INTRO TO QUANTUM COMPUTING

LECTURE #22

Quantum Hardware

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04/18/2021

ANNOUNCEMENTS

Welcome Back!

QUANTUM HARDWARE LECTURE SERIES

Lecture 1 - Conditions and metrics for building a quantum computer

What systems can be used for quantum computing?

How do we compare different quantum processors?

Lecture 2 - Quantum hardware implementations

What are different ways to build qubits and quantum processors

A few frequently asked questions compiled by Akshay:

1. Are the different qubit types meant for different applications?
2. Are electrons and photons qubits?
3. How are gates physically applied to qubits?
4. Is the Bloch sphere 'real'?
5. What does it look like physically when we entangle qubits? How is entanglement actually implemented?

THE QUANTUM ALGOS LANDSCAPE

Deutsch -Jozsa

First theoretical demonstration of quantum advantage!

Uses an Oracle

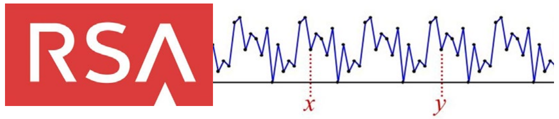
$$O(1) \ll O(2^n)$$

Exponential Quantum Speedup!

QUANTUM ADVANTAGE

Shor's Algorithm

Super -polynomial speedup for factoring using the QFT!



Cracking RSA Requires Factoring & Period Finding

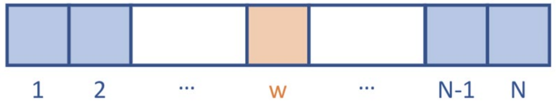
The Quantum Fourier Transform Encodes Frequency in Phase

$$O(\log(n)^3) \ll O(n^{1.9})$$

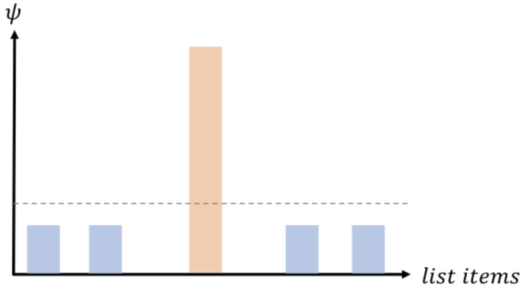
Super-Polynomial Quantum Speedup!

Grover Search

Quadratic speedup for search using amplitude amplification!



Unstructured Search



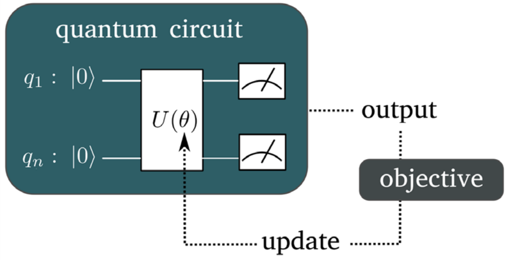
Leverages Amplitude Amplification

$$O(\sqrt{n}) \ll O(n)$$

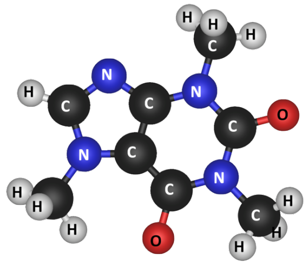
Quadratic Quantum Speedup!

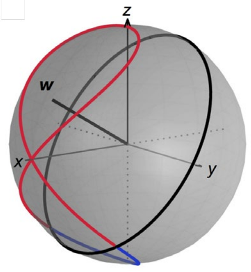
Near -Term Algos

Applications of noisy, small available quantum devices!



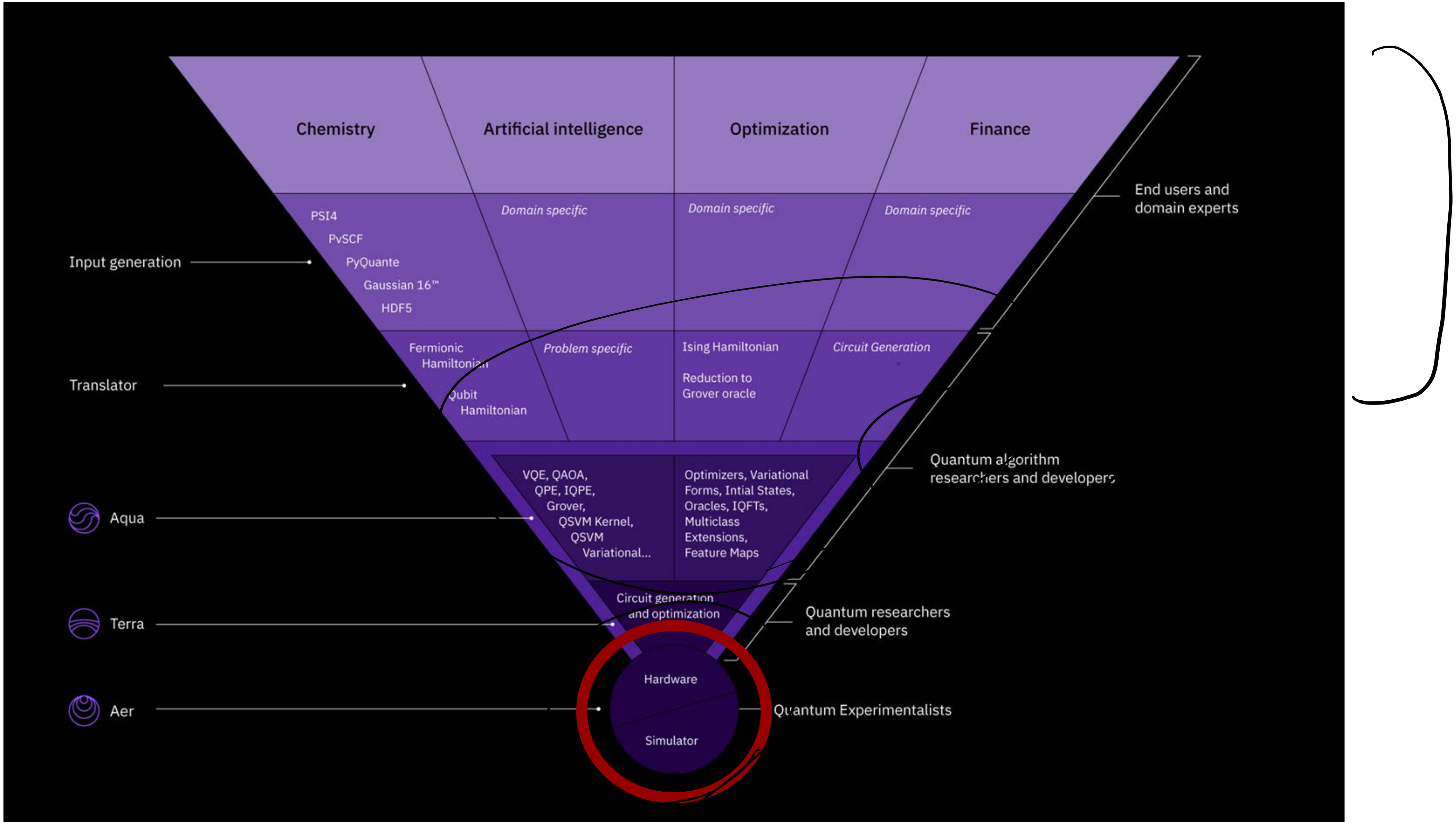
Hybrid Quantum-Classical Algos





Using Quantum to Solve Important Problems!

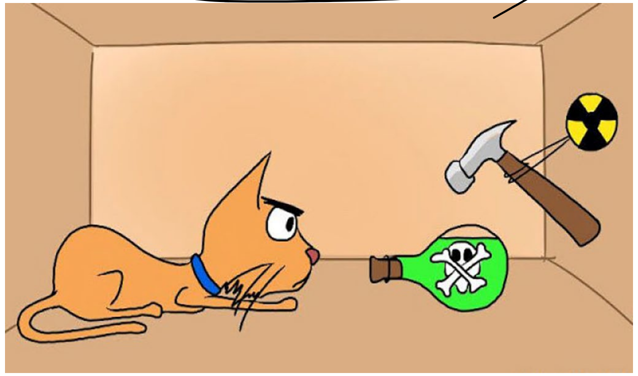
Quantum Stack



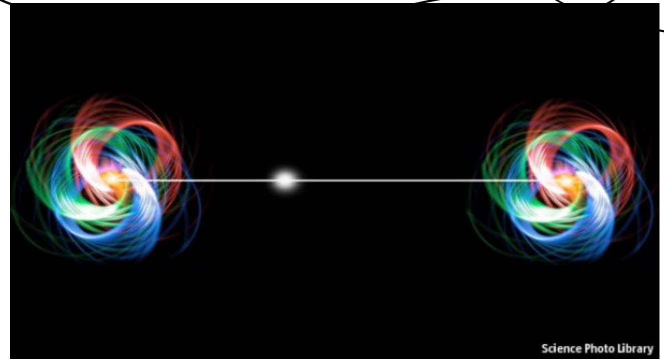
What do we need for running algorithms

- ➔ Many qubits
- ➔ Either with no noise (error), or error-corrected
- ➔ And:

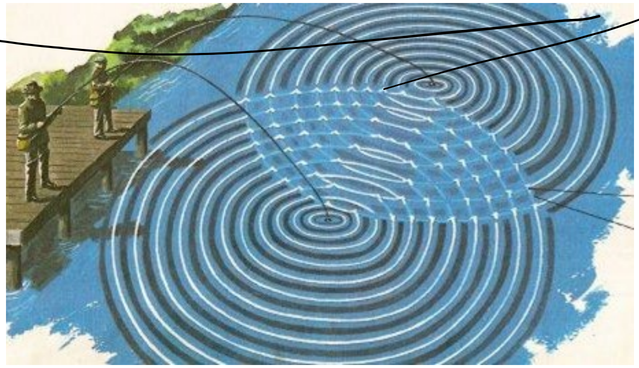
SUPERPOSITION



ENTANGLEMENT

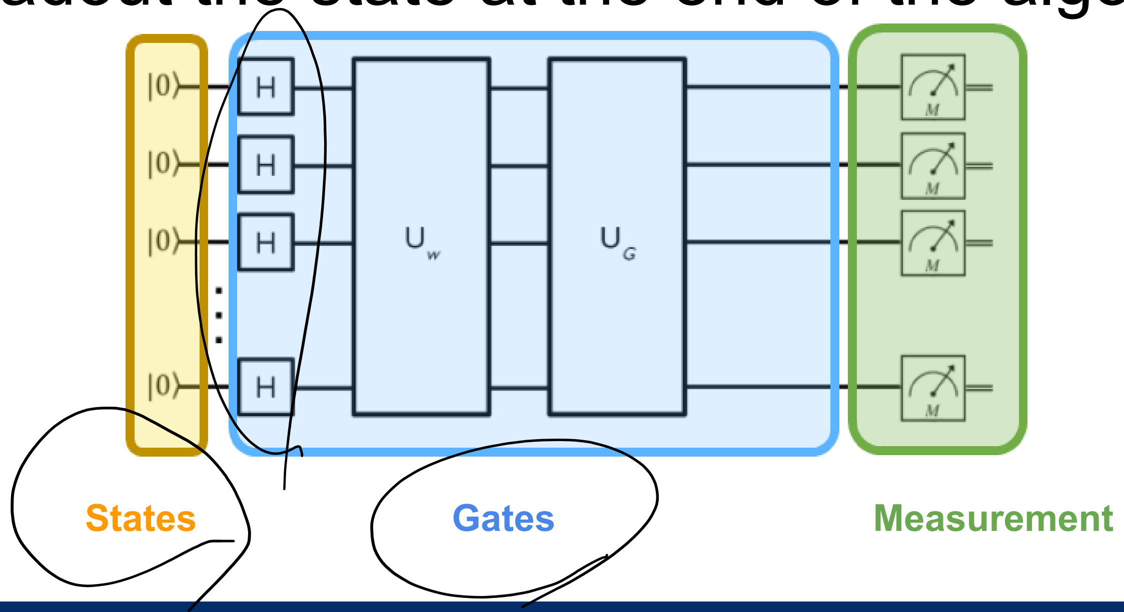


QUANTUM INTERFERENCE



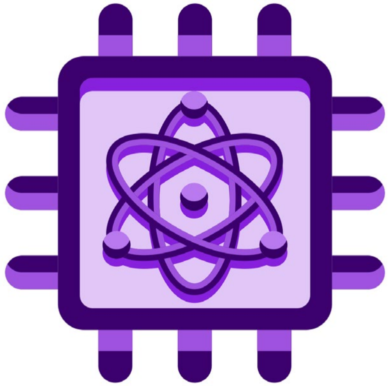
Properties of a Quantum Computer

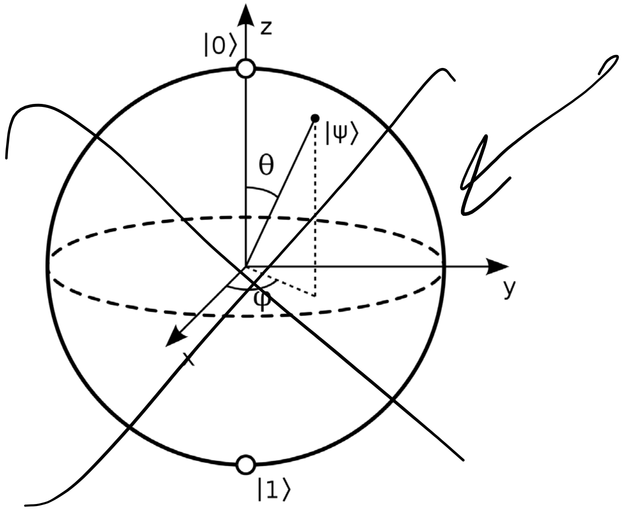
- Enough* qubits to run algorithms
- A way to fix errors if they occur
- A set of gates that are "universal"
- Capability to readout the state at the end of the algorithm

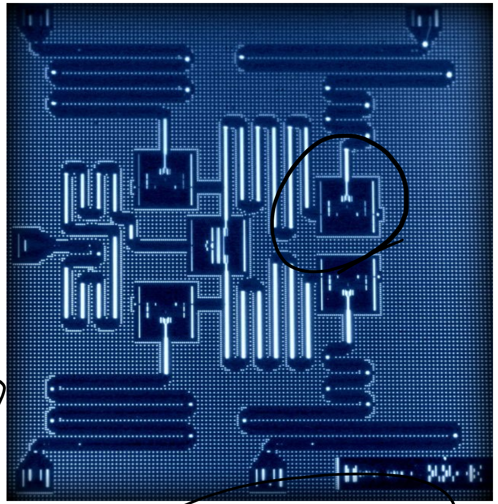


Quantum Hardware Platforms

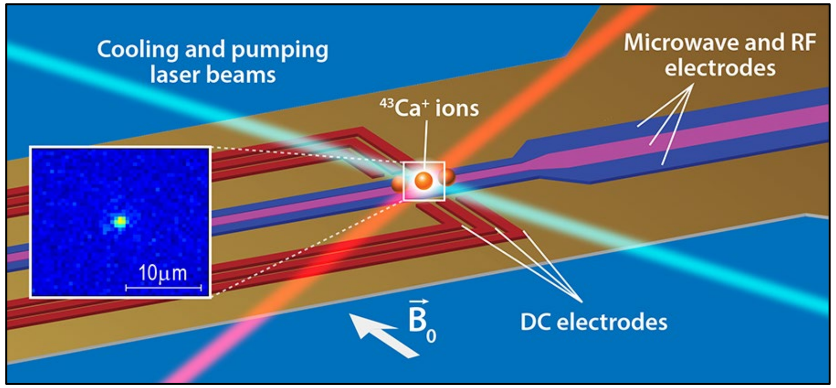
What will be the ' *quantum transistor* '?
Are we still in the '*quantum vacuum tube*' era ?



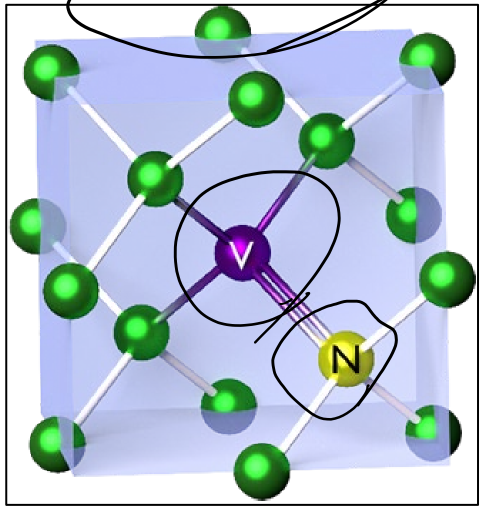




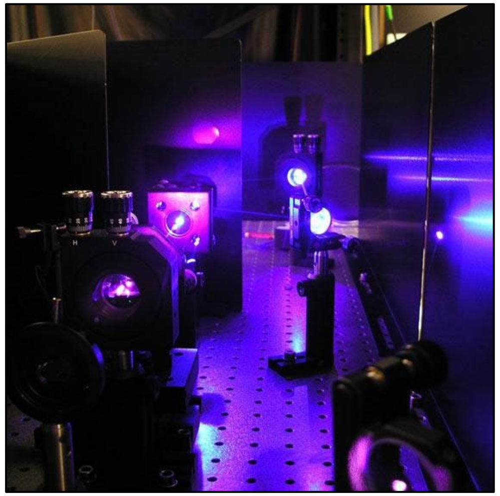
Superconducting



Trapped Ion

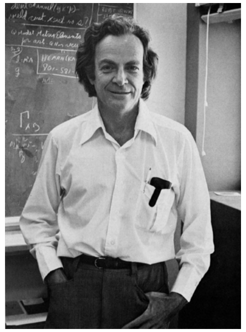


Diamond NV Centers



Photonics

Quantum Computer Past, Present, Future

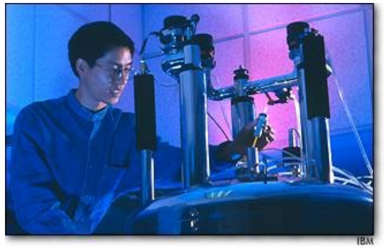


1981

Feynman proposes a framework for simulating the evolution of quantum systems.

Peter Shor shows that quantum computers can factorize large integers efficiently.

1994

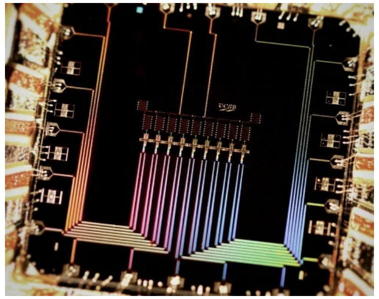


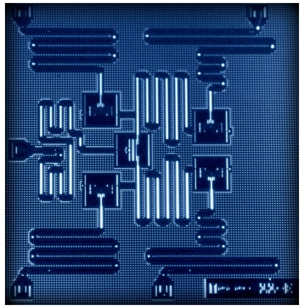
1998

First experimental demonstration of a quantum algorithm. A working 2-qubit NMR quantum computer.

Few-qubit processors & error detection

2012



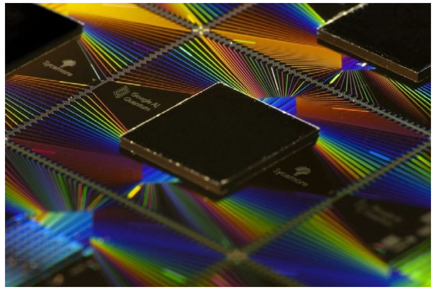


2017

Cloud-based Quantum Computing

Quantum Supremacy

2019



Why can’t we run grover’s on a meaningful dataset today?

- No enough qubits
- Noisy qubits
- Imperfect gates

Learning objectives

- ➔ So far we have assumed a perfect quantum computer. How to decide What systems are capable of performing quantum computation?

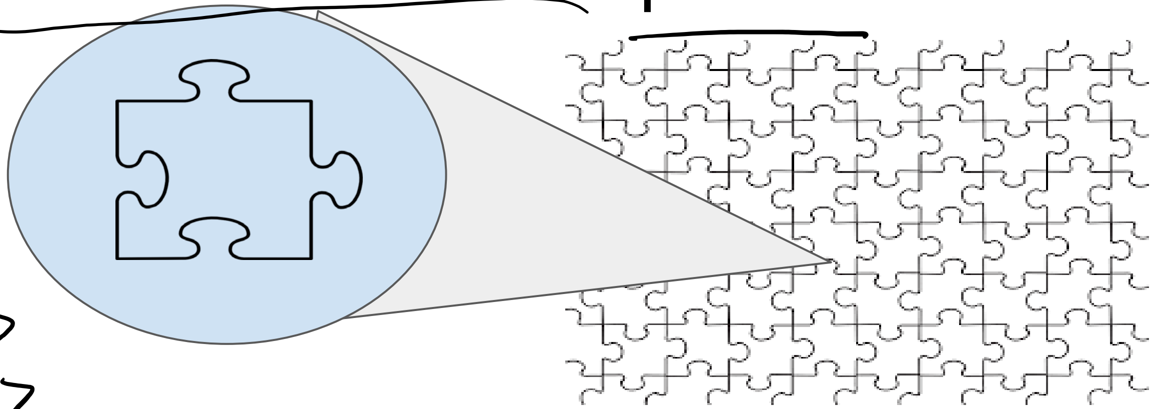
- ➔ How do we decide how good is a given quantum computer?

DiVincenzo criteria

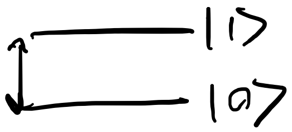
Set of ***five*** basic conditions for the physical realization of a quantum computer

DiVincenzo criteria

1. A scalable physical system with well -characterized qubits



qubits: two-level system



well-characterized: good grasp of the properties of the system. i.e. energy difference between $|0\rangle$ and $|1\rangle$

DiVincenzo criteria

2. The ability to initialize the state of the qubits

we usually start with qubits in $|0\rangle$

DiVincenzo criteria

3. Long relevant decoherence* times, much longer than the gate operation time

decoherence times: The amount of time that the qubits preserves its quantum properties

DiVincenzo criteria

4. A "universal" set of quantum gates

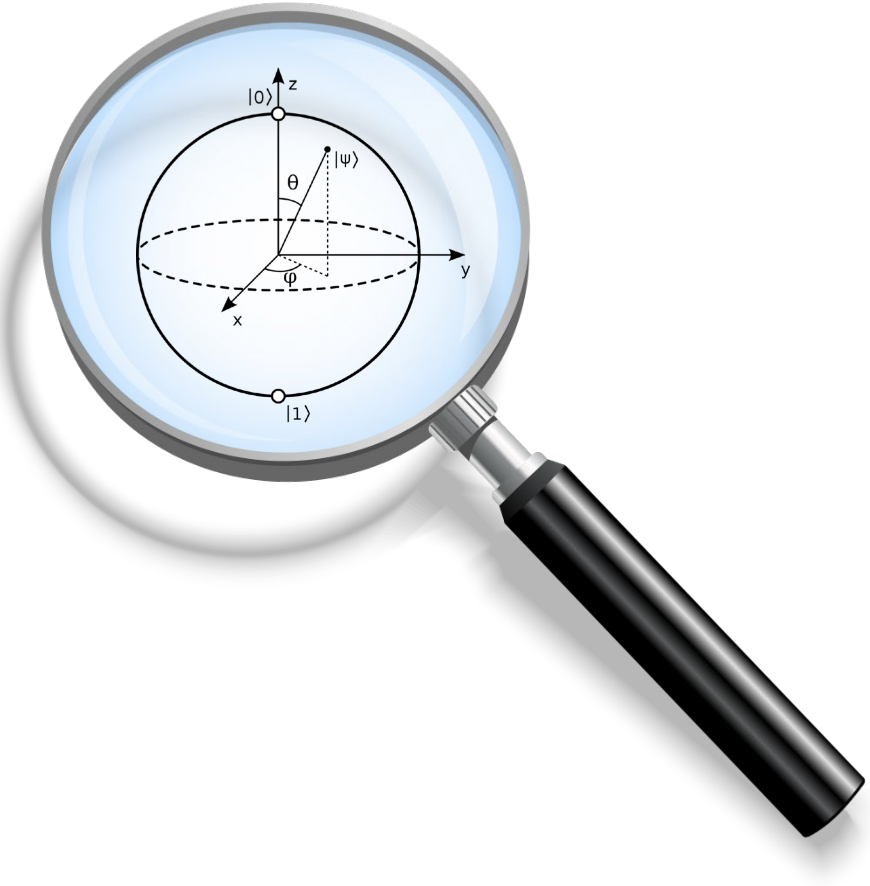
$$\{H, T, CNOT\}$$

$$T = \sqrt{S} \qquad e^{i \pi/8 Z} \quad (R_Z(\pi/4))$$

$$S = \sqrt{Z}$$

DiVincenzo criteria

5. A qubit -specific measurement capability



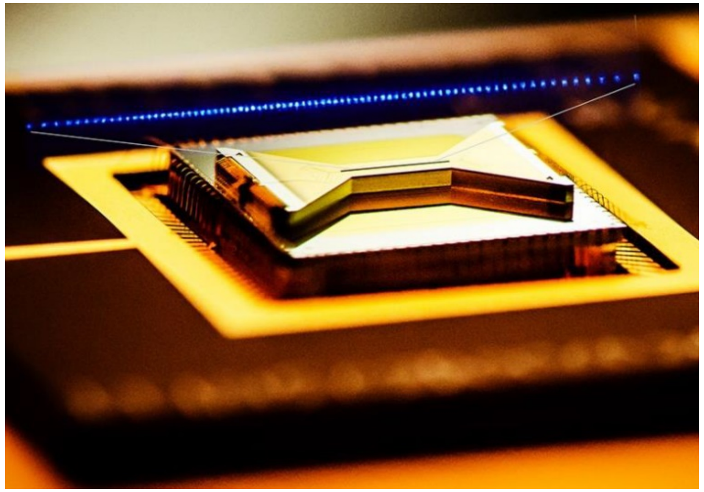
10 MIN BREAK!

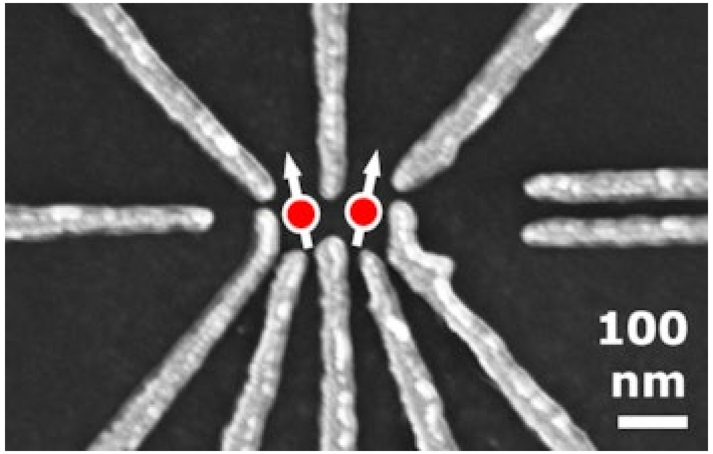
back @ 2:41 pm EST

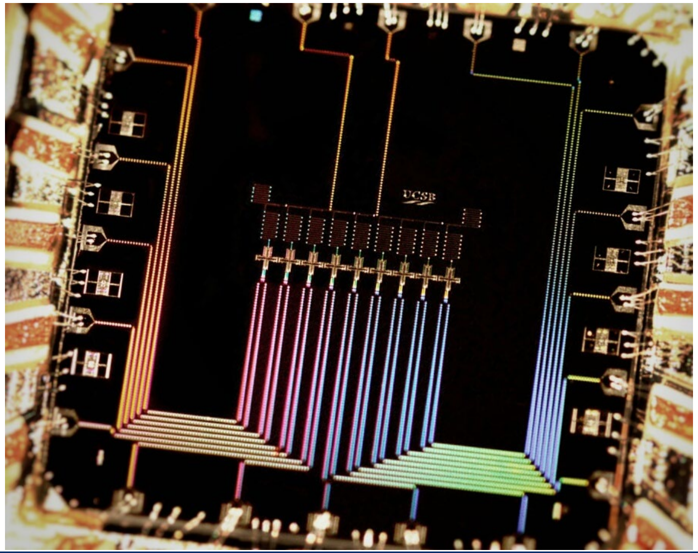
DiVincenzo criteria

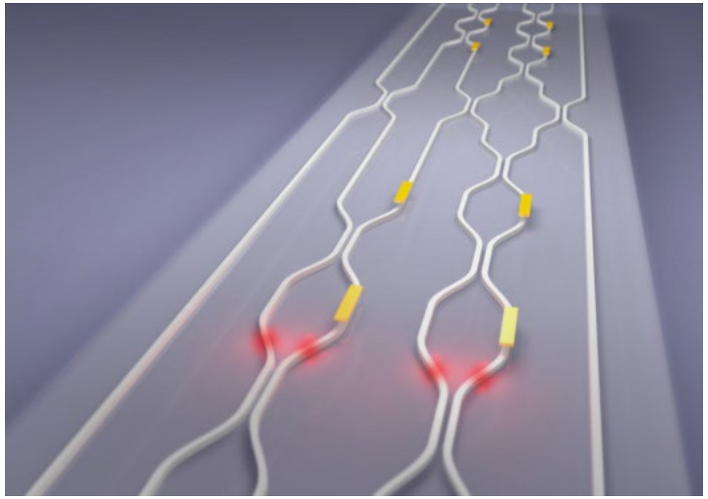
DiVincenzo's criteria

- Scalable two-level quantum system
- Initializable
- Long relevant decoherence time
- Universal set of gates
- Efficiently measurable







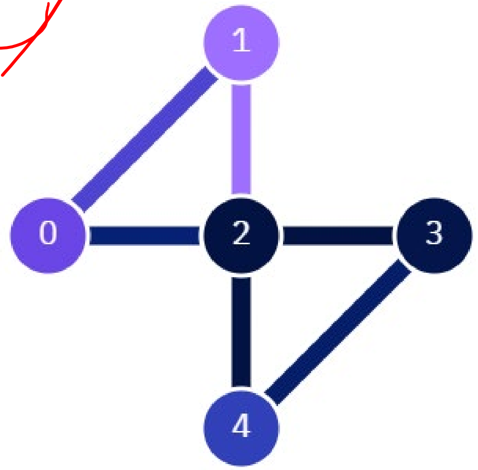


Quantum Hardware Spec Sheet

What are some metrics that can tell us about the quality of the quantum hardware

Which processor is better?

1) ibmq_5_yorktown



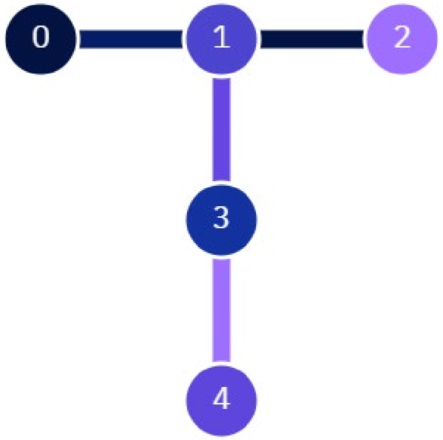
Avg. CNOT Error: 2.726e-2

Avg. Readout Error: 6.916e-2

Avg. T1: 53.74 us

Avg. T2: 33.09 us

2) ibmq_belem



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3) ibmq_bogota

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Avg. T1: 128.51 us

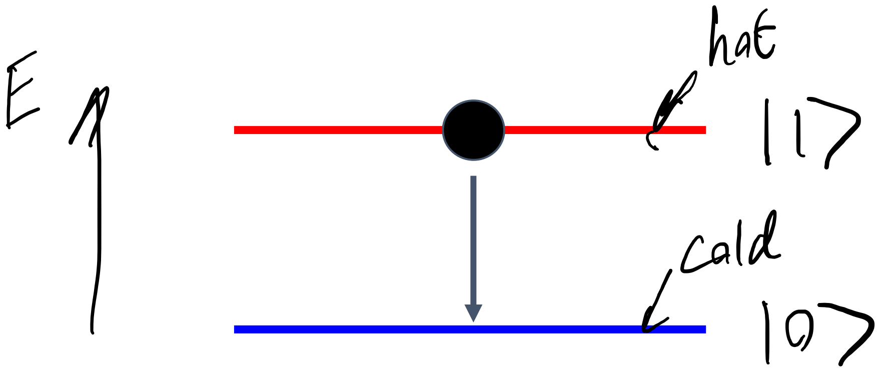
Avg. T2: 171.52 us

Qubit relaxation

Physical systems tend to dump energy into their surrounding

example:

hot coffee getting cold



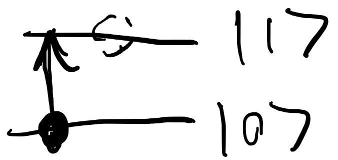
qubit decaying to lower energy state

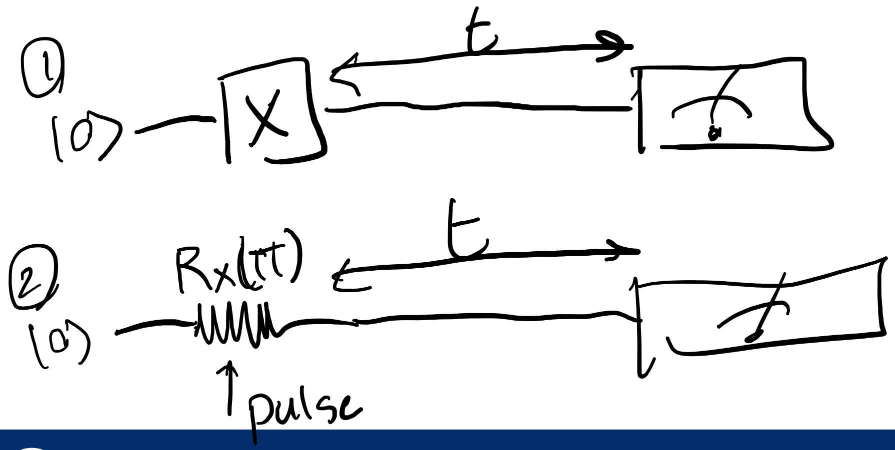
Qubit relaxation

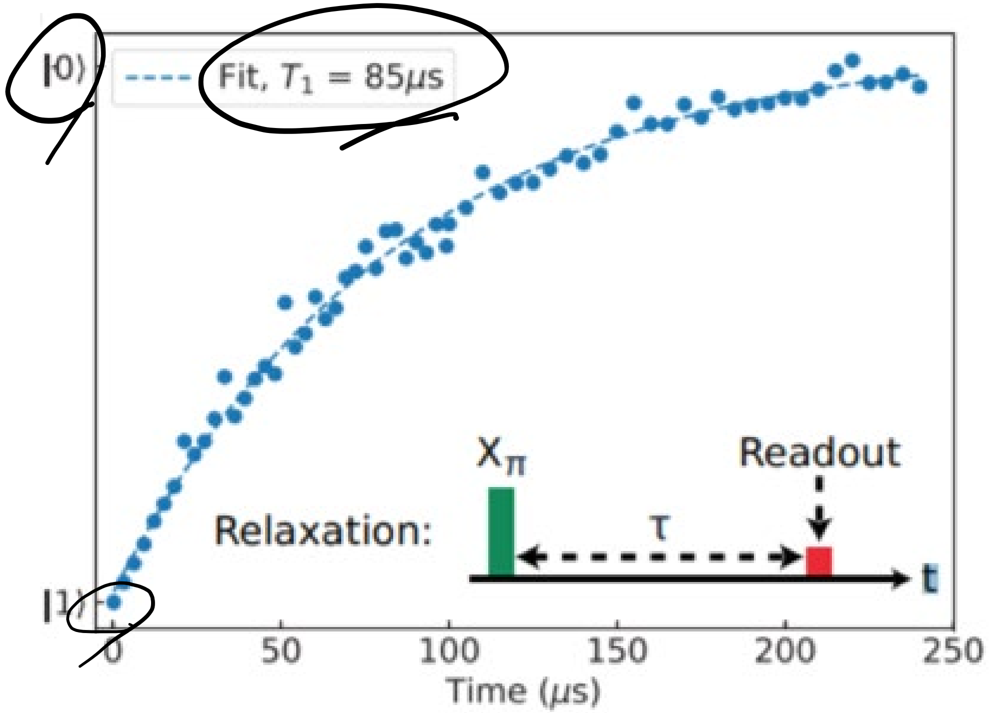
The qubit state decays from $|1\rangle$ to $|0\rangle$ over time

relaxation time: T1

$p(|1\rangle) \overset{c}{=} e^{-t/T1}$



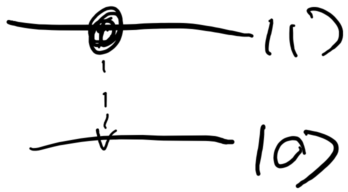




How to make better

- Qubits that are more isolated from the environment
  - Better material
  - Reduce loss mechanisms

- Make transition from 1 to 0 more difficult

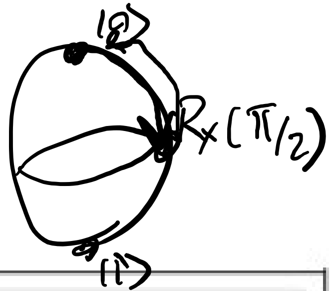


Qubit decoherence

Quantum systems lose their coherence as a result of interacting with the environment

- Quantum superposition turns into a classical probability distribution
- Lose the ability of quantum interference

Qubit decoherence



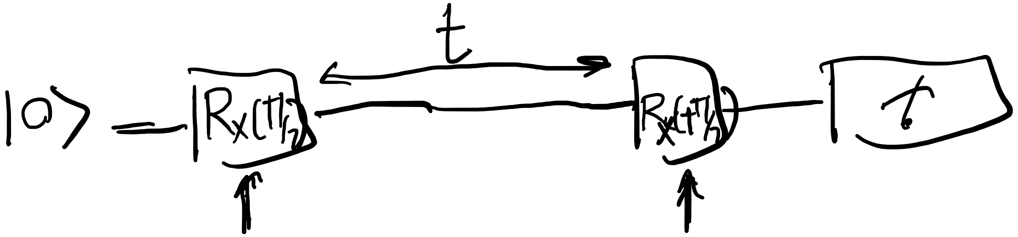
The qubit loses it's quantum coherence over time

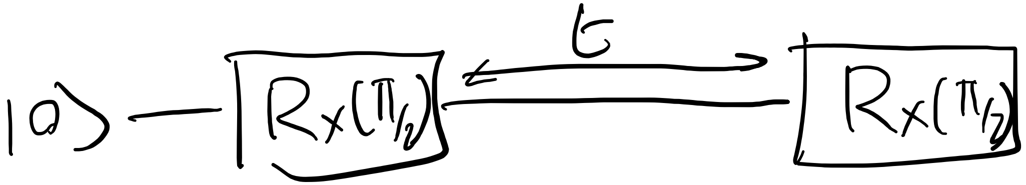
decoherence time: T2

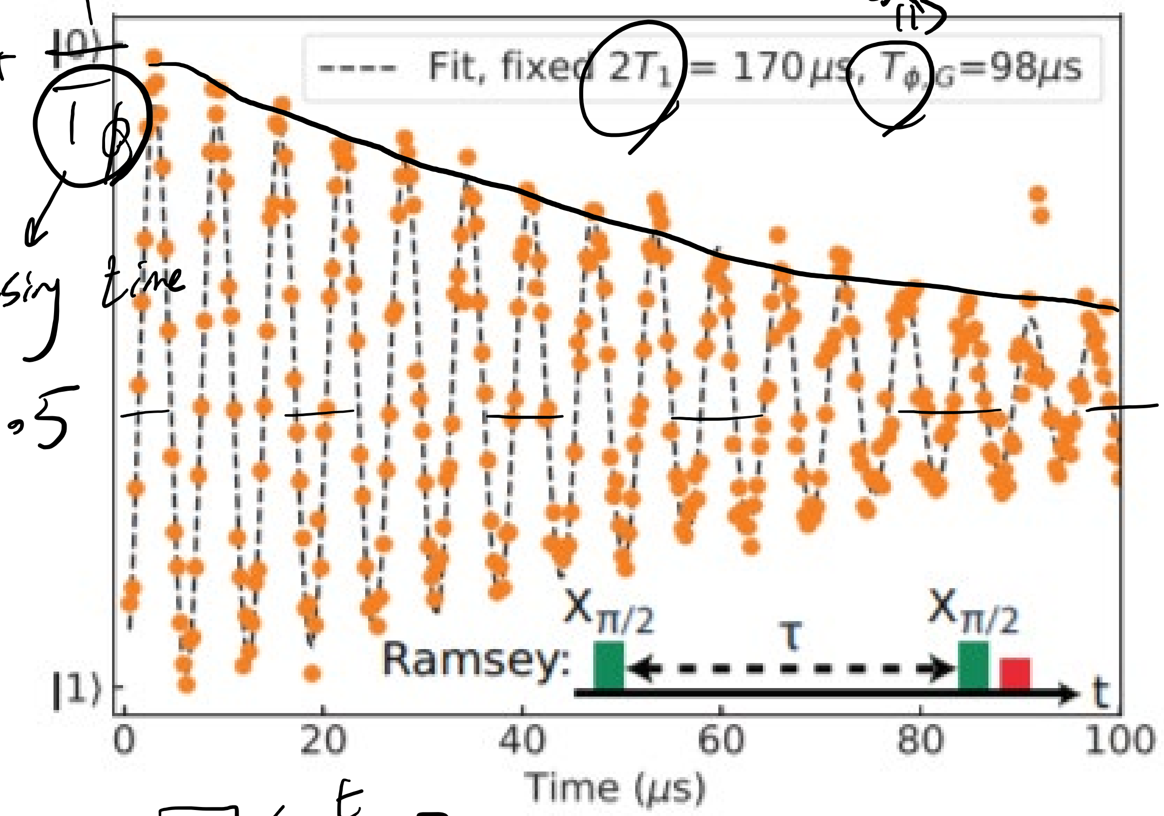
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

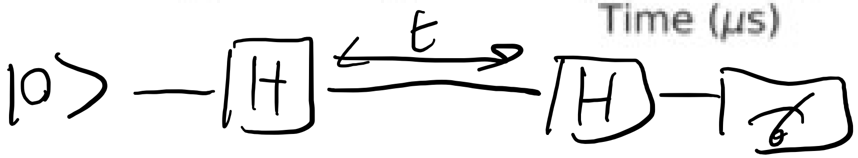
dephasing time

Ramsey experiment:

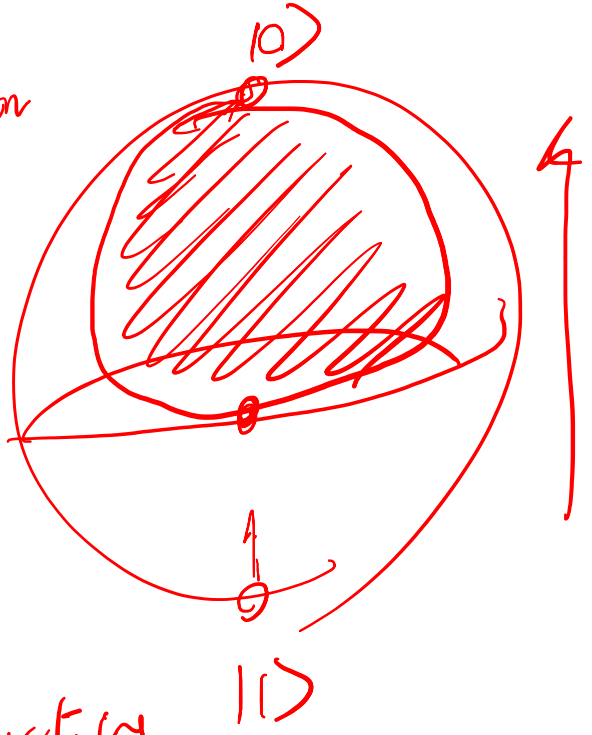




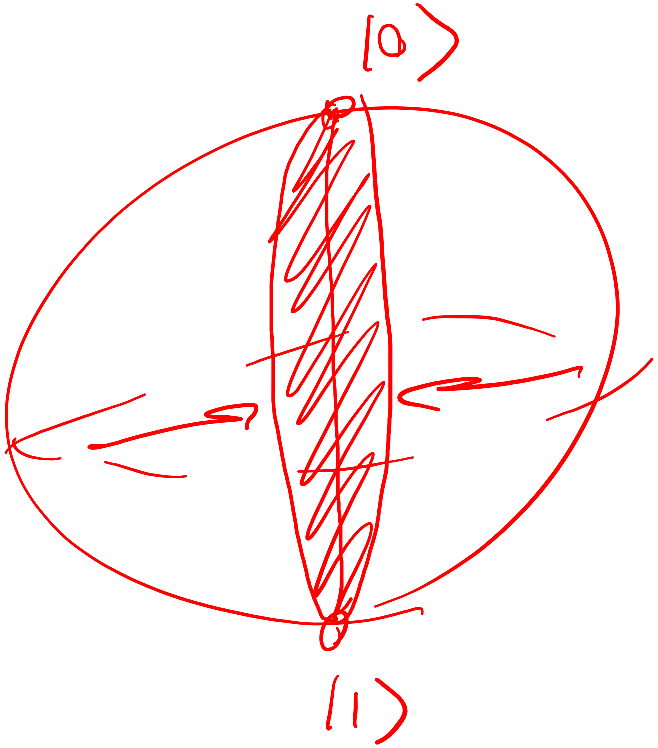




Relaxation



Decoherence



superconducting

1- qubit : ~10ns 99.99%

2-qubit : ~10ns – 200ns 99. → 99.5% on processor

T_1, T_2 ~ 100μs for quantum processors

How to make better

- Qubits that are more isolated from the environment
  - Reduce the environment noise
  - Make qubits less susceptible to noise

- ~~Make transition from 1 to 0 more difficult~~

Real life example

Article | Published: 26 August 2020

Impact of ionizing radiation on superconducting qubit coherence

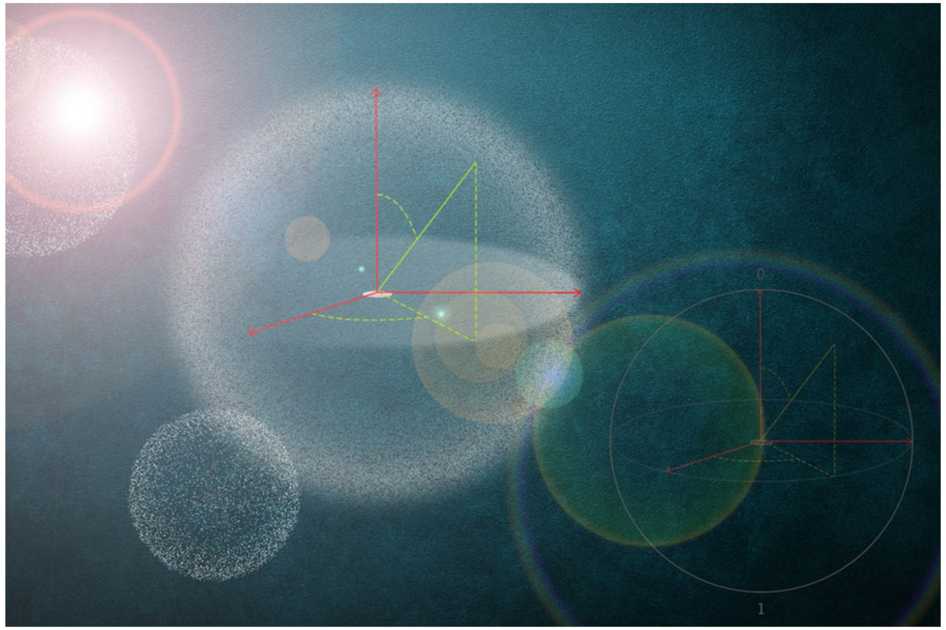
Antti P. Vepsäläinen, Amir H. Karamlou, John L. Orrell, Akshunna S. Dogra, Ben Loer, Francisca Vasconcelos, David K. Kim, Alexander J. Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Simon Gustavsson, Joseph A. Formaggio, Brent A. VanDevender & William D. Oliver

Nature **584**, 551–556(2020) | Cite this article

Cosmic rays may soon stymie quantum computing

Building quantum computers underground or designing radiation-proof qubits may be needed, researchers find.

Jennifer Chu | MIT News Office
August 26, 2020



Quantum gates

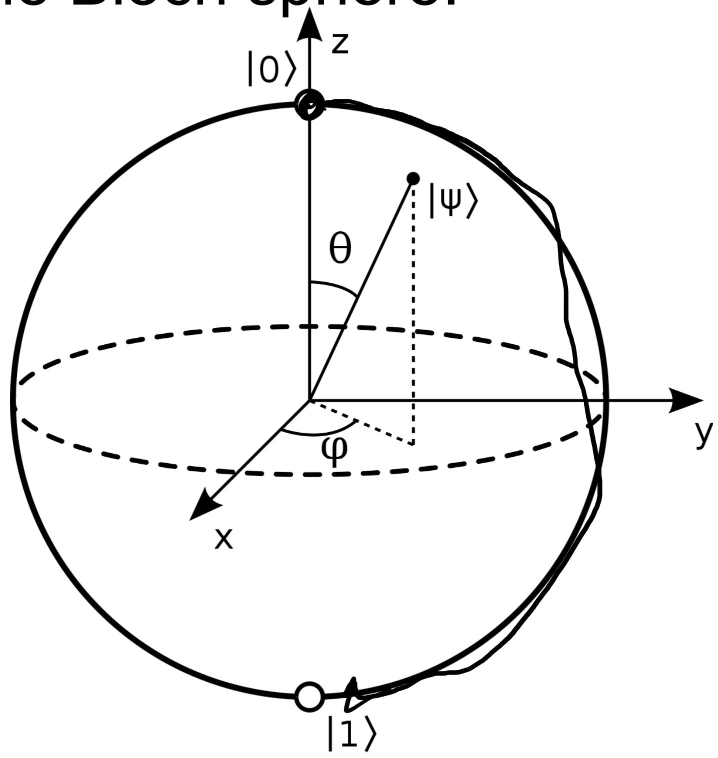
What are some metrics that can tell us about the quality of the quantum hardware

How good are our gates?

Quantum control is hard!

There are a continuous set of possible position on the Bloch sphere!

Lots of room for error



How good are our gates?

We quantify quantum gates using gate ***fidelity***

Perfect gate have a fidelity of 1 (100%)

$f = 1 - \text{error rate}$

How to do we measure the gate fidelity?

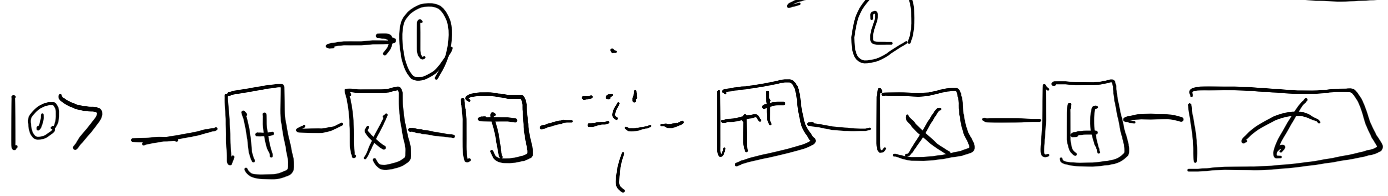
That's an active research question!

How good are our gates?

We quantify quantum gates using gate ***fidelity***

$\{H, T, X\}$

One popular example is randomized benchmarking:



$HH = I \quad TT^\dagger = I$

$XX = I$

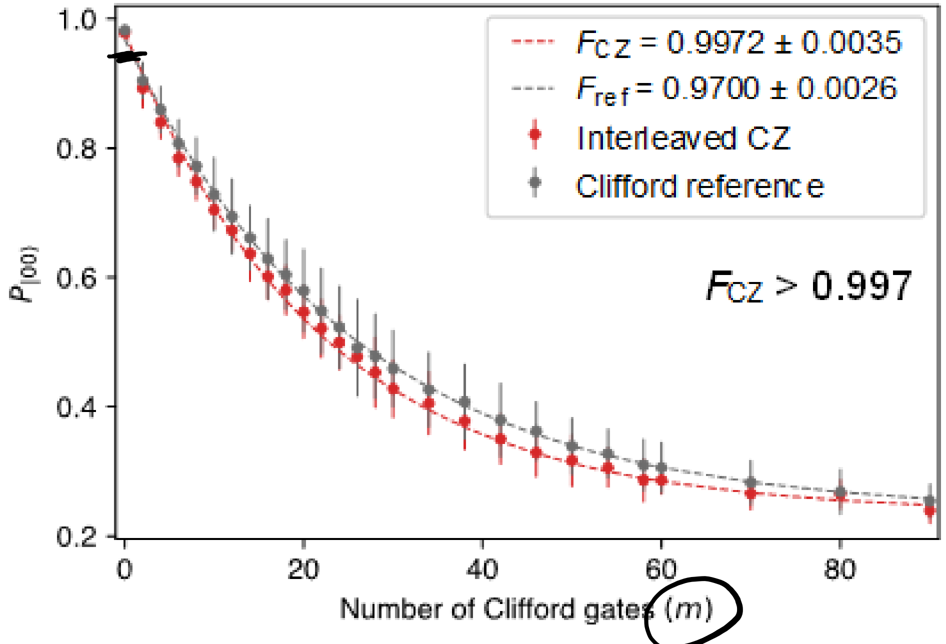
m is # of gates

ideally 1

error <1

$C F^m \rightarrow F = .997$ (or 99.7%)

fidelity



How good are our gates?

A .995 (99.5%) gate fidelity sound good! (or does it?)

What if we have a circuit with 200 of these gates?

overall fidelity of the circuit $= (.995)^{200} = 0.367$ (or 36.7%)

(we want $> .66$)

what if we had .999 (99.9%) fidelity?

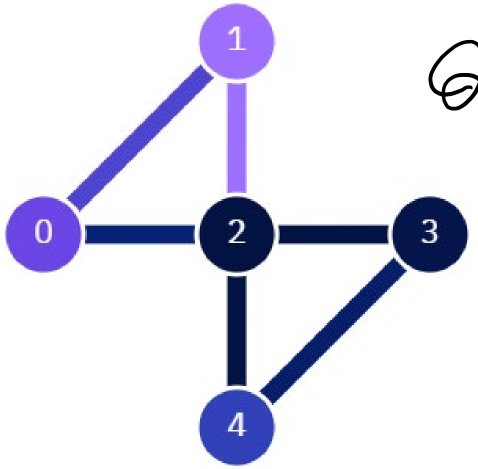
$(.999)^{200} = 0.819$ (81.9%)

Which processor is better?

Quantum Volume?

1) ibmq_5_yorktown

QV=8



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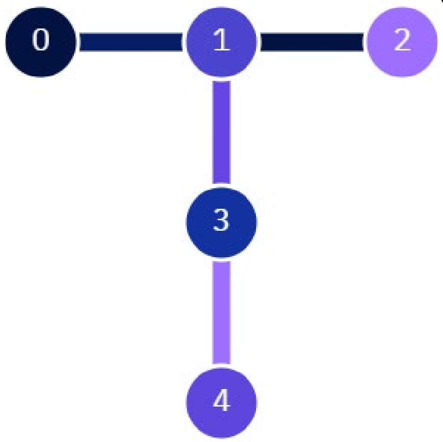
2) ibmq_belem

QV=16



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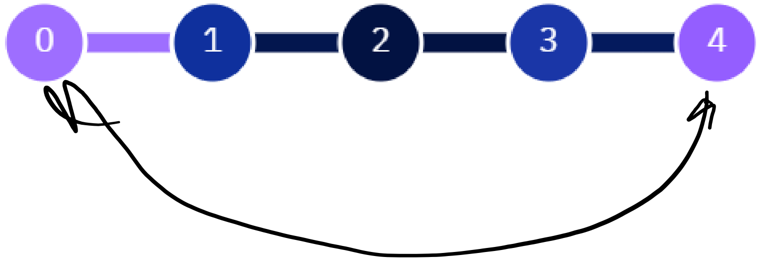
QV=32



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