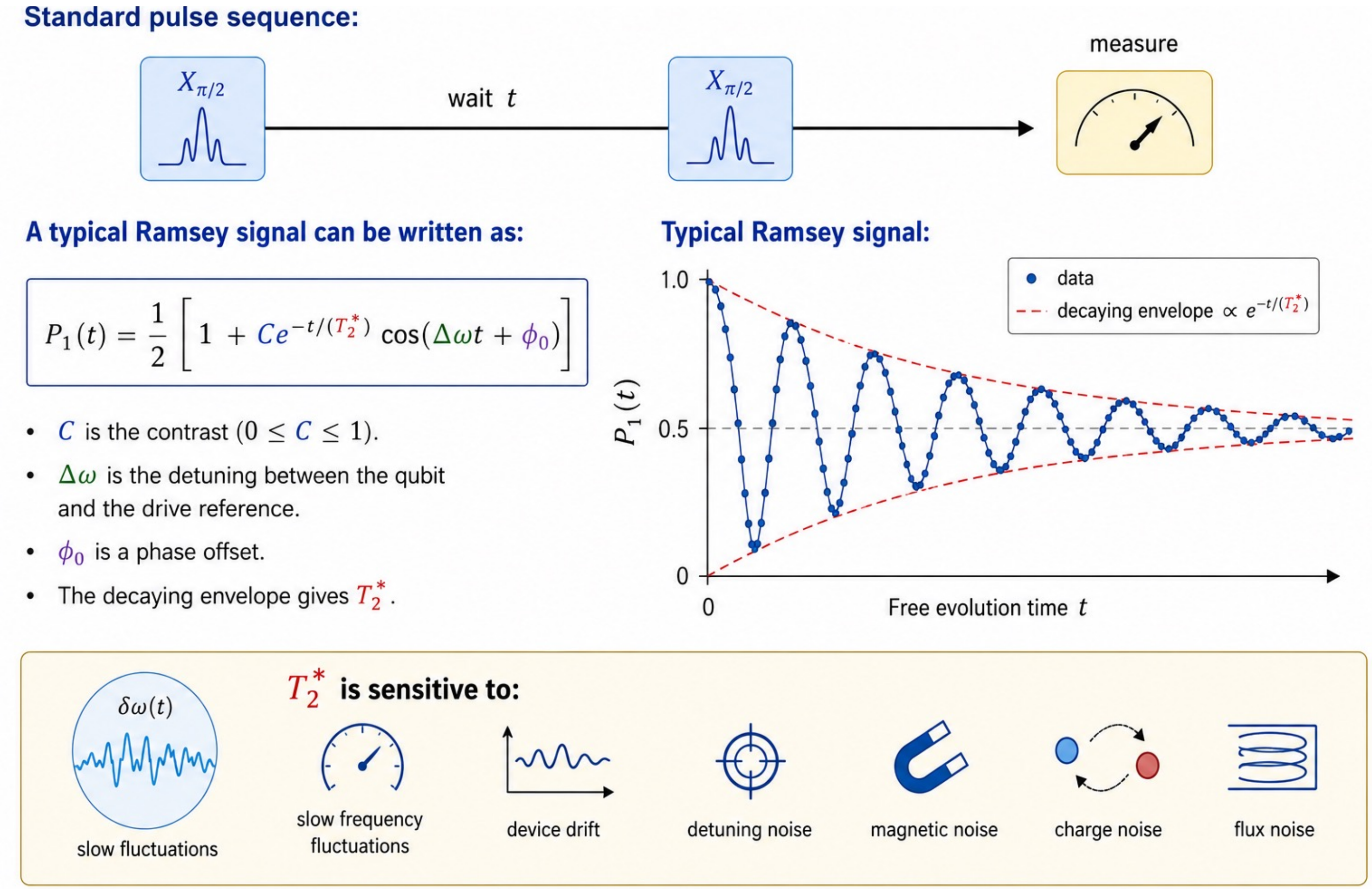
C is the contrast
$\Delta\omega$ is the detuning between the qubit and the drive reference
ϕ_0 is a phase offset

The decaying envelope gives T_2*.

T_2* is sensitive to slow frequency fluctuations, device drift, detuning noise, magnetic noise, charge noise, and flux noise.

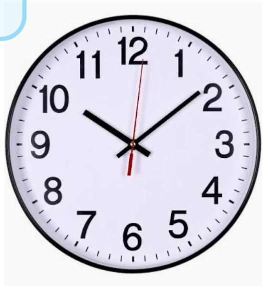
T_2* Ramsey experiments

Initialize $|0\rangle \rightarrow X_{\pi/2} \rightarrow$ wait $t \rightarrow X_{\pi/2} \rightarrow$ measure P_1



T_2,echo

T_2,echo is measured by inserting a refocusing π pulse in the middle of the free-evolution period.



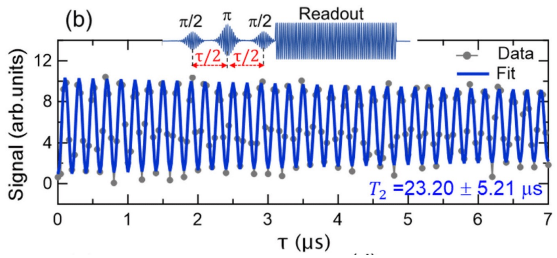
The purpose of the π pulse is to partially cancel slow or quasi-static dephasing noise.

The Hahn echo pulse sequence is:

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

The measured signal is often fit with:

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



where C is the contrast and n depends on the noise spectrum (different noise spectra can produce different decay shapes)

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n=1 corresponds to a simple exponential decay.

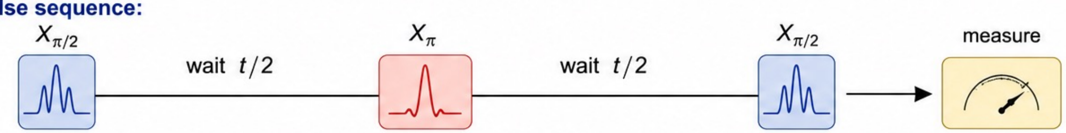
.

T_2,echo   Initialize $|0\rangle \rightarrow X_{\pi/2} \rightarrow$ wait $t/2 \rightarrow X_{\pi} \rightarrow$ wait $t/2 \rightarrow X_{\pi/2} \rightarrow$ measure P_1

$T_{2,\mathrm{echo}}$ is measured by inserting a refocusing π pulse in the middle of the free-evolution period.

The purpose of the π pulse is to partially cancel slow or quasi-static dephasing noise.

Hahn echo pulse sequence:



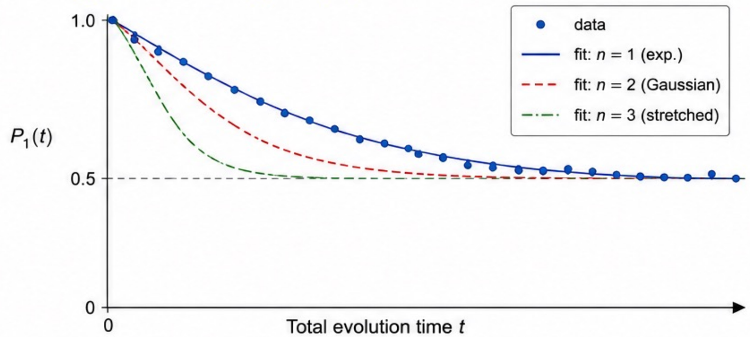
Measured signal:

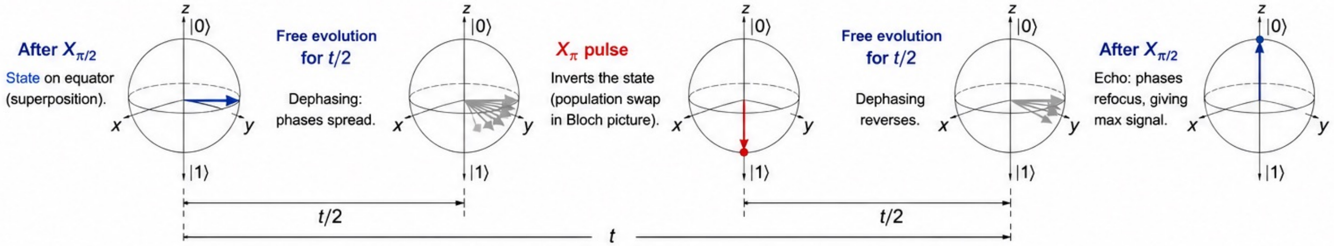
The measured excited-state probability $P_1(t)$ is often fit with:

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

- C is the contrast ($0 \leq C \leq 1$).
- $T_{2,\mathrm{echo}}$ is the echo coherence time.
- n depends on the noise spectrum (different noise spectra can produce different decay shapes).
- $n = 1$ corresponds to a simple exponential decay.

Typical echo decay (example):





Dephasing

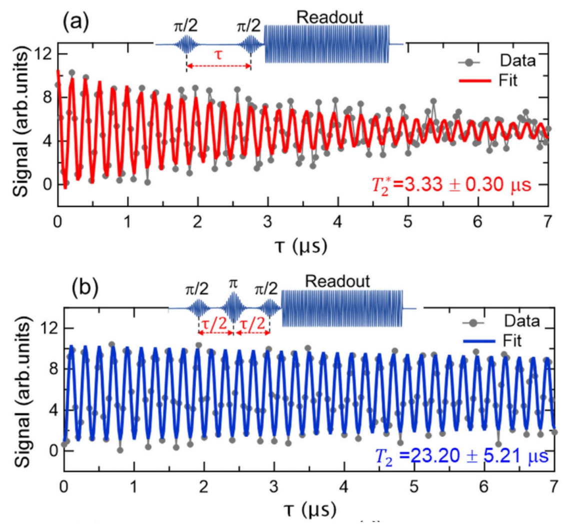
During free evolution, a small frequency shift changes the phase accumulated by the qubit.

If this shift is slow compared with the experiment, the qubit accumulates a similar unwanted phase during the first and second halves of the sequence.

The π pulse reverses the direction of phase accumulation.
As a result, slowly varying dephasing noise is partly refocused during the second half.
This is why echo experiments often give a longer coherence time than Ramsey experiments.

T_2^*

$T_{2,echo}$



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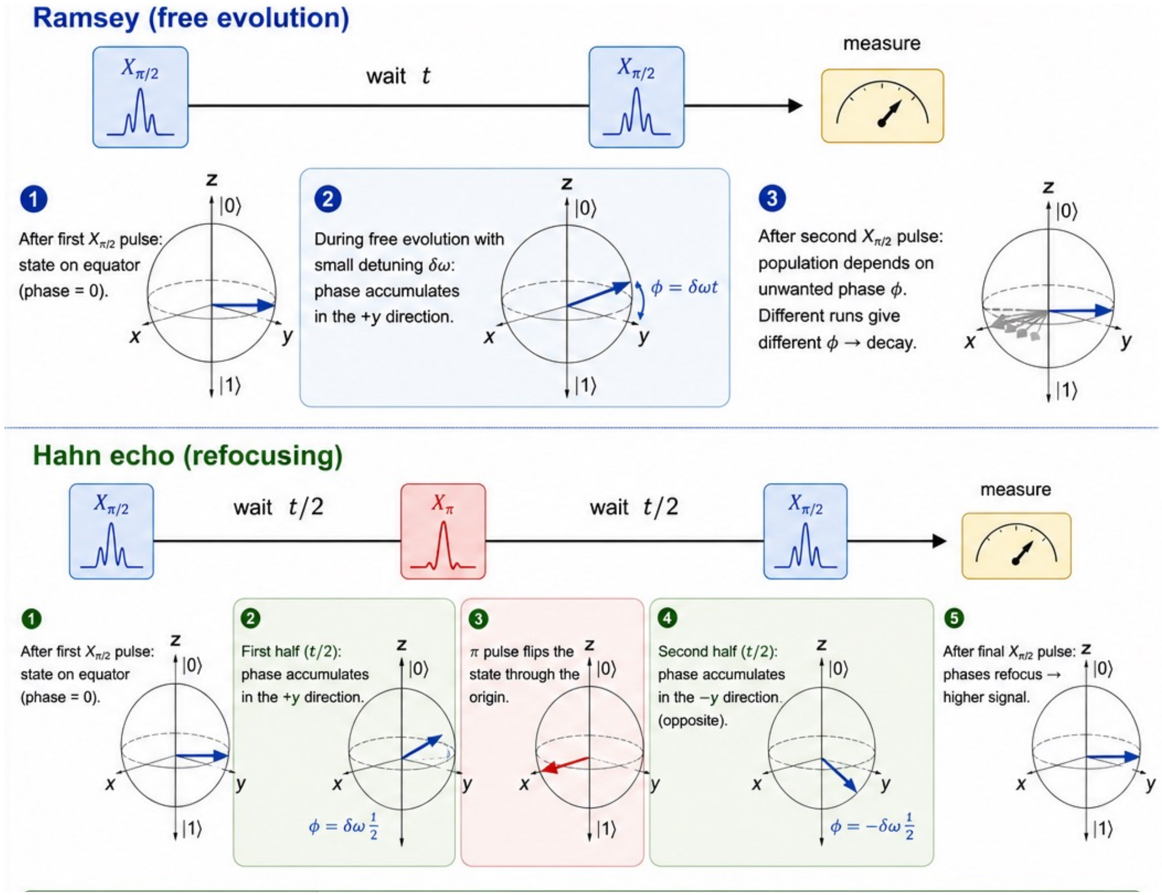
T_2^* measures free dephasing.
$T_{2,echo}$ measures coherence after refocusing slow noise.

If $T_{2,echo}$ is much longer than T_2^*, slow frequency noise is an important source of dephasing.

Relation between T_2 and T_2*

T_2*

T_2



- T_2^* measures free dephasing.
- $T_{2,\mathrm{echo}}$ measures coherence after refocusing slow noise.

If $T_{2,\mathrm{echo}}$ is much longer than T_2^*, slow frequency noise is an **important source of dephasing**.

Platform	Typical good T_2^* scale	Typical good T_2 / echo scale	Key remark
Superconducting transmons	$10 - 100\mu s$	$50 - 300\mu s$	Echo gives modest gain
High-coherence SC qubits	$0.1 - 1\text{ms}$	$0.3 - 1\text{ms}$	Best devices reach ms scale
Semiconductor spin qubits	$\text{ns} - \mu s$	$\mu s - s$	Echo can strongly improve T_2
Trapped ions	s	s–min	Very stable internal states
Neutral atoms	s	s–min	Ground states long-lived
Photonic qubits	not usually T_2-limited	not usually T_2-limited	Main issue is photon loss

Typically

$$T_2^* \leq T_2$$

Relation between T_1 T_2 and T_ϕ

T_1 measures energy relaxation.
T_2 measures loss of phase coherence.

For many qubit systems:

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

This gives the upper bound:

$$T_2 \leq 2T_1$$

Note: T_ϕ
is usually **not measured directly**

$$T_\phi = \left(\frac{1}{T_2} - \frac{1}{2T_1} \right)^{-1}$$

The term T_ϕ. describes pure dephasing: loss of phase coherence not caused by energy relaxation.
Common mistake:
A long T_1 does not automatically imply a long T_2.

A qubit may keep its energy, while still losing phase coherence through low-frequency noise.

Laboratory sequence: from spectroscopy to coherence

Qubit-State metrics

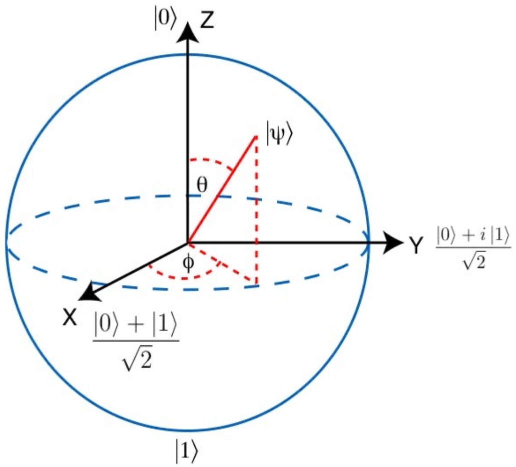
Metrics that quantify whether a physical qubit preserves quantum information.

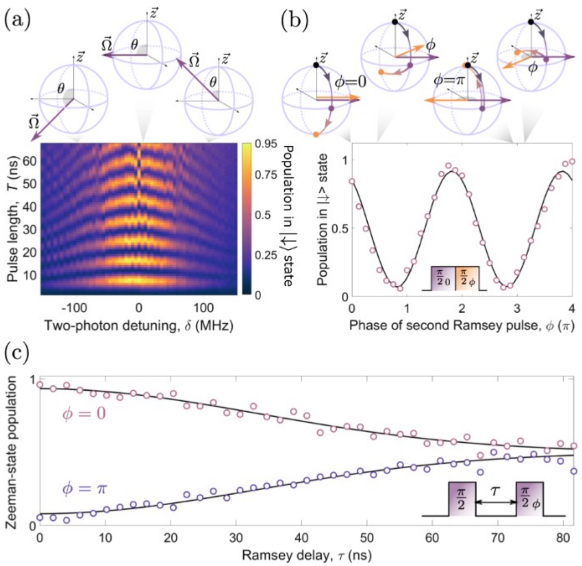
Metric	Meaning	Main experimental question
T_1	Energy relaxation time	How long does the excited-state population survive?
T_2*	Inhomogeneous dephasing time	How long does a freely evolving superposition keep phase coherence?
$T_{2,echo}$	Echo coherence time	How much slow dephasing noise can be refocused?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

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

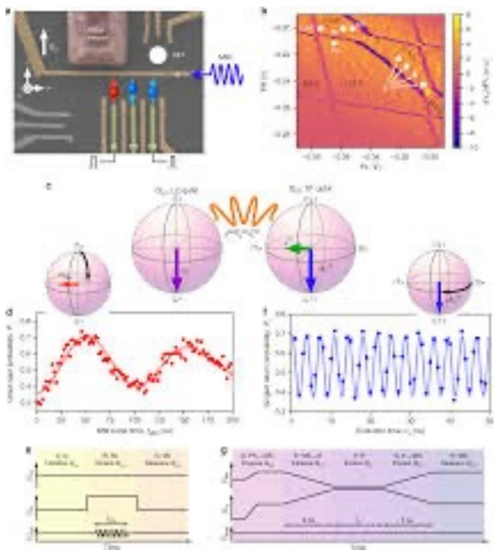
Noise

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

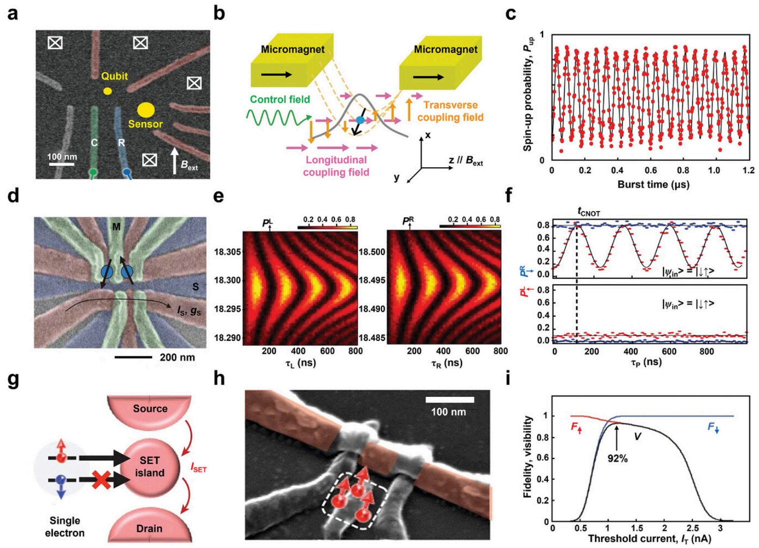




Quantum Inf 5, 95 (2019)



Nat Commun **9**, 5066 (2018)



Adv. Phys. Res., 4: 2400146

Practical characterization workflow

A qubit is not benchmarked immediately.

It is first identified, controlled, and calibrated.

Typical sequence (order matters): spectroscopy → Rabi oscillations → **T_1 → Ramsey → echo** → gate calibration → benchmarking

Spectroscopy identifies the qubit frequency.

Rabi oscillations calibrate pulse amplitude and duration.

Ramsey and echo quantify phase coherence and detuning noise.

Gate calibration refines amplitude, duration, phase, and detuning.

Benchmarking is meaningful only after the device has been properly characterized.

Qubit spectroscopy: where is the transition?

Before controlling a qubit, we must identify the relevant transition frequency.

A control field is scanned until it is resonant with the qubit transition: $\omega_d \approx \omega_{01}$

At resonance, the qubit response changes.

Depending on the platform, the control field may be microwave, radiofrequency, optical, or voltage-based.
At resonance, the drive induces transitions between the two qubit states. $|0\rangle \leftrightarrow |1\rangle$

The resonance linewidth gives qualitative information about decoherence:

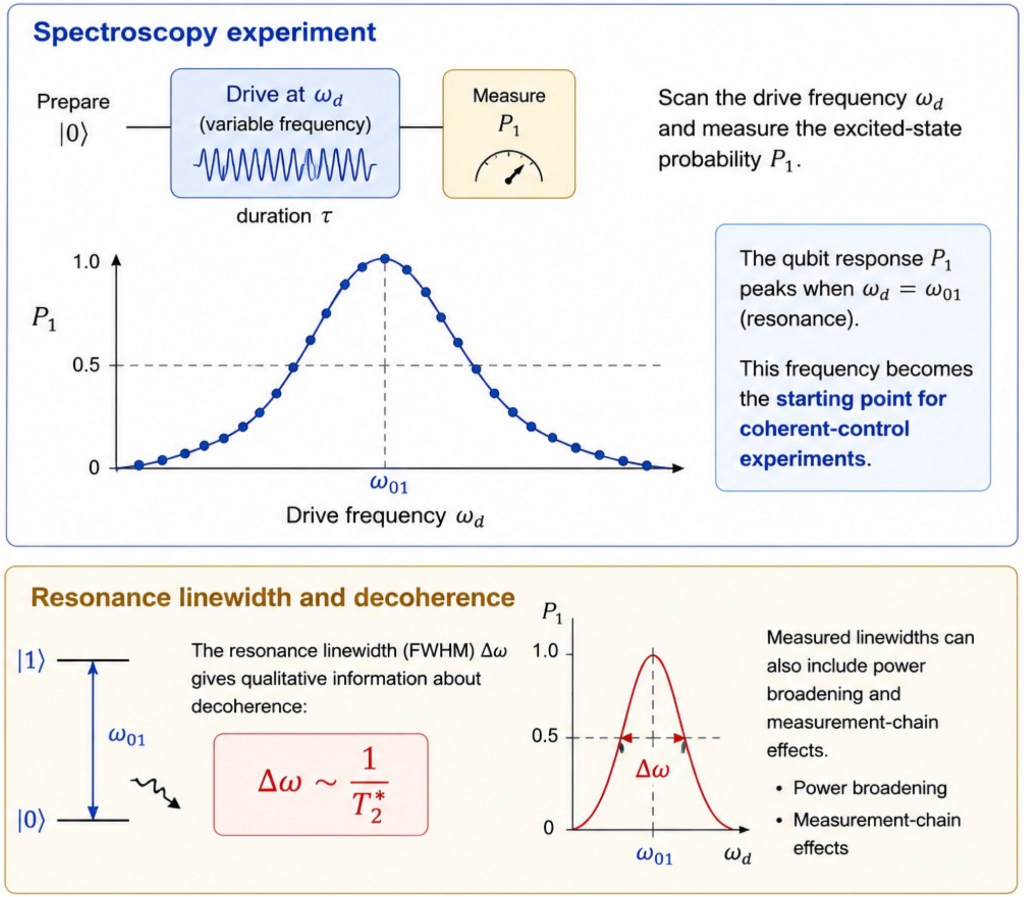
$$\Delta\omega \sim \frac{1}{T_2^*}$$

Qubits with finite coherence time cannot have a perfectly sharp transition frequency

Measured linewidths can also include power broadening and measurement-chain effects.

This frequency becomes the starting point for coherent-control experiments.

Qubit spectroscopy $|0\rangle \rightarrow \omega_d$ scan $\rightarrow$ measure P_1



Coherent control

A perfectly stable qubit transition would give a very narrow spectral line.

In reality, phase coherence lasts only for a finite time:

$$\text{coherence} \sim e^{-t/T_2^*}$$

A finite lifetime in time produces a finite width in frequency:

$$\Delta\omega \sim \frac{1}{T_2^*}$$

short T_2^* $\Rightarrow$ broad resonance
long T_2^* $\Rightarrow$ narrow resonance

The linewidth gives a first qualitative estimate of dephasing, but precise coherence times are usually measured with Ramsey and echo experiments.

Rabi oscillations (population oscillation)

Rabi oscillations calibrate the pulse duration and amplitude needed for rotations (X_{π} and $X_{\pi/2}$ for example).

A gate is the ideal mathematical operation.

A pulse is the physical signal that implements it.

In the lab, we do not apply an abstract matrix directly. We apply a microwave, laser, RF, or voltage pulse with a specific frequency, duration, amplitude, phase, and shape.

Calibration means finding the pulse parameters that make the physical pulse produce the desired quantum gate.

Rabi oscillations (population oscillation)

A resonant control pulse drives oscillations between the two qubit states.

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

For a resonantly driven qubit, the excited-state probability oscillates approximately as:

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

Ω_R is the Rabi frequency.

The pulse length or pulse amplitude is varied.

The measured oscillations identify the pulse parameters for calibrated rotations:

$$X_\pi, \quad X_{\pi/2}, \quad Y_\pi, \quad Y_{\pi/2}$$

Rabi oscillations are the experimental bridge between an abstract gate and a calibrated physical pulse.

Rabi oscillations (population oscillation)

A resonant control pulse drives population transfer between the qubit states:

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

On the Bloch sphere, this produces rotations around axes in the equatorial plane.
The pulse phase selects the rotation axis:

$$\boxed{\phi_p = \pi/2 \quad \Rightarrow \quad Y_\theta \phi_p = 0 \quad \Rightarrow \quad X_\theta}$$

Rabi oscillations are used to calibrate: $X_\pi, \quad X_{\pi/2}, \quad Y_\pi, \quad Y_{\pi/2}$

A Z rotation is different: it changes the relative phase, not the population.

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

Z_ϕ: phase rotation, usually calibrated differently

Rabi oscillations are visible because the population oscillates.
Z rotations require phase-sensitive characterization.

Rabi experiment

Pulse sequence: control pulse of variable length or amplitude → measure

<u>Procedure:</u>

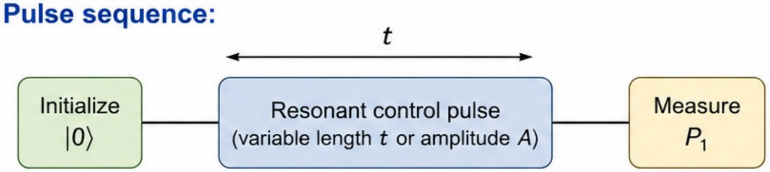
1. Initialize the qubit close to $|0\rangle$.
2. Apply a resonant control pulse.
3. Vary the pulse length or amplitude.
4. Measure the excited-state probability P_1.
5. Identify pulse parameters corresponding to: $\pi/2, \quad \pi, \quad 2\pi$

Physical interpretation:

A π pulse transfers population from $|0\rangle$ to $|1\rangle$.
A $\pi/2$ pulse creates an equal superposition.
A 2π pulse returns the qubit to its initial state.

Rabi experiment   Initialize $|0\rangle \;\rightarrow\; X_\theta \;\rightarrow\;$ measure P_1

Pulse sequence:



Drive frequency: $\omega_d \approx \omega_{01}$

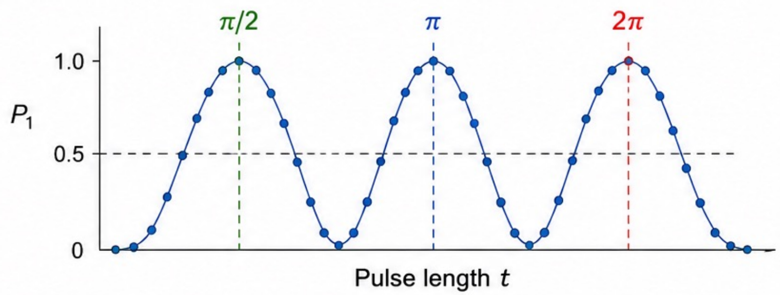
Measure: excited-state probability P_1

Procedure:

1. Initialize the qubit close to $|0\rangle$.
2. Apply a resonant control pulse.
3. Vary the pulse length t or amplitude A.
4. Measure the excited-state probability P_1.
5. Identify pulse parameters corresponding to:

$\pi/2$ π 2π

Measured signal (Rabi oscillations):

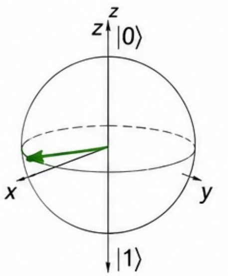


Physical interpretation:

$\pi/2$ pulse

Creates an equal superposition.

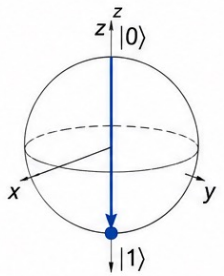
State on equator of Bloch sphere.



π pulse

Transfers population from $|0\rangle$ to $|1\rangle$.

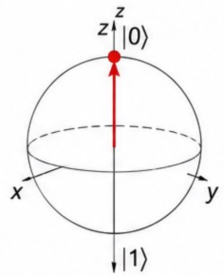
State at south pole.



2π pulse

Returns the qubit to its initial state.

State back at north pole ($|0\rangle$).



Gate time vs coherence time

A useful dimensionless estimate is:

$$N_{coh} \sim \frac{T_2}{t_{gate}}$$

It gives a simple intuition: the gate time should be much shorter than the coherence time.

A large value of N_{coh} means that many gate operations can, in principle, fit within the coherence time.

However, fast gates are not automatically high-fidelity gates.

Gate accuracy also depends on: pulse calibration, leakage, crosstalk, control noise, environmental noise…

Fast gates are useful only if they are also accurately calibrated and remain inside the computational subspace.

Leakage

A physical qubit often has more than two energy levels:

$$|0\rangle, \quad |1\rangle, \quad |2\rangle, \quad |3\rangle, \ldots$$

The computational subspace is only: $\{|0\rangle, |1\rangle\}$

Leakage occurs when population leaves this subspace.

For example: $|1\rangle \rightarrow |2\rangle$

This is different from a bit-flip or phase error.
In a bit-flip or phase error, the state remains inside the qubit subspace.

In leakage, part of the state is no longer encoded in the qubit.

Leakage reduces the validity of the two-level approximation.
A good physical qubit must keep the dynamics inside the computational subspace.

Pulse shaping and leakage suppression

An ideal gate is a unitary operation on the computational subspace.
A physical gate is a time-dependent control pulse applied to a real multi-level system.

Short pulses reduce gate time, but they broaden the pulse spectrum.

Broad spectral content can drive unwanted transitions, for example: $|1\rangle \rightarrow |2\rangle$

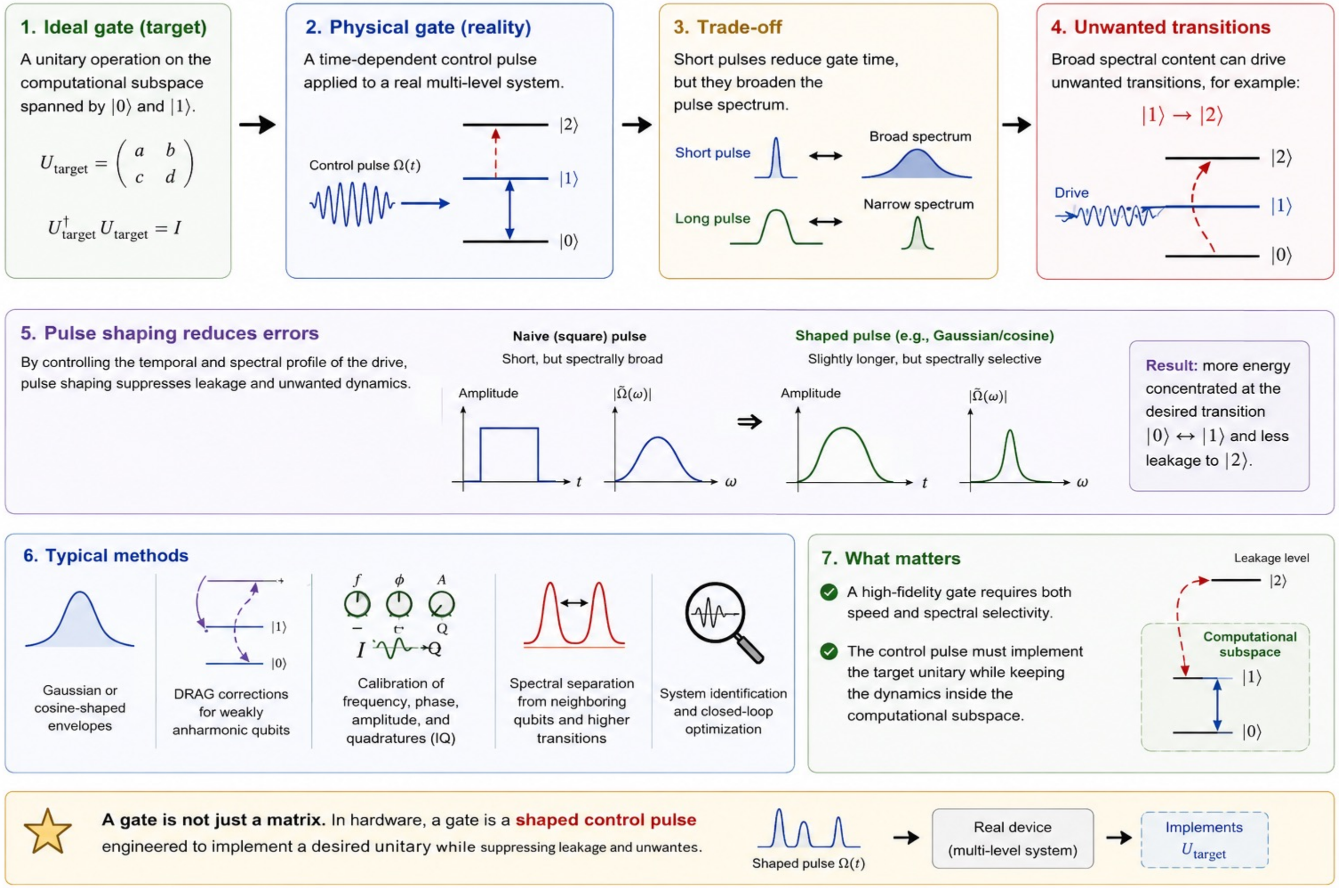
Pulse shaping reduces these errors by controlling the temporal and spectral profile of the drive.

Typical methods include: Gaussian or cosine-shaped envelopes, DRAG corrections for weakly anharmonic qubits, calibration of frequency, phase, amplitude, and quadratures, spectral separation from neighboring qubits and higher transitions…

A high-fidelity gate requires both speed and spectral selectivity.

The control pulse must implement the target unitary while keeping the dynamics inside the computational subspace.

Pulse shaping and leakage suppression



Gate fidelity: ideal vs real operations

An ideal quantum gate is represented by a unitary operation U.
In the laboratory, the implemented operation is a noisy physical process, denoted $\boldsymbol{E}$

Gate fidelity quantifies how close the experimental operation is to the target gate.

For a pure input state, define: $\rho_\psi = |\psi\rangle\langle\psi|$

A state-dependent fidelity can then be written as: $F(\psi) = \langle\psi|U^\dagger E(\rho_\psi)U|\psi\rangle$

In practice, experiments usually report an average gate fidelity over a suitable set or distribution of input states. Gate fidelity measures whether the physical pulse implements the intended quantum operation.

<u>Single-qubit gates are usually easier than two-qubit gates.</u>
Two-qubit gates are often the dominant bottleneck because they require controlled interactions, synchronization, and suppression of crosstalk and leakage

Readout fidelity: from qubits to bits

Measurement maps a quantum state onto a classical result.

Ideally: $|0\rangle \rightarrow 0, \qquad |1\rangle \rightarrow 1$

<u>In reality, measurement errors occur:</u> $P(1|0) > 0, \qquad P(0|1) > 0$

The two assignment fidelities are: $F_0 = P(0|0), \qquad F_1 = P(1|1)$

The average readout fidelity is: $F_{RO} = \frac{F_0+F_1}{2}$

The readout assignment matrix is:

$$Measured\ 1 \quad P(1|0) \quad P(1|1)$$

Readout fidelity measures how reliably the physical measurement converts qubit states into classical bits.

SPAM (preparation and measurement) errors

SPAM means state preparation and measurement.

SPAM errors include imperfect initialization, thermal population, pulse errors during preparation, and readout assignment errors.

Common mistake to avoid. A measured error rate in a simple experiment may include gate error and SPAM error.

Separating them requires careful protocols.

Single-Qubit tomography

Quantum state tomography is the reconstruction of a quantum state from measurement data.

For one qubit, the density matrix can be written in the Pauli basis:

$$\rho = \frac{1}{2}(I + \langle X \rangle X + \langle Y \rangle Y + \langle Z \rangle Z)$$

Therefore, a single-qubit state can be reconstructed by measuring three expectation values:

$$\langle X \rangle, \qquad \langle Y \rangle, \qquad \langle Z \rangle$$

These are the components of the Bloch vector.

Physical meaning:
$\langle Z \rangle$ tells us the population imbalance between $|0\rangle$and $|1\rangle$.
$\langle X \rangle$ and $\langle Y \rangle$ tell us about coherences and relative phase.

Tomography connects the abstract density matrix to experimentally measurable Pauli averages.

Single-Qubit tomography

Why does tomography not scale?

Full state tomography for n qubits requires a number of measurements that grows exponentially with n.

Process tomography is even more demanding, because it attempts to reconstruct an entire quantum operation.

Tomography is conceptually clean and useful for small systems, but it does not scale to large processors.

Randomized benchmarking

Randomized benchmarking estimates the average error rate of gates without requiring full process tomography.

The standard idea is:

random Clifford sequence → inverse Clifford → measure survival probability

The survival probability is fitted as a function of sequence length m:

$$P(m) = Ap^m + B$$

The parameter p is related to the average error per Clifford.
The constants A and B absorb state-preparation and measurement effects.

Randomized benchmarking asks:
How rapidly do errors accumulate when many gates are applied?

Randomized benchmarking

A **Clifford gate** is a quantum gate that maps Pauli operators to Pauli operators under conjugation.

$$CPC^{\dagger} = P'$$

where P and P' are Pauli operators.

Geometrically, single-qubit Clifford gates rotate the Bloch sphere so that the X, Y, and Z axes are mapped onto each other.

In randomized benchmarking, Clifford gates are useful because they are easy to invert and their error accumulation can be efficiently analyzed.

Interleaved and simultaneous RB

- *Interleaved RB estimates the error of a specific gate by inserting it between random Clifford operations.*

- *Simultaneous RB runs benchmarking sequences on multiple qubits at the same time to reveal crosstalk and parallel-operation errors.*

Cross-entropy benchmarking

Cross-entropy benchmarking is commonly used for random circuit sampling experiments.

The basic idea is to compare measured bitstring probabilities with the probabilities predicted for the ideal circuit.

This is useful for testing complex circuits, but it is not a universal application-level measure of useful quantum computation.

Other benchmarking

Quantum volume, layer fidelity, and circuit-level benchmarks

Processor-level performance depends on more than isolated gate fidelity.

Relevant quantities include:
quantum volume, layer fidelity, CLOPS, algorithmic benchmarks.

A component metric is not the same as application performance.

Real circuits expose connectivity overhead, crosstalk, leakage, calibration drift, compiler choices, and readout Type equation here.errors.

Circuit level metrics

Isolated gate metrics are not enough.

Useful quantum circuits depend on the accumulation of many errors across the full experiment.

A rough circuit error budget can be written as:

$$\epsilon_{total} \sim N_{1q}\epsilon_{1q} + N_{2q}\epsilon_{2q} + N_{meas}\epsilon_{meas} + \epsilon_{idle} + \epsilon_{crosstalk} + \epsilon_{leak}$$

This is not a rigorous formula. It is a compact way to understand why deep circuits fail.
Each term represents a different contribution to the total circuit error:

$N_{1q}\epsilon_{1q}$ **single-qubit gate errors**
$\boldsymbol{N_{2q}\epsilon_{2q}}$ **two-qubit gate errors**
$N_{meas}\epsilon_{meas}$ **measurement errors**
ϵ_{idle} **errors accumulated while qubits wait**
$\epsilon_{crosstalk}$ unwanted effects from simultaneous operations
ϵ_{leak} population leaving the computational subspace

A processor is not judged only by its best gate. It is judged by how errors accumulate across a full circuit.

NISQ metrics vs Fault – Tolerant metrics

As quantum processors move toward error correction, the relevant question shifts from physical-device performance to logical reliability.

Category	NISQ / Early-Device Metrics	Fault-Tolerant Metrics
Scale	Number of physical qubits	Number of logical qubits
Gate quality	Single- and two-qubit fidelities	Logical error rate
Memory	Coherence times	Logical lifetime
System performance	Quantum volume, layer fidelity, CLOPS	Code distance and threshold behavior
Circuit execution	Circuit depth and success probability	Decoder speed and physical-to-logical overhead

NISQ metrics characterize noisy hardware.
Fault-tolerant metrics characterize the ability to protect and process logical quantum information at scale.

What makes a good physical qubit?

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?

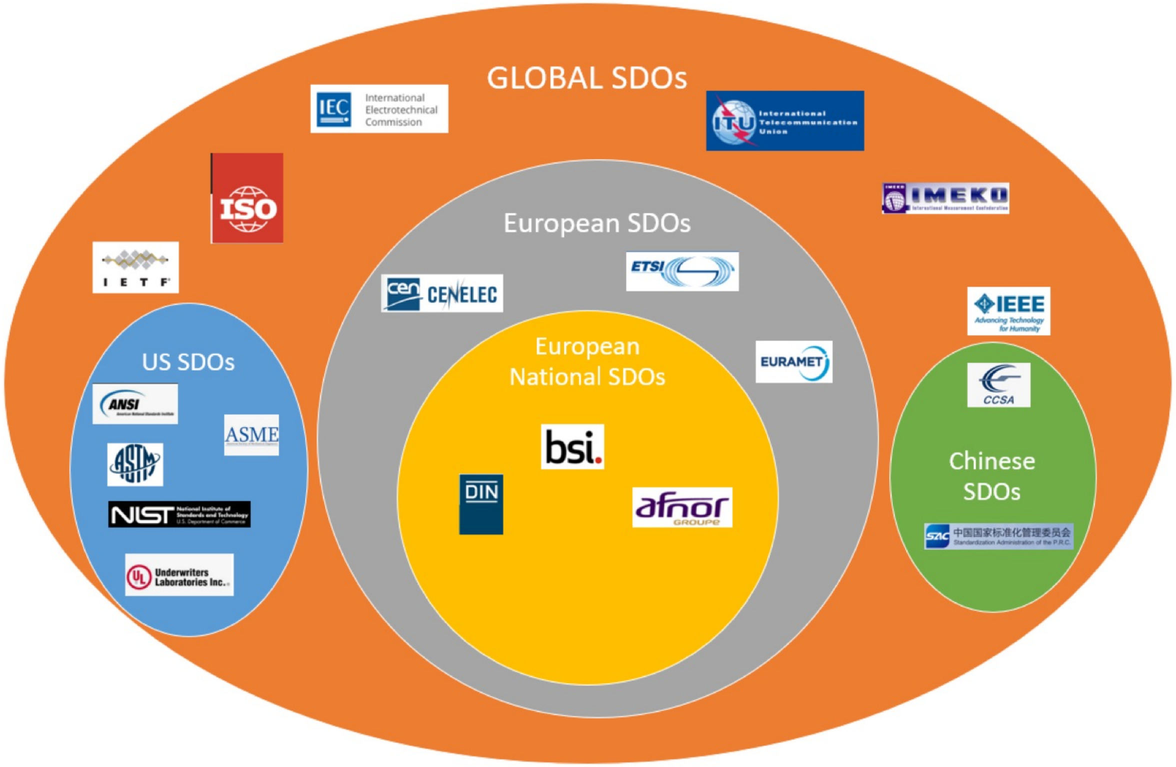
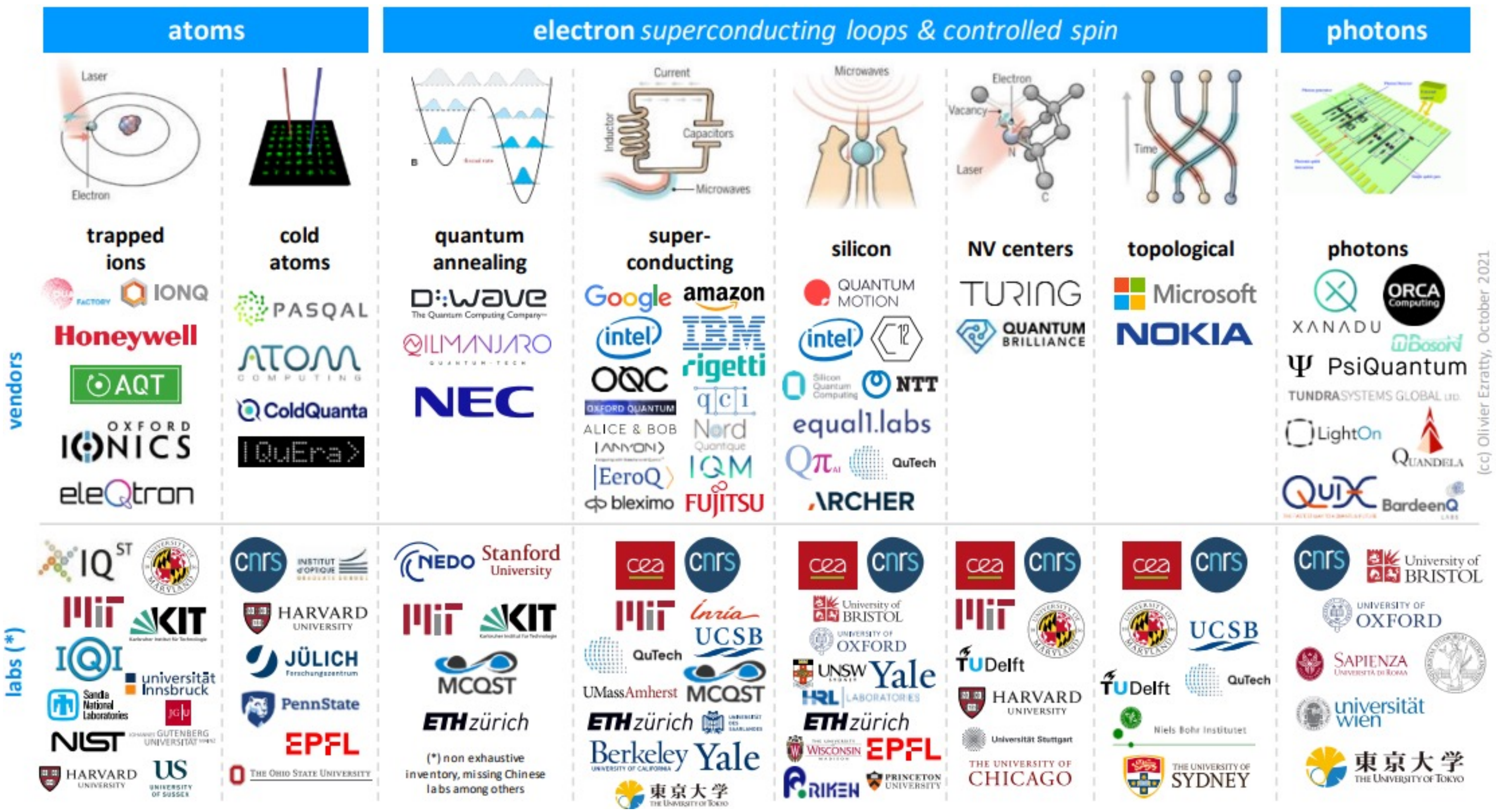


Figure 0-1: The standardisation ecosystem for QTs

Qubits


atoms
electron superconducting loops & controlled spin
photons
trapped ions
cold atoms
quantum annealing
super-conducting
silicon
NV centers
topological
photons
vendors
labs (*)
(*) non exhaustive inventory, missing Chinese labs among others
(cc) Olivier Ezratty, October 2021

Thank you
for your attention

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