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Elements of Quantum Computing and Qubits

Mattia Checchin

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18 – 20 July 2018

Outline

- * Introduction
- * What is a qubit?
- * How does a qubit work?
- * Quantum state manipulation
- * Qubit readout
- * Quantum computing R&D at Fermilab
- * Conclusions

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* Introduction

* What is a qubit?

* How does a qubit work?

* Quantum state manipulation

* Qubit readout

* Quantum computing R&D at Fermilab

* Conclusions

I - What is a quantum computer?

- * A quantum computer is a computation framework based on quantum mechanics phenomena:
 - Superposition of states
 - Entanglement
- * The computational building block of quantum computers are so-called qubits (quantum bits)
- * Any qubit is a quantum system defined by ground $|0\rangle$ and excited $|1\rangle$ states
- * A quantum computer would have many qubits coupled together, along with input control lines and output measurement lines
- * The first step in operating a quantum computer would be to prepare all the qubits in the ground state:

$$|\Psi(0)\rangle = |0\rangle|0\rangle|0\rangle|0\rangle|0\rangle \dots |0\rangle|0\rangle|0\rangle|0\rangle|0\rangle$$

II - What is a quantum computer?

- * A quantum computer performs “gate operations” by applying a perturbation (force, current, voltage, magnetic field, photon, rf drive...) to the qubits
- * Any gate outcome is a transformation of the qubit state which will evolve from the ground state $|\Psi(\mathbf{0})\rangle$ to the state $|\Psi(\mathbf{t})\rangle$ in a time t
- * The perturbation lasts for a specified time and the time-evolution of the state is completely deterministic! With the right perturbation you could flip any qubit state from 0 to 1 (NOT) or perform other operations....
- * After a series of gates, each qubit may be left in 0, or in 1, or in an entangled quantum superposition of 0 and 1... both 0 and 1 simultaneously and correlated with the state of other qubits ... a very non-classical result
- * The state of each qubit is then measured, producing a result of the calculation: a string of $|0\rangle$ and $|1\rangle$. **The result is probabilistic!**

What's the deal?

- * Let's assume a 2 bit register. All the possible states the system can access is:

$$State = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{cases} 00 \\ 01 \\ 10 \\ 11 \end{cases} \Rightarrow \mathbf{2^2 = 4 \text{ possible states}}$$

- * Let's now assume a 2 qubit quantum register. Since the qubit can be 0 and 1 simultaneously, the quantum register is defined by the superposition of states $\left| \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\rangle$ (as if we had 4 PC working in parallel). All the possible states the system can access is:

$$|\Psi\rangle = a_1 \underbrace{\left| \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\rangle}_{\begin{matrix} a_1 \\ \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix} \end{matrix}} + a_2 \underbrace{\left| \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\rangle}_{\begin{matrix} a_2 \\ \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix} \end{matrix}} + a_3 \underbrace{\left| \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\rangle}_{\begin{matrix} a_3 \\ \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix} \end{matrix}} + a_4 \underbrace{\left| \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\rangle}_{\begin{matrix} a_4 \\ \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix} \end{matrix}} ; \sum_i^n |a_i|^2 = 1$$

$$\Rightarrow \mathbf{2^{2^2} = 16 \text{ possible states!}}$$

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What is a qubit?

* Classical bit:

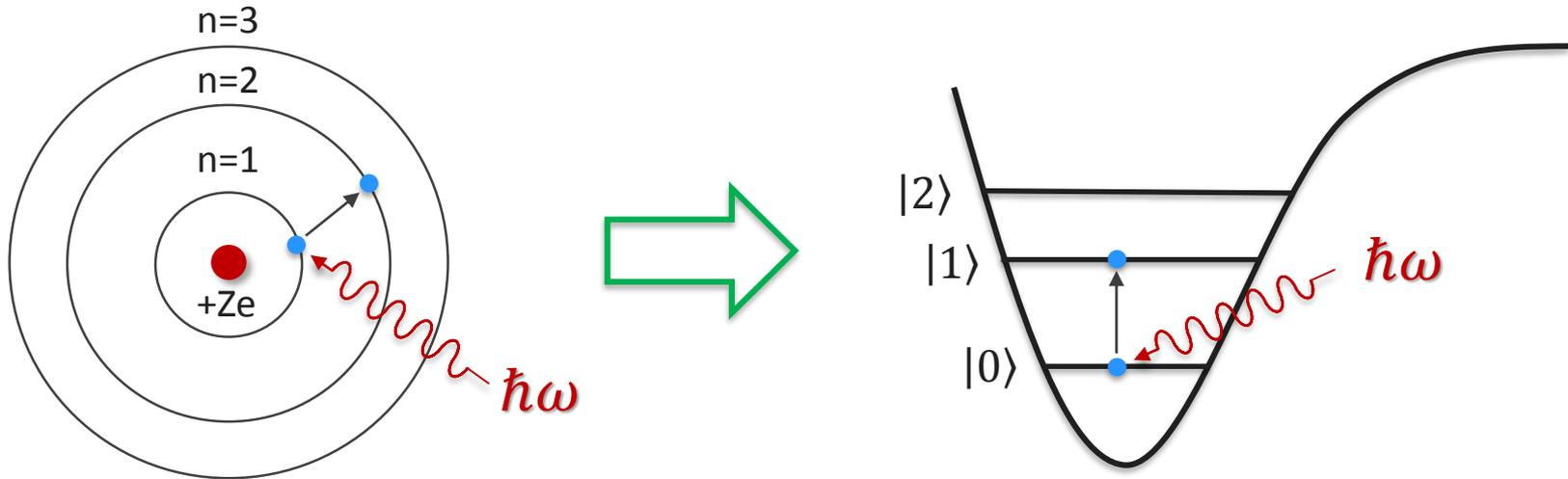
- Based on transistor
- Described by 2 possible states:
 - 0 – “off”
 - 1 – “on”

* Quantum bit:

- ANY two energy levels quantum system
- Described by the linear combination ($|\Psi\rangle$) of 2 quantum states
 - $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$
 - $|0\rangle$ – ground state
 - $|1\rangle$ – excited state
- $|\alpha|^2$ and $|\beta|^2$ probabilities that the qubit is in the state $|0\rangle$ or $|1\rangle$ respectively

Atoms: natural qubits

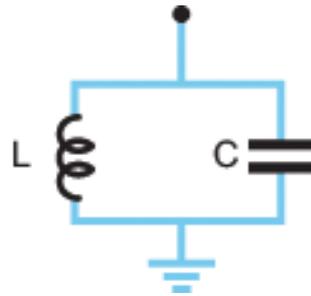
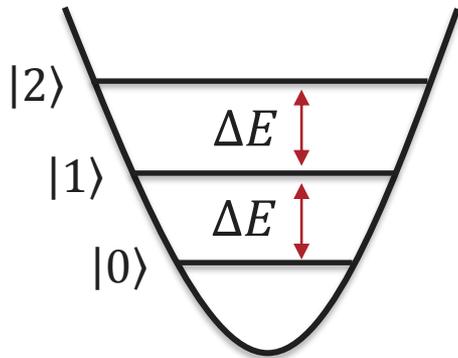
- * Nature already provide us with qubits: ATOMS!



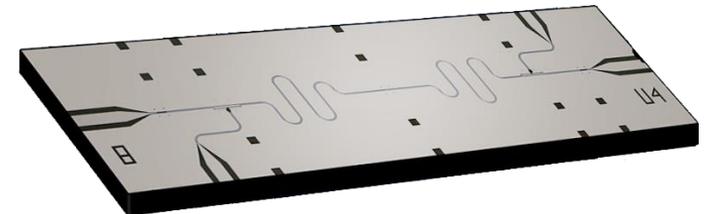
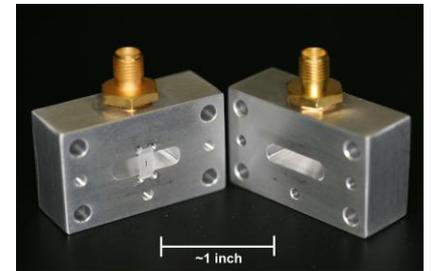
- * I can select an electronic transition between two orbitals and define a two level system
- * HOWEVER, atoms are difficult to manipulate, electronic transitions are in the range of visible/UV spectrum, etc...

Resonators: not yet qubits

- * If we take a single resonant mode of any resonator, it looks like a harmonic oscillator

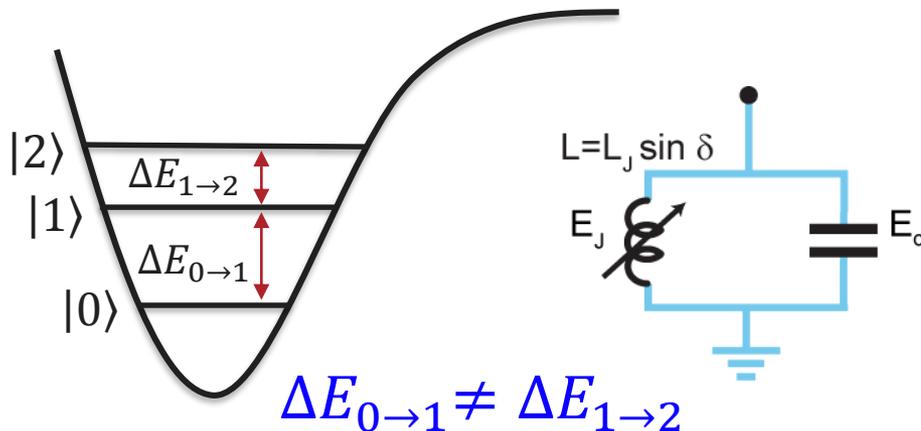


- * HOWEVER, the energy separation between levels is even \Rightarrow I cannot select a specific transition



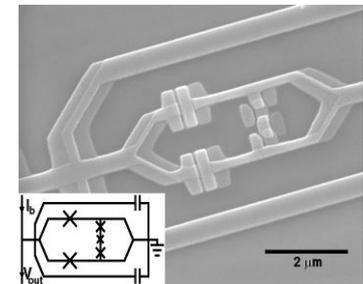
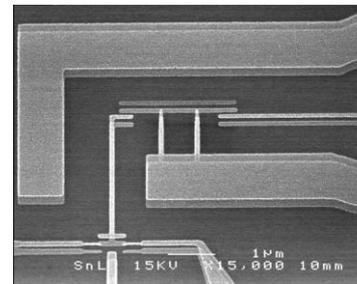
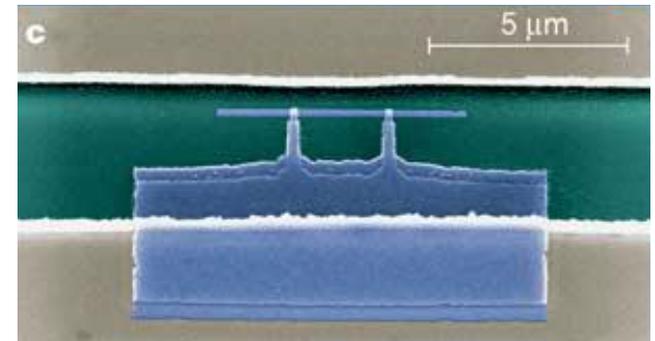
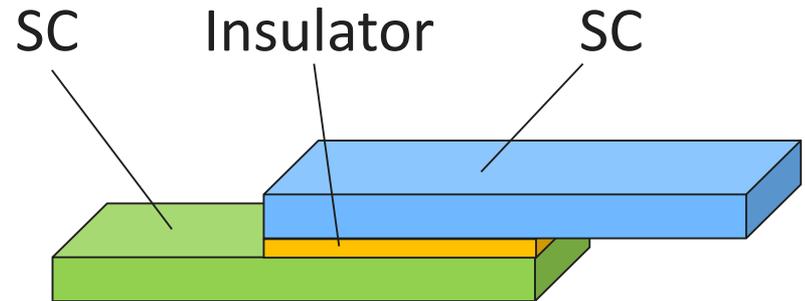
Superconducting qubits

- * As of now the most adopted
- * Based on Josephson junctions: non-linear inductors



- * Behaves as an anharmonic LC resonator, transitions can be tuned in the microwave spectra
 \Rightarrow **a perfect artificial atom!**

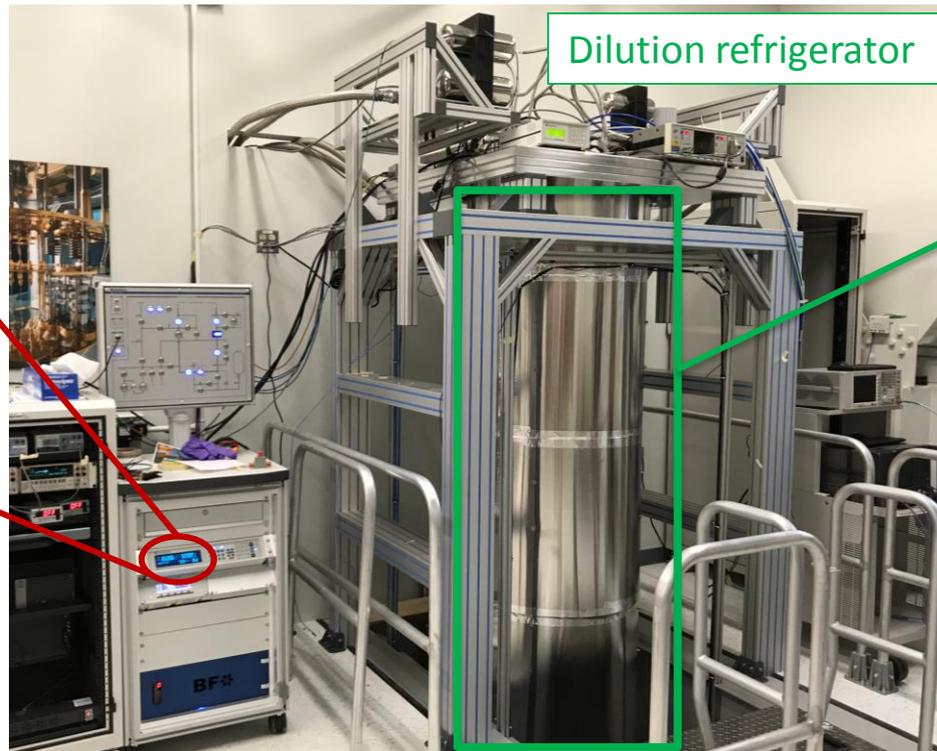
Schematics of a Josephson junction



Typical layout of a quantum computation experiment

- * Very low temperature (milli-Kelvin) are mandatory to avoid thermal excitation of the qubit!

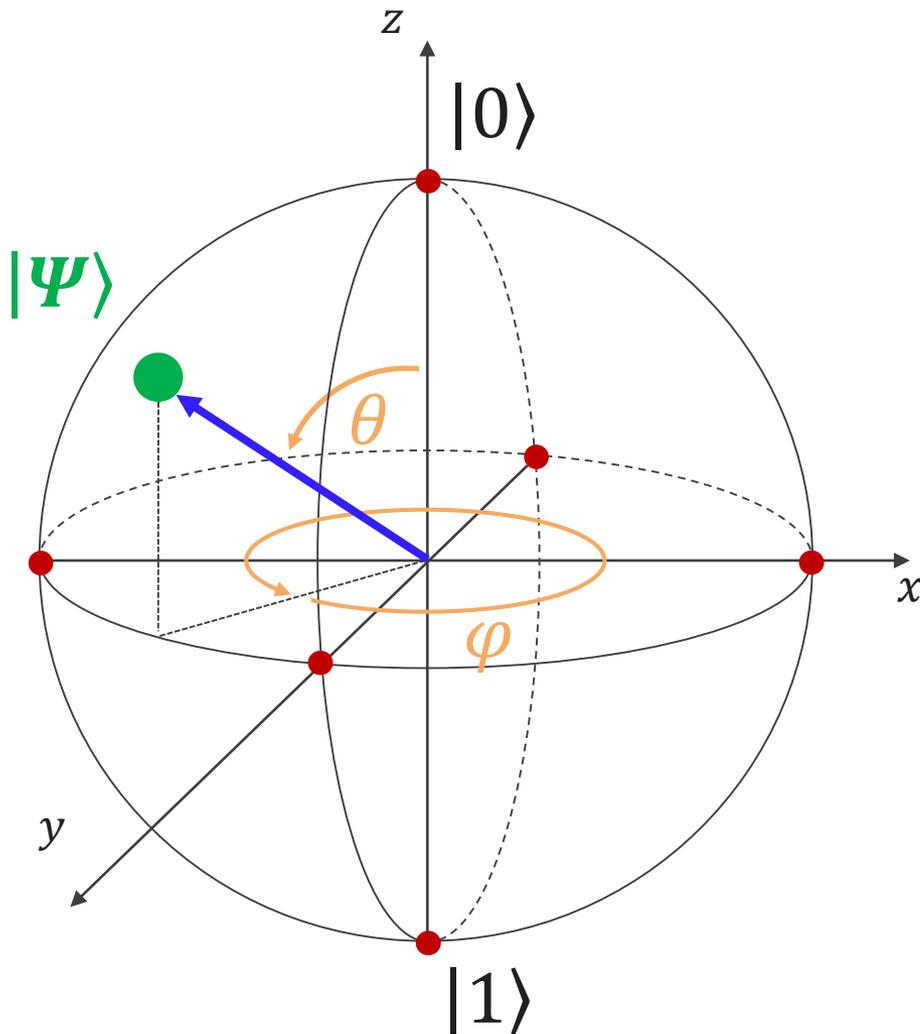
$$\kappa_B T < \hbar \omega$$



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The Bloch sphere



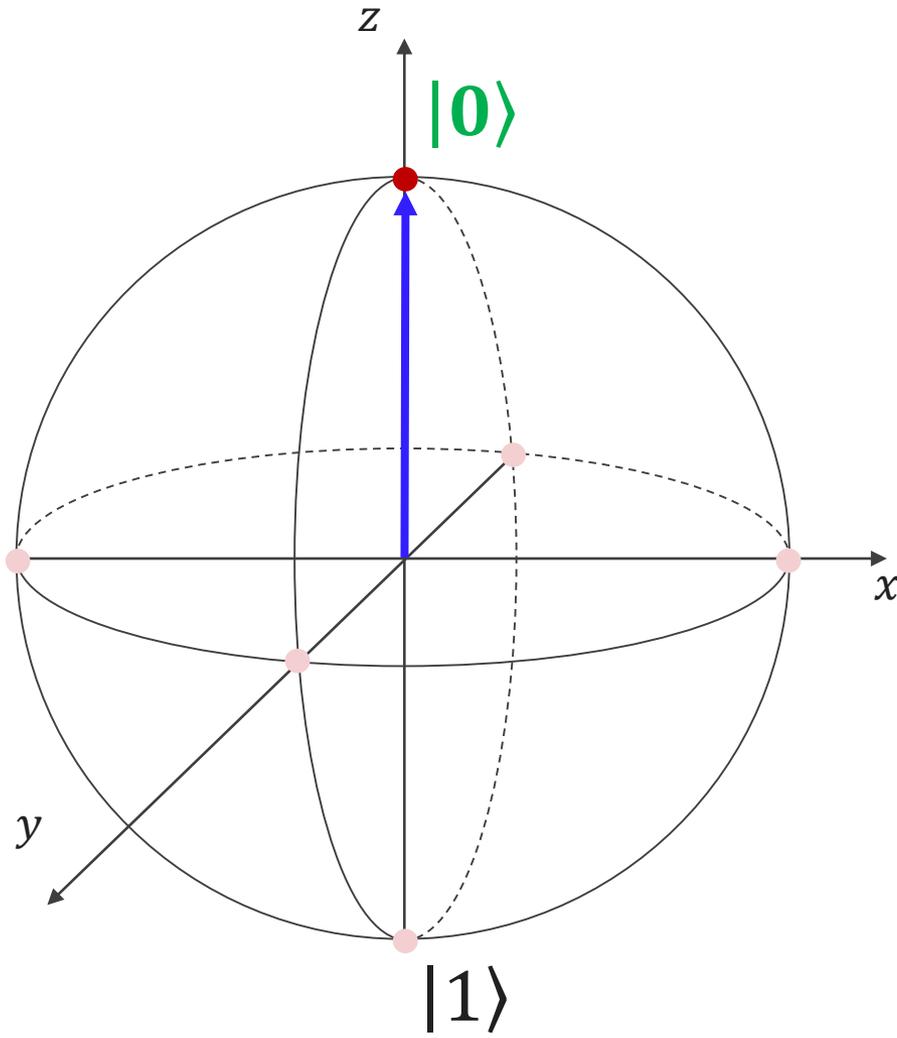
Any pure quantum state of a qubit can be visualized as a point on a unit sphere. This is the “Bloch sphere”.

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

Where:

- * $\alpha = \cos\left(\frac{\theta}{2}\right)$
- * $\beta = e^{i\varphi}\sin\left(\frac{\theta}{2}\right)$
- * $|\alpha|^2 + |\beta|^2 = 1$

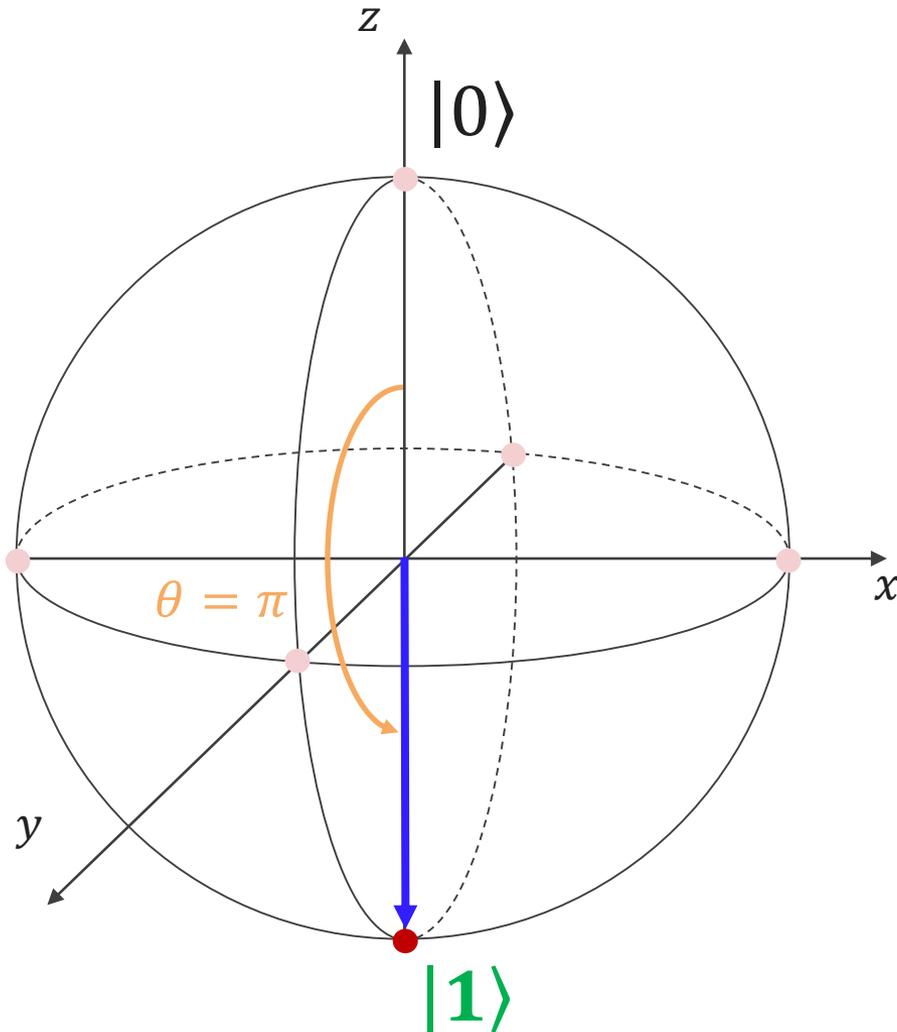
The Bloch sphere: example 1



* $\theta = 0$

$$\begin{aligned} |\Psi\rangle &= \cos\left(\frac{\theta}{2}\right) |0\rangle + e^{i\varphi} \sin\left(\frac{\theta}{2}\right) |1\rangle \\ &= \cos(0) |0\rangle + e^{i\varphi} \sin(0) |1\rangle \\ &= |0\rangle \end{aligned}$$

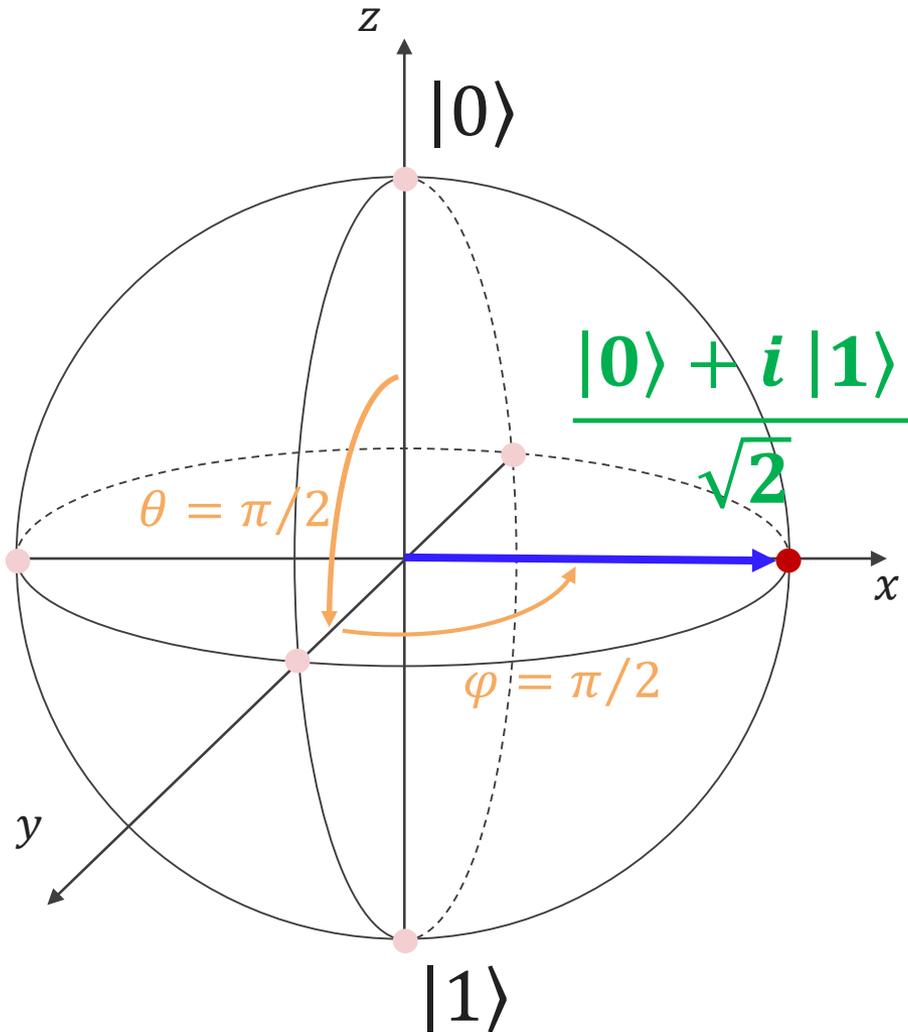
The Bloch sphere: example 2



* $\theta = \pi$

$$\begin{aligned} |\Psi\rangle &= \cos\left(\frac{\theta}{2}\right) |0\rangle + e^{i\varphi} \sin\left(\frac{\theta}{2}\right) |1\rangle \\ &= \cos\left(\frac{\pi}{2}\right) |0\rangle + e^{i\varphi} \sin\left(\frac{\pi}{2}\right) |1\rangle \\ &= e^{i\varphi} |1\rangle \end{aligned}$$

The Bloch sphere: example 3



* $\theta = \pi/2, \varphi = \pi/2$

$$\begin{aligned} |\Psi\rangle &= \cos\left(\frac{\theta}{2}\right) |0\rangle + e^{i\varphi} \sin\left(\frac{\theta}{2}\right) |1\rangle \\ &= \cos\left(\frac{\pi}{4}\right) |0\rangle + e^{i\frac{\pi}{2}} \sin\left(\frac{\pi}{4}\right) |1\rangle \\ &= \frac{|0\rangle + i |1\rangle}{\sqrt{2}} \end{aligned}$$

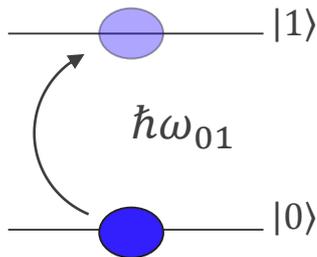
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I - Qubit driven at the transition frequency

- * Let's assume a qubit with transition energy ΔE
- * The qubit is at its ground state $|0\rangle$
- * Let's apply a EM perturbation with frequency $\omega_{01} = \Delta E/\hbar$
- * The qubit state will evolve with time:

$$|\Psi(t)\rangle = \alpha(t) |0\rangle + \beta(t) |1\rangle$$



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

$$|\beta|^2 = 0$$

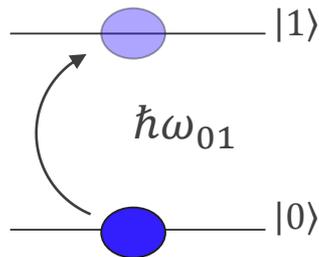


Ground state

II - Qubit driven at the transition frequency

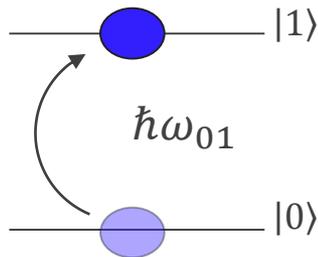
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$$|\alpha|^2 = 1$$

$$|\beta|^2 = 0$$



$$|\alpha|^2 = 0$$

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

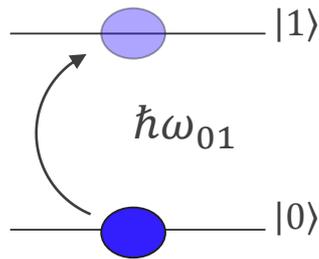


Absorption

III - Qubit driven at the transition frequency

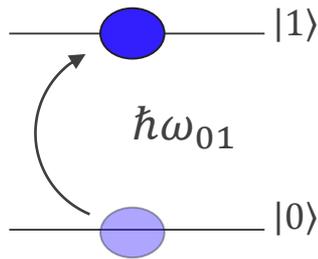
- * Let's assume a qubit with transition energy ΔE
- * The qubit is at its ground state $|0\rangle$
- * Let's apply a EM perturbation with frequency $\omega_{01} = \Delta E/\hbar$
- * The qubit state will evolve with time:

$$|\Psi(t)\rangle = \alpha(t) |0\rangle + \beta(t) |1\rangle$$



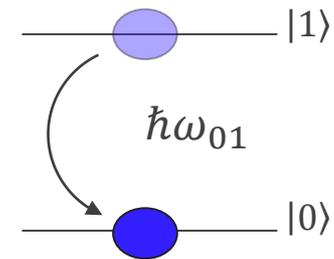
$$|\alpha|^2 = 1$$

$$|\beta|^2 = 0$$



$$|\alpha|^2 = 0$$

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



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

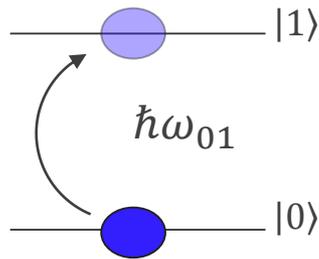
$$|\beta|^2 = 0$$

Stimulated emission

IV - Qubit driven at the transition frequency

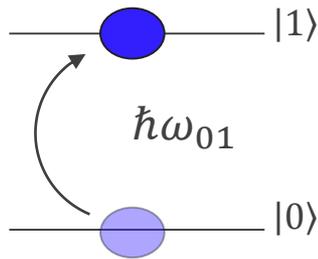
- * Let's assume a qubit with transition energy ΔE
- * The qubit is at its ground state $|0\rangle$
- * Let's apply a EM perturbation with frequency $\omega_{01} = \Delta E/\hbar$
- * The qubit state will evolve with time:

$$|\Psi(t)\rangle = \alpha(t) |0\rangle + \beta(t) |1\rangle$$



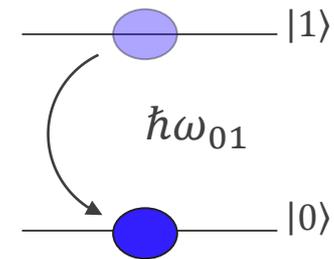
$$|\alpha|^2 = 1$$

$$|\beta|^2 = 0$$



$$|\alpha|^2 = 0$$

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



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

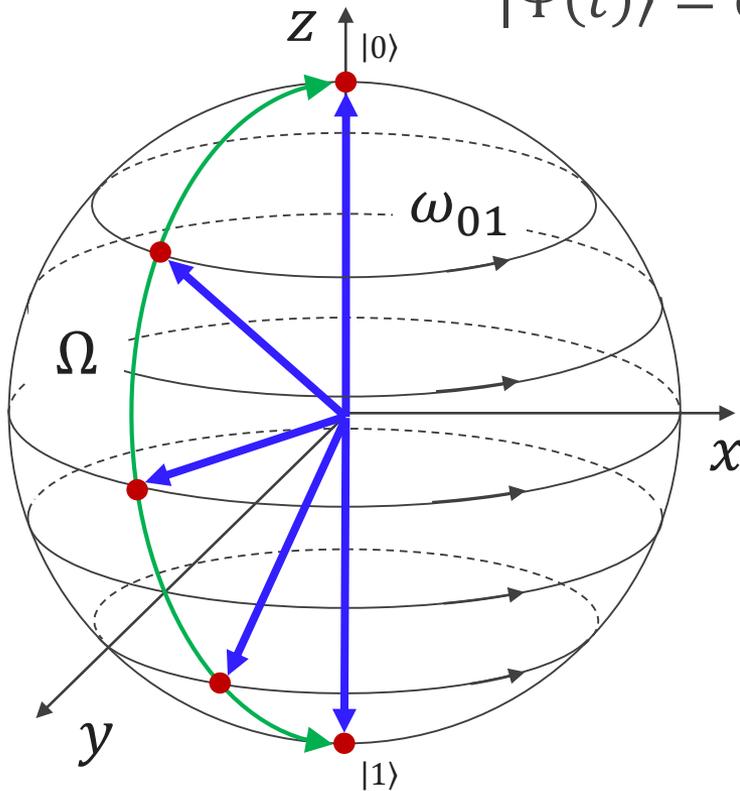
$$|\beta|^2 = 0$$



Driven qubit: quantum state evolution

- * Let's drive the qubit with frequency $\omega_{01} = \Delta E / \hbar$
- * The qubit state will be:

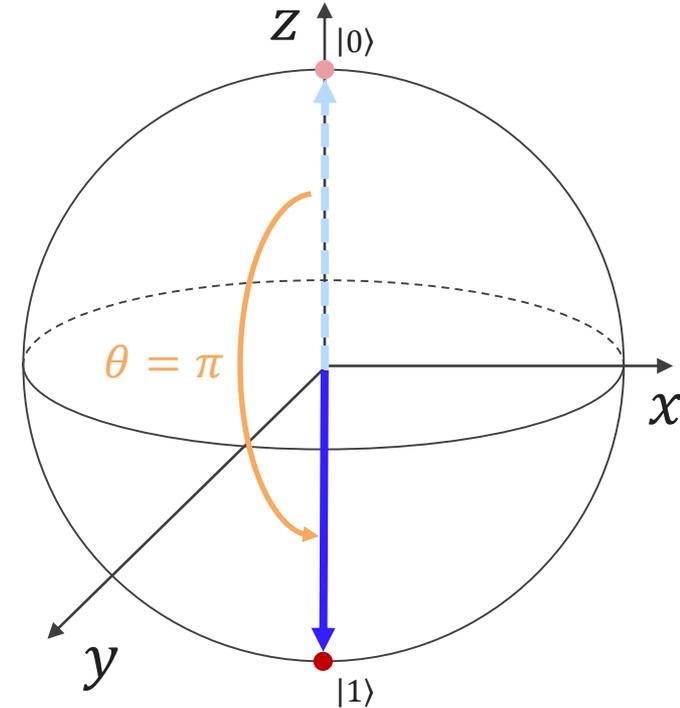
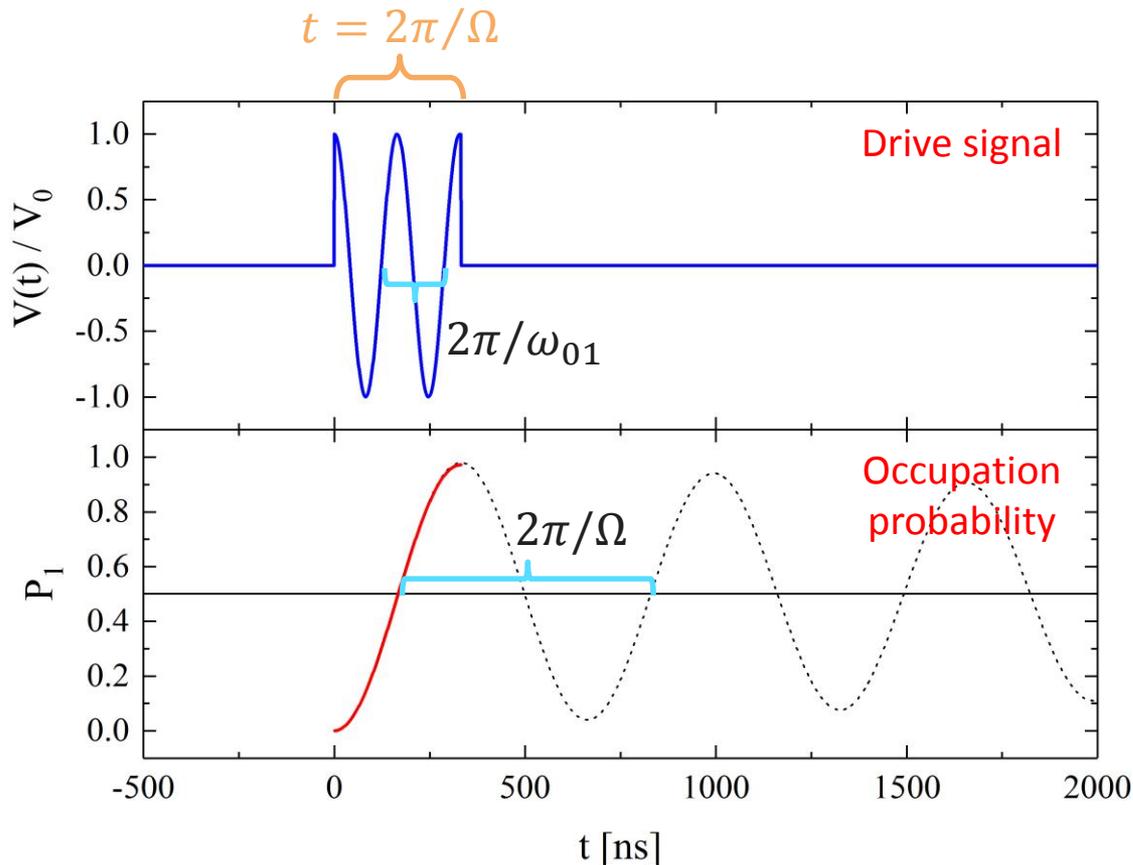
$$|\Psi(t)\rangle = \cos\left(\frac{\Omega t}{2}\right) |0\rangle + e^{i\varphi\omega_{01}t} \sin\left(\frac{\Omega t}{2}\right) |1\rangle$$



- * $|\Psi(t)\rangle$ oscillates between $|0\rangle$ and $|1\rangle$ with frequency Ω , the Rabi frequency
- * $|\Psi(t)\rangle$ precesses around z with frequency ω_{01}
- * By controlling pulses length and time delays any state is accessible

Example: π -pulse (NOT)

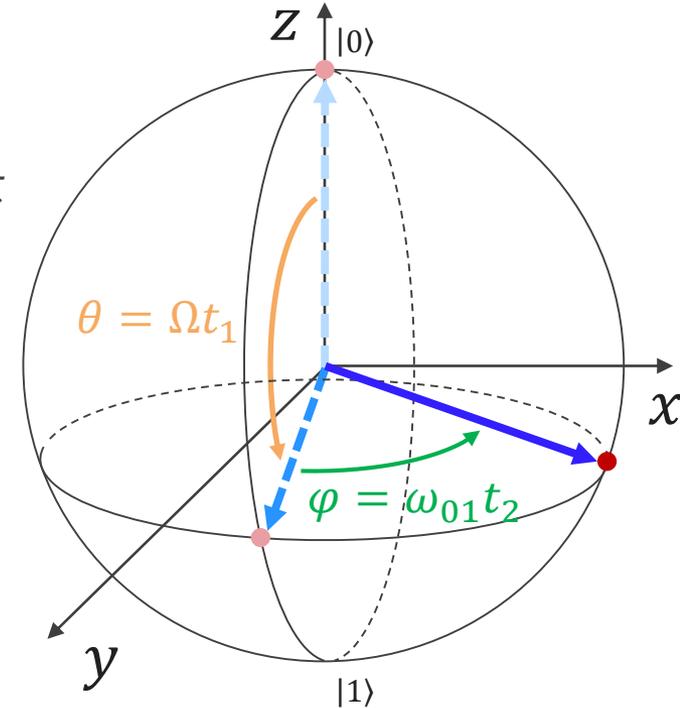
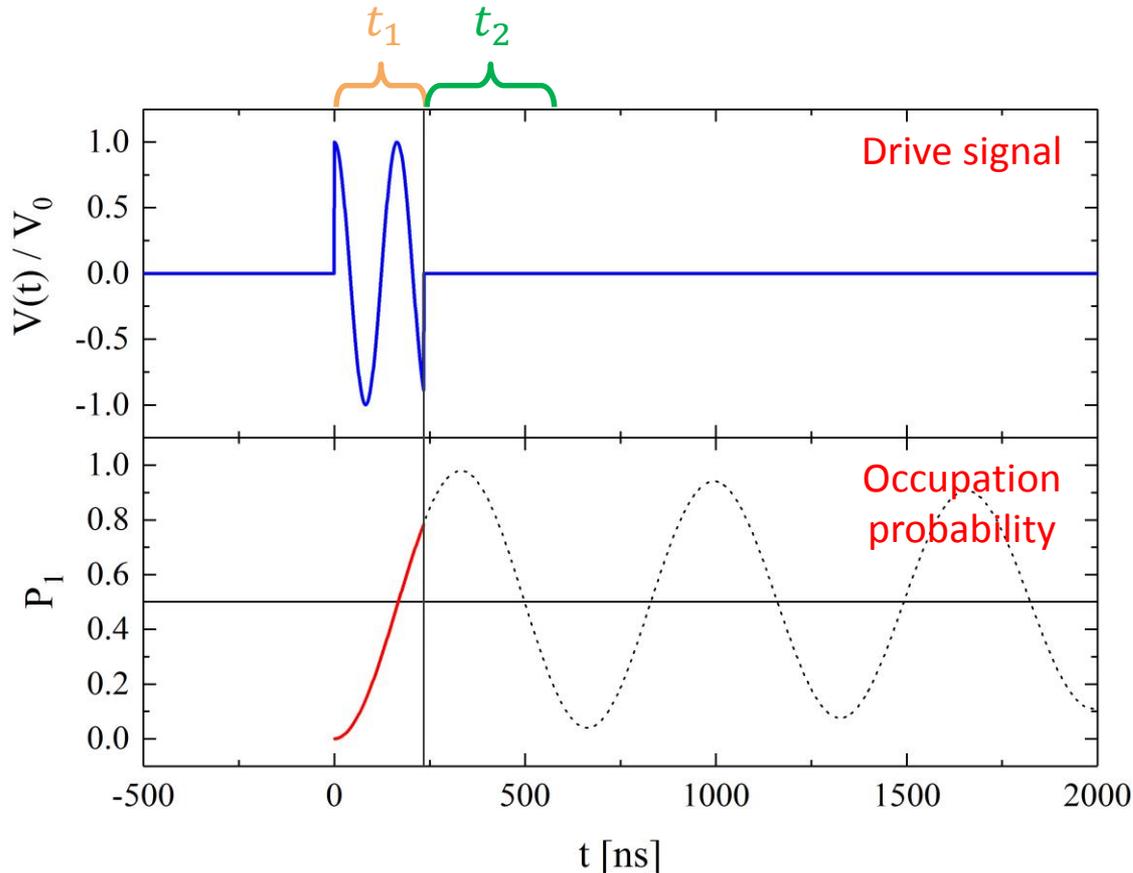
- * π -pulse is the qubit equivalent of a classical NOT operation: $|0\rangle \rightarrow |1\rangle$



$$\alpha(t) = \cos\left(\frac{\Omega t}{2}\right)$$
$$\beta(t) = e^{i\omega_{01}t} \sin\left(\frac{\Omega t}{2}\right)$$

Example: controlling the phase of states superposition

- * A superposition states precesses steadily about the z-axis with frequency ω_{01}
- * In time t the phase φ will advance of $\omega_{01}t$



$$\alpha(t) = \cos\left(\frac{\Omega t}{2}\right)$$

$$\beta(t) = e^{i\omega_{01}t} \sin\left(\frac{\Omega t}{2}\right)$$

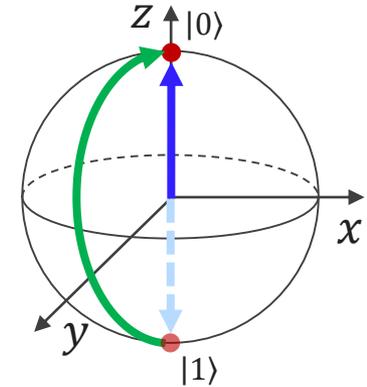
Qubit decoherence mechanisms

Quantum information is stored in amplitude and phase...but it can be lost!

$$\text{Decoherence time: } \frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}$$

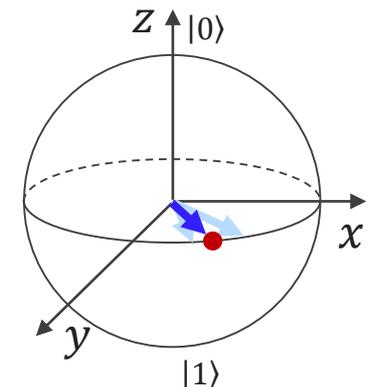
- **Energy relaxation**

- * Due to finite relaxation time T_1 of the first excited state
 - Need qubits that do not lose energy quickly... must not radiate electromagnetic energy or couple to other quantum systems



- **Dephasing**

- * Random fluctuations in qubit energy level spacing causes random fluctuations in phase φ of superposition states
 - Phase information lost on time scale T_φ
 - Design qubit so it can't couple to anything



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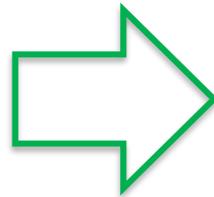
The Schrödinger cat problem



- * The observation of a quantum state (measurement) collapses the system state in one of its eigen-states
- * We loose info on superposition of states
⇒ **bad for quantum computation!**

Superposition of states

$$\frac{1}{\sqrt{2}}|\text{cat alive}\rangle + \frac{1}{\sqrt{2}}|\text{cat dead}\rangle$$



Measurement

The cat is alive

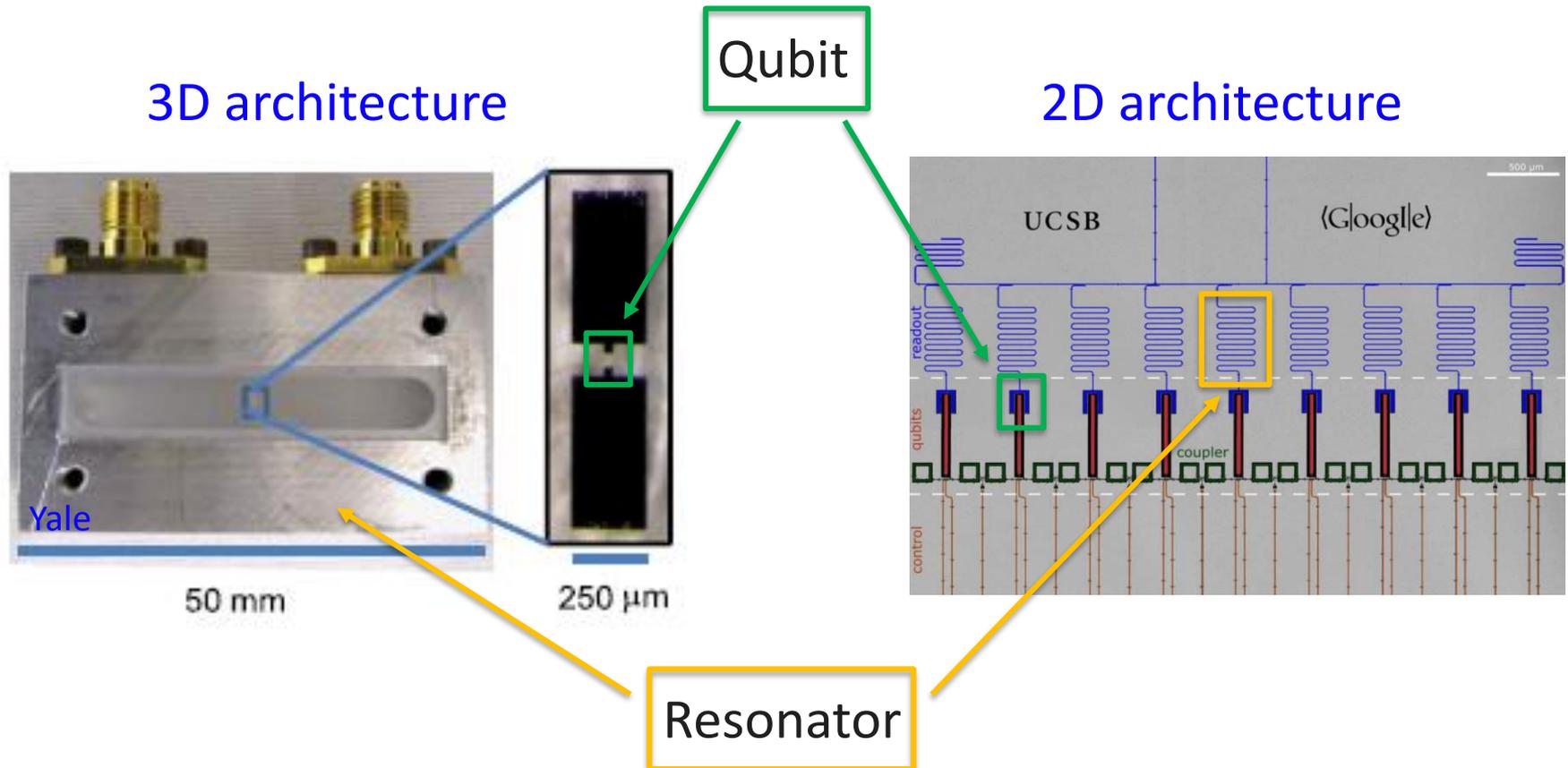


The cat is dead



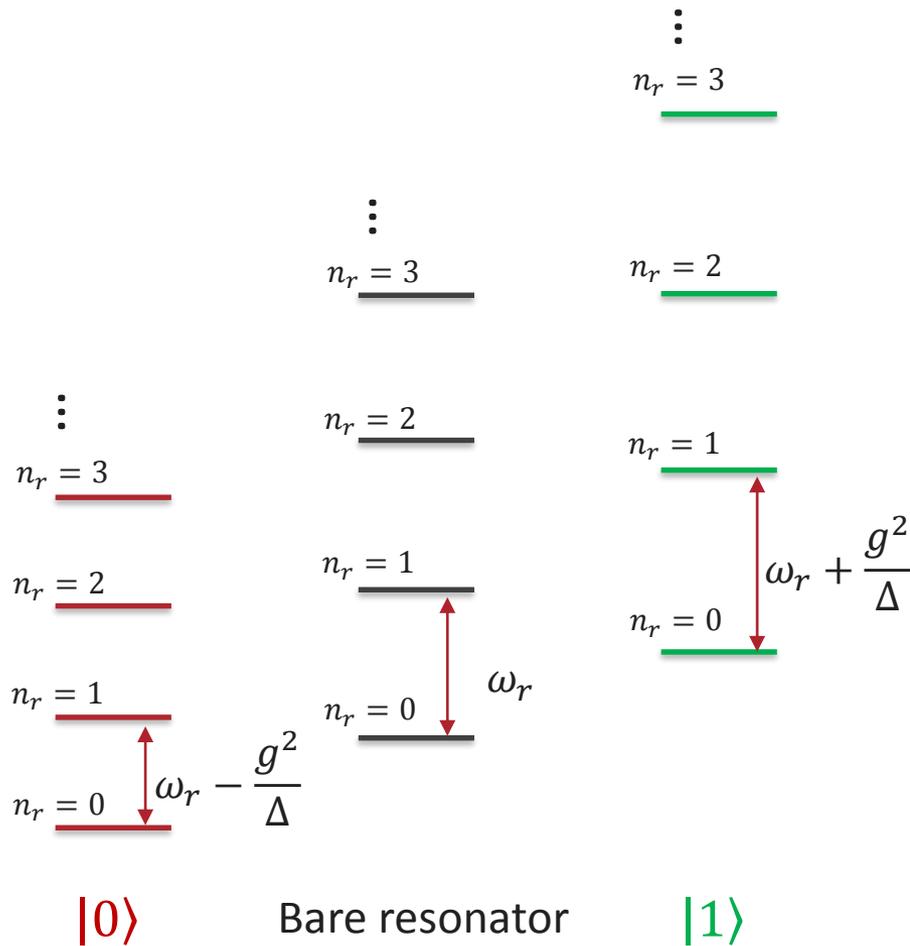
Quantum non-demolition measurements

- * Resonator coupled to a qubit
- * *Probing the perturbation on the resonator induced by the state of the qubit*

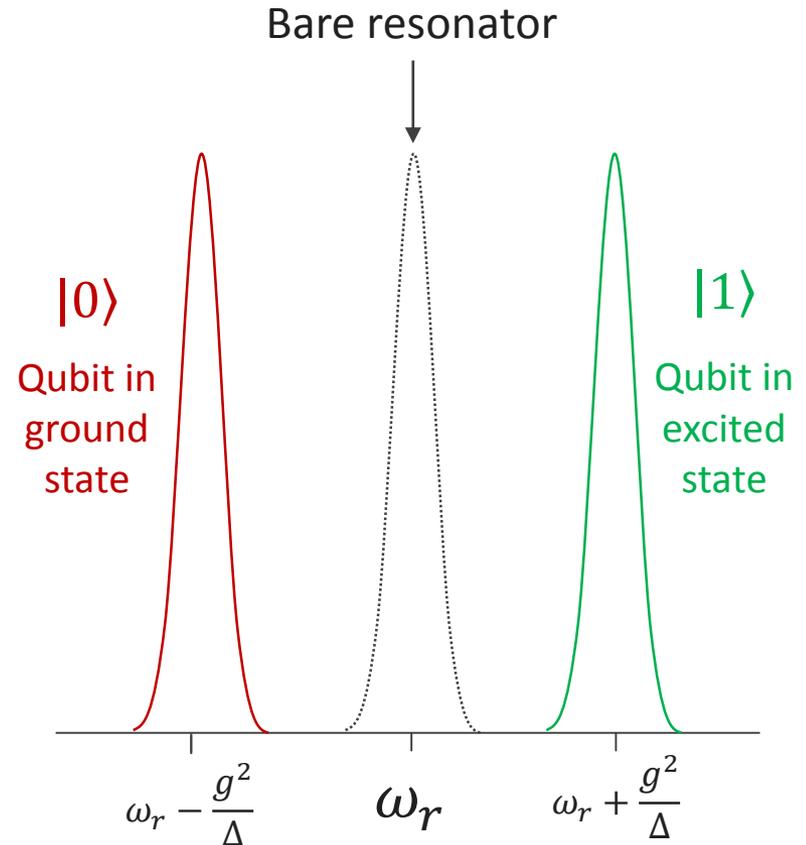


Perturbation of the resonator frequency

Energy spectrum



Frequency spectrum



Δ = detuning = $\omega_q - \omega_r \sim 1 \text{ GHz}$
 g = coupling $\sim 100 \text{ MHz}$

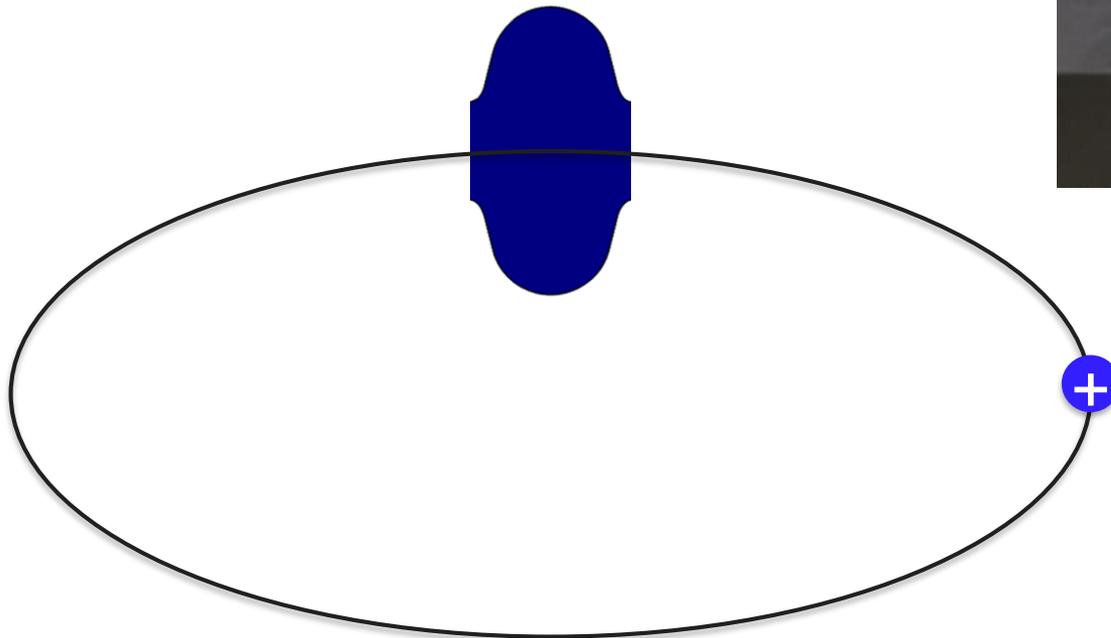
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SRF Cavities: from accelerators to quantum computing

SRF cavities typically used to accelerate charged particles because:

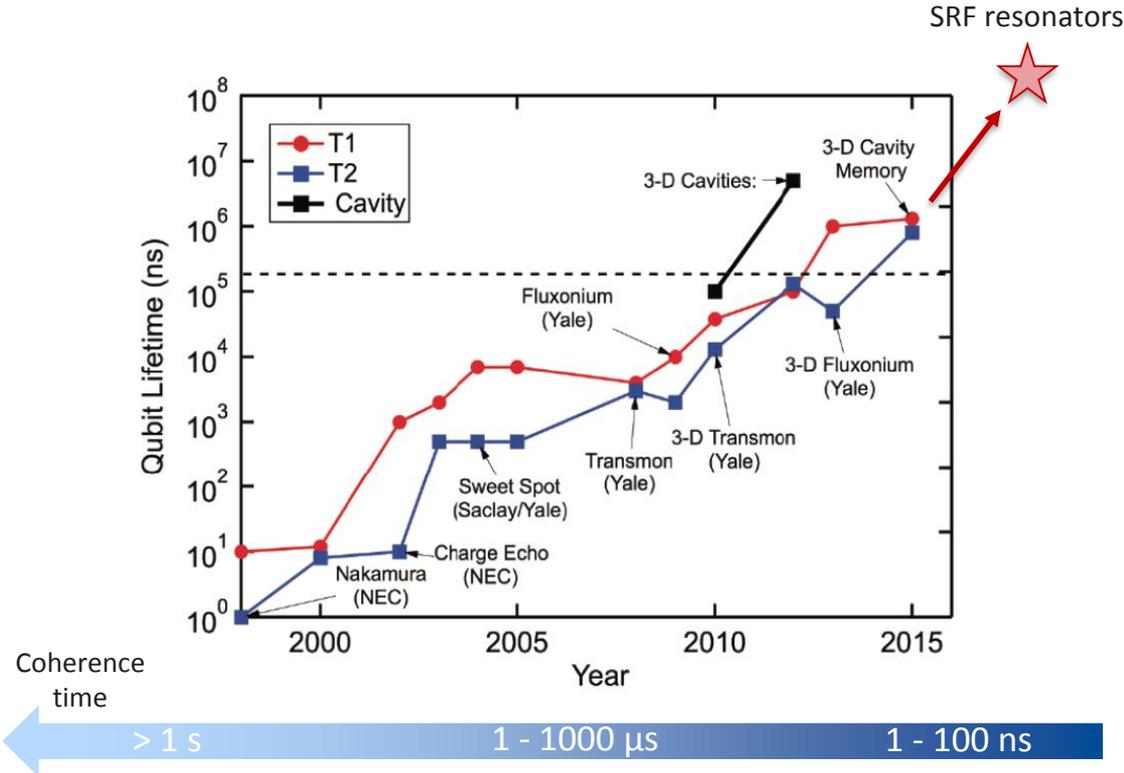
- * Very high Q-factors:
 $Q_0 > 10^{10}$ (low power dissipation)
- * Very high accelerating voltages:
 $V_{acc} \cong 40,000,000 \text{ V}$ in 1 m



HOWEVER,
high Q-factor resonators
are also needed to
increase coherence time
in **quantum computers!**

SRF technology to enable high coherence qubits

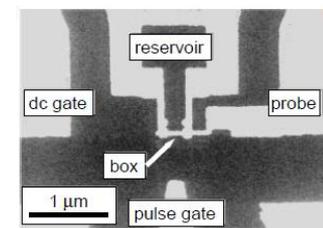
- * High quality factor (Q_0)
3D resonators enables longer coherence time
 - High $Q_0 \Rightarrow$ narrow BW
 - Very quiet EM environment
- * $Q_0 < 10^8$ currently with 3D architecture of qubits
- * **SRF** technology capable to provide $Q_0 > 10^{11}$
 - Usually adopted to accelerate particles in HEP accelerators
 - Promises 3D qubits with x1000 longer coherence



SRF technology

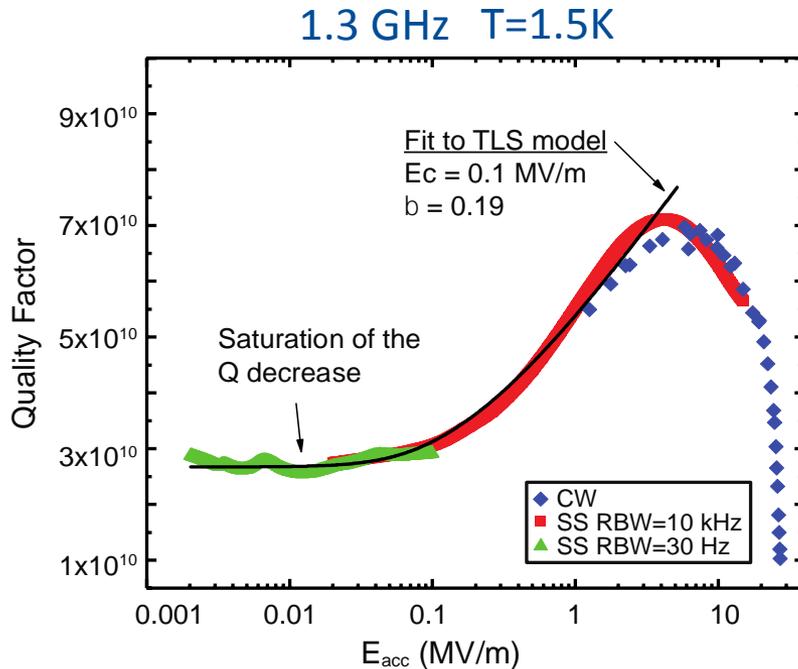


Transmon 3D architecture
H. Paik *et al.*, Phys. Rev. Lett. (2011)



Cooper-pair box
Y. Nakamura *et al.*, Nature (1999)

First measurements towards quantum regime



Now measured down to
 $\langle N \rangle \sim 1000$ photons

Good news: low field Q
 saturates at $Q > 3 \times 10^{10}$

PHYSICAL REVIEW LETTERS

Understanding Quality Factor Degradation in Superconducting Niobium Cavities at Low Microwave Field Amplitudes

A. Romanenko[†]

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

D. I. Schuster[‡]

The James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA

(Received 11 May 2017)

In niobium superconducting radio frequency (SRF) cavities for particle acceleration, a decrease of the quality factor at lower fields—a so-called *low field Q slope* or LFQS—has been a long-standing unexplained effect. By extending the high Q measurement techniques to ultralow fields, we discover two previously unknown features of the effect: (i) saturation at rf fields lower than $E_{acc} \sim 0.1$ MV/m; (ii) strong degradation enhancement by growing thicker niobium pentoxide. Our findings suggest that the LFQS may be caused by the two level systems in the natural niobium oxide on the inner cavity surface, thereby identifying a new source of residual resistance and providing guidance for potential nonaccelerator low-field applications of SRF cavities.

DOI:

Modern and planned state-of-the-art particle accelerators employ hundreds or thousands of three-dimensional superconducting radio frequency (SRF) niobium cavities [1,2] for particle acceleration. In operation, a beam of charged particles (e.g., electrons, positrons, protons, heavy ions) is accelerated by the electric field along the axis of the cavity. The phase of the field is such that particles always see an accelerating field along their trajectories. Maintaining the large electromagnetic fields inside cavities leads to dissipation, and—compared to normal conducting technology—SRF cavities provide an extremely low power consumption, thereby permitting continuous wave (CW) operation as well as enabling superior beam quality.

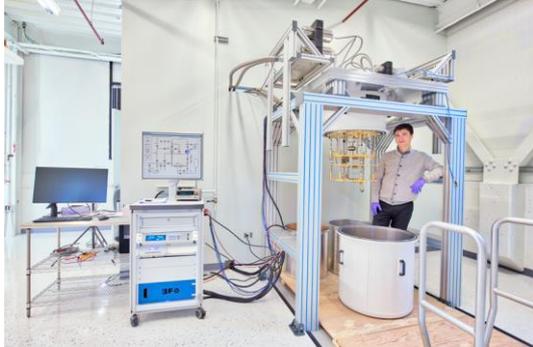
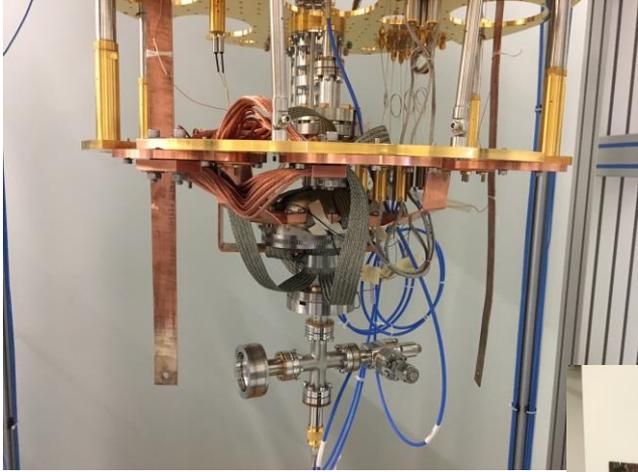
Physics and technology of SRF cavities has progressed

factor (Q) at low rf fields $E_{acc} \lesssim 5$ MV/m—the so called “low field Q slope” (LFQS). Reported experimental investigations [1,7,8] showed a continuous decrease of Q down to ~ 0.2 MV/m, the lowest field explored. Most recent studies [9] indicate that the increase in average surface resistance (decrease in Q) in LFQS does not come from the thermally excited quasiparticle contribution described by Mattis and Bardeen [10], but is a part of the residual surface resistance contribution. The residual resistance currently sets the limit to the maximum possible SRF cavity quality factors [11], and it plays the dominant role for subgigahertz range SRF-based accelerators. Understanding the physics of all the mechanisms behind residual resistance is among the major remaining challenges for further SRF progress

A. Romanenko and D. I. Schuster,
 Phys. Rev. Lett. 119, 264801 (2017)

New quantum computing lab at Fermilab

...some pics...

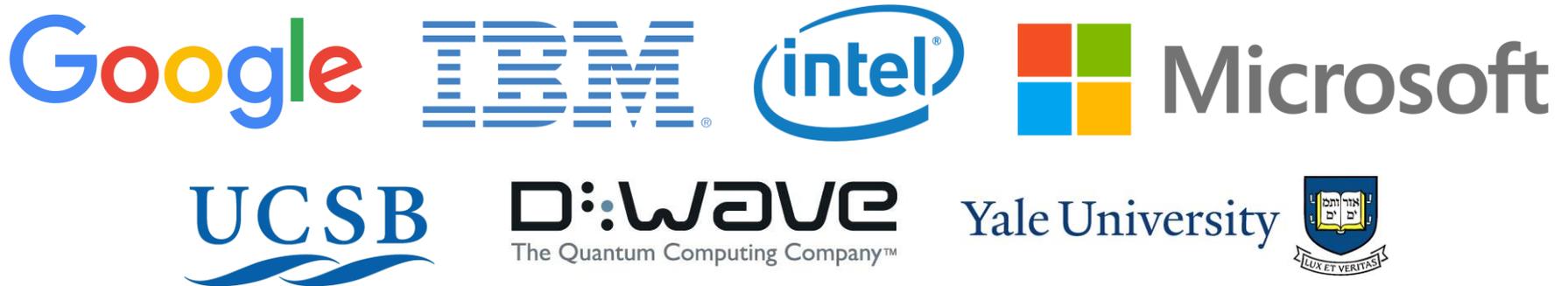


Outline

- * Introduction
- * What is a qubit?
- * How does a qubit work?
- * Quantum state manipulation
- * Qubit readout
- * Quantum computing R&D at Fermilab
- * **Conclusions**

Quantum Information Science (QIS) and Fermilab

Many universities and silicon valley industries did the main breakthroughs in quantum computation...



...and others...

...Fermilab is new in the QIS scene, but seeks to become competitive in this field by providing extensive knowhow on high Q-factor SRF resonators

Conclusions

- * The last decade has seen remarkable progress towards building a quantum computer
- * In superconducting qubits, the lifetimes have improved by orders of magnitude and the longest lifetimes exceed 1 millisecond
- * Superconducting qubits and trapped ion qubits have advanced to the point where they can be scaled up to many more qubits
- * Things should get “interesting” at the 30 to 100 qubit level
- * Key research issues:
 - *Eliminating/reducing sources of relaxation and dephasing*
 - *High-fidelity gates and read out*
 - *Implementing error correction*
 - *Controllable coupling of qubits*
 - *Reaching small, medium and large scale integration*