Seminar 10

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Quantum Computing Hardware

Week 10 | November 27, 2022

Lecture Overview

- Quantum hardware: a brief introduction
- Types of qubit implementations
- The physical process of running a circuit
- Noise & errors
- Today's quantum hardware reserach & industry landscape

Key Questions:

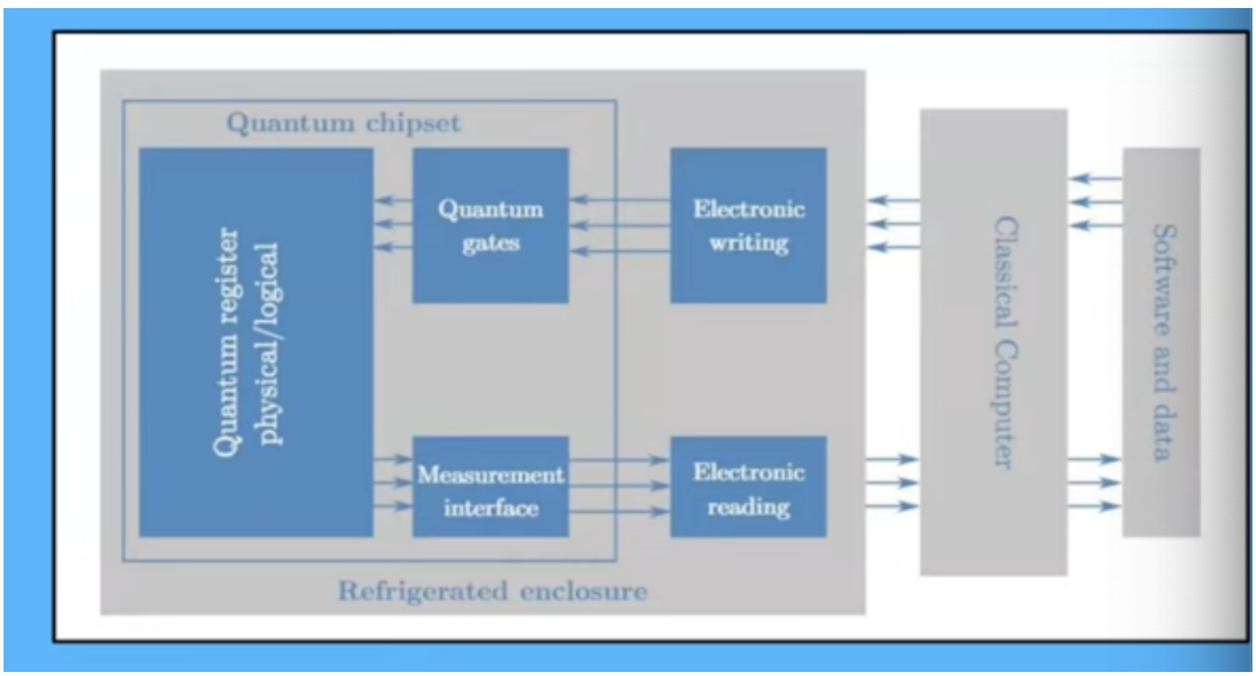
- What are the physical components of a quantum computer
- What physically happens when you run a circuit on quantum hardware
- We don't have useful quantum hardware yet…Why?
- What is the state of hardware in the quantum computing industry today?

A Note on Hardware:

- There isn't one universal type of quantum computer. There are a LOT of different quantum computers because there are many different physical approaches to quantum computation
- The choice of qubits largely defines what the quantum computer looks like and how it is built
- Different qubits, different ways to apply gates, different applications for these hardware configurations

Intro Qauantum Hardware

Quantum computations relies on multiple hardware and software components working together in tandem. Today's focus will be on the hardware side of the computer.

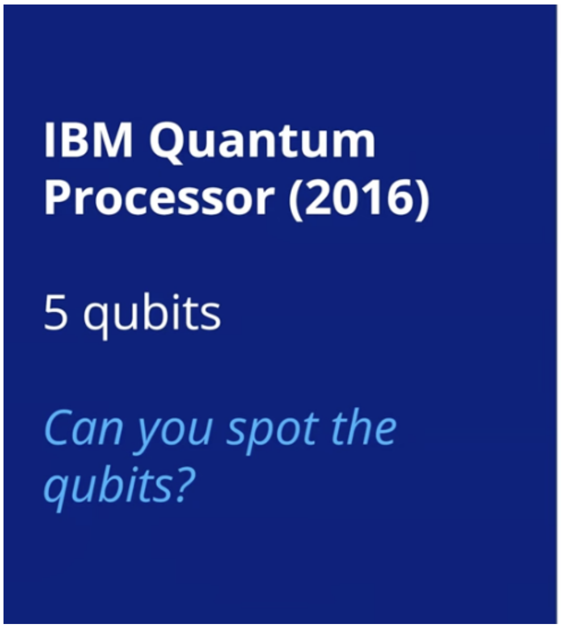


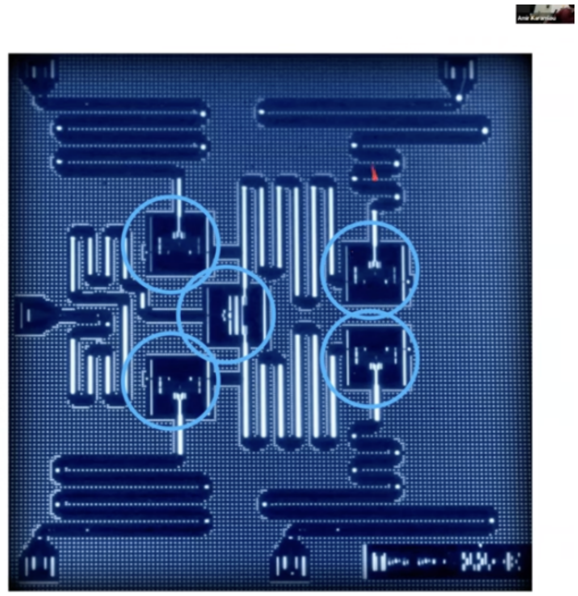
Deconstructing a Superconducting Quantum Computer:

- Referred to as a "chandelier" (inside of a dilution refrigerator)
- The way our quantum computer is constructed depends on the type of qubits that are used

Quantum hardware can be divided into tow parts: The Quantum Chipset (qubits) and The Refrigerated Enclosure (hardware to operate communicate with the qubits)

The quantum chipset is roughly the size of a US Penny (sits at the bottom of superconducting system). This place is called the Quantum Processing Unit (QPU) since that is where the coldest temperatures can be hit. This is referred to the “brain” of the quantum computer. QPU is susceptible to noise from the outside world.



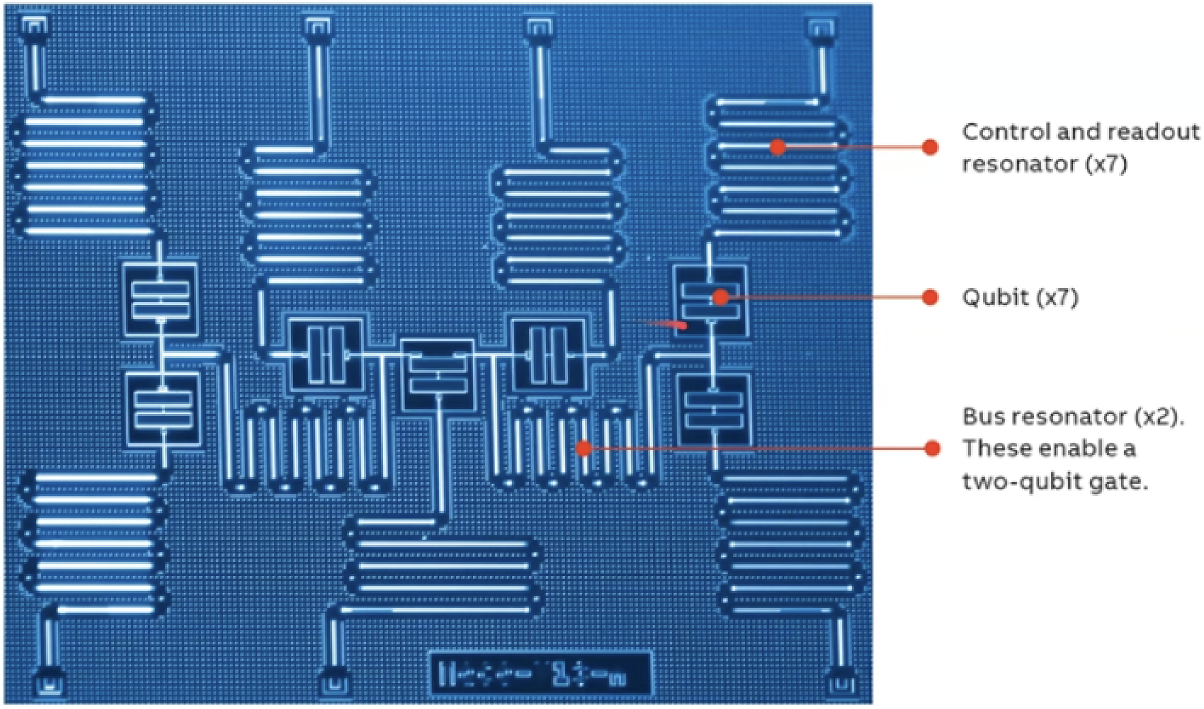


6 years later…

IBM Osprey Processor (2022) - 433 Qubits. Now there are qubits on different layers not all on the same layers. This tired approach will allow us to expand the size of our QPU greatly.

Other Components of the QPU:

There are other mechanisms called resonators that help is control and communicate with the qubits



Source: *https://new.abb.com/news/detail/74736/quantum-computing-the-hype-and-hopes*

Qubits and Their Environments:

- To understand the challenges we must understand the distinction between qubits (fundamental unit of computation) and their environment (everything else)
- - Unlike classical bits, qubits are highly sensitive to their surroundings or environments
- In order to hold their quantum state (and provide us with useful information) we need to isolate qubits form their environment
- Qubits are Notoriously Hard to Control
    - Today's qubits rarely make it one one-thousandth of a second before making an error because of the environment
    - We can protect our qubits from the environment heat by keeping them extremely cold (dilution refrigerator)

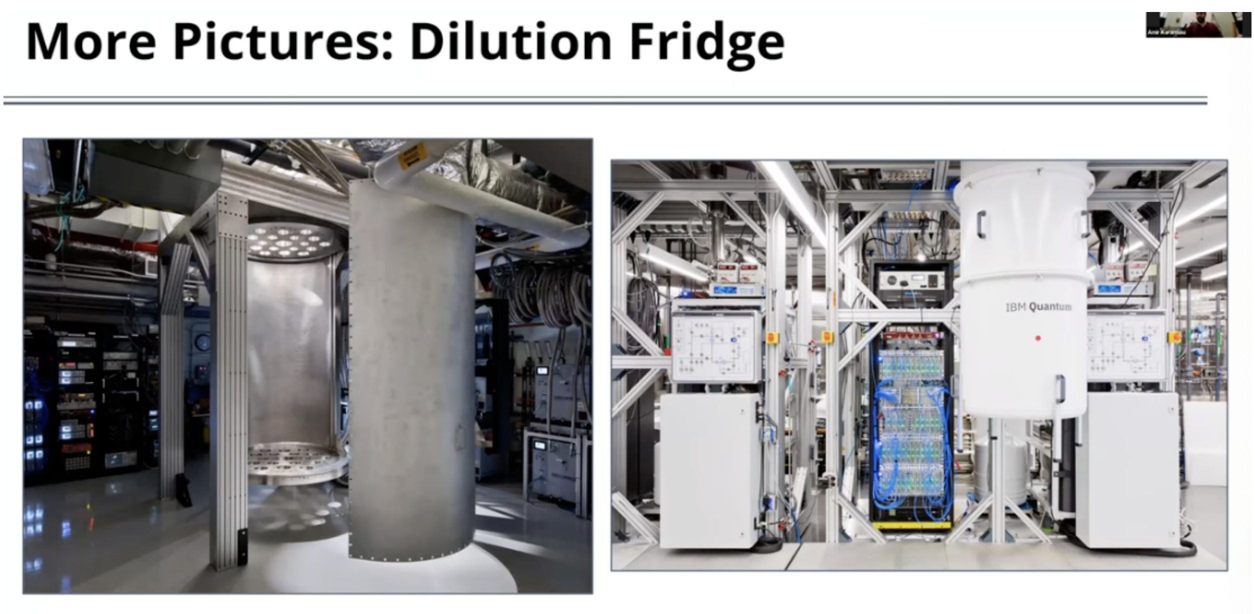
The Dilution Refrigerator

- For qubits to do anything useful, they need to be isolated from their environment. The purpose of this machine is to keep the qubits cold (almost absolute zero ~ 0.01

Kelvin - colder than outer space)

- Qubits are extremely sensitive to their environment and don't maintain their states for very long
    - Cold temperatures will allow a low probability for heat to be absorbed and cause an error
- **Closed Cycle Refrigeration:**
    - Two mixtures of helium are prepared with different concentrations (one more dilute than the other)
    - When mixtures are brought together, they naturally want to balance each other out by mixing together
    - But this particular combination need heat to mix together. It does this by extracting heat form its surroundings. With pumps, this can happen cyclically
    - We engineer the combination to extract heat almost exclusively from where we keep the quantum chip

More Dilution Fridges:



Qubits

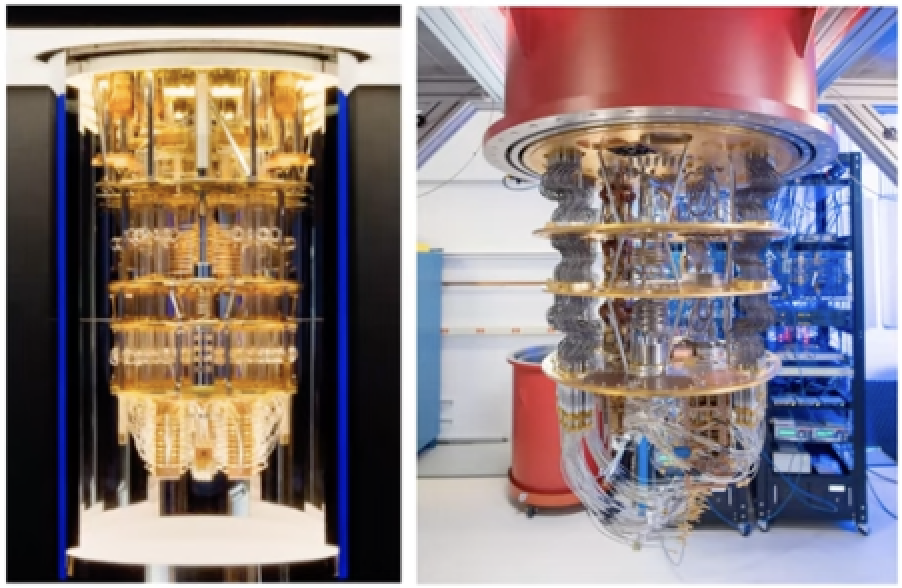
A fragmented qubit landscape

- Classical bits are universally made of transistors
- The materials used for qubits are varied
- Different qubits have their own pros/cons

Qubits are **two-level** quantum systems that can encode information

Exploring 4 types of qubits:

- Superconducting qubits
  - Engineering artificial atoms using circuits made of superconducting material
  - Superconductivity: As electricity moves through normal resistance, it experiences resistance; Material resistance drops as temperature gets lower
  - For some materials, the resistance sharply drops to o at a critical temperature (superconductor -fundamentally a quantum phenomenon)
  - In superconducting quantum computers, gates are applied through microwave pulses. The fundamental component of most superconducting qubits is the Josephson Junction:
    - Two superconducting on either side of a thin insulating barrier, which forces current to quantum tunnel through it.
    - Josephson junctions can be engineering to make different properties of a circuit discrete, which allows us to encode the “0” and “1” state into them
    - Examples:



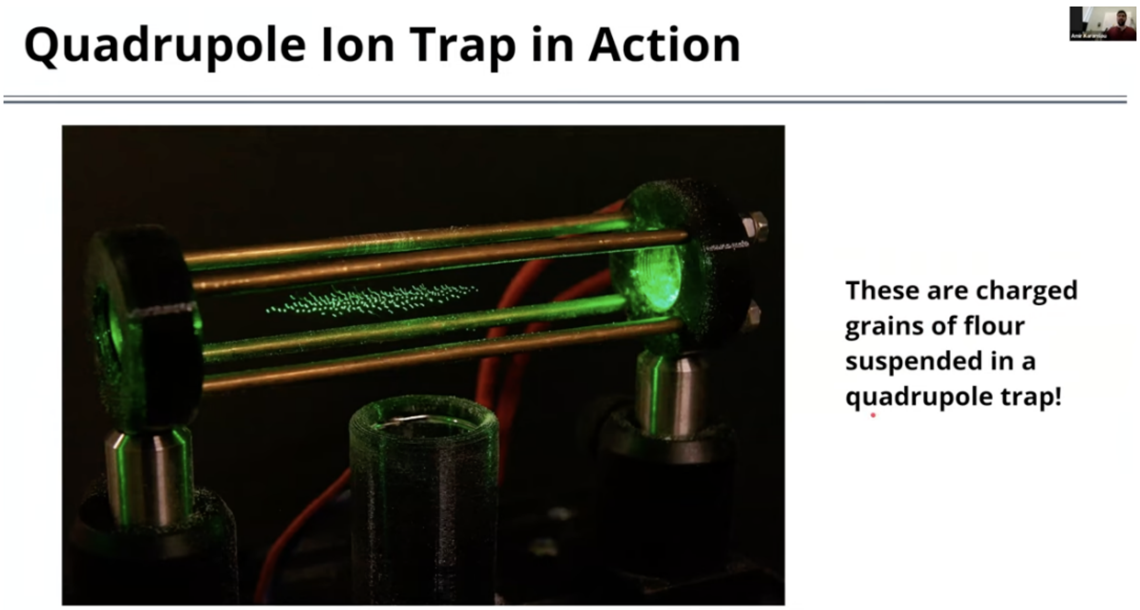
Superconducting qubits are among the most widely-used qubits in the industry right now: Key players: IBM Q, Google Quantum AI, Rigetti Computing, AWS, Intel, IQM, Alibaba, DWave

- Pros:
    - Faster operation time than other qubits
    - Uses microwave and radio frequency technology which is well-developed
    - High quality gates and readout
- Cons:
    - Qubits are very short-lived and hey close their information almost immediately and therefore require error correction techniques
    - Requires cooling to mK temperature - need bigger dilution fridges for larger processors

- Photonic Qubits
    - Photons are particles of light. While they are particles, photons can still have wave-like qualities, like wavelength, frequency, etc..

    - One approach to photonic quantum computing is linear optics Quantum computation (LOQC. This approach has already demonstrated quantum advantage
    - A prominent use case of LOQC is quantum communication because if its compatibility with existing lnear optic infrastructure + ease of sending light long distances.
    - LOQC operates photon using linear optical elements like mirrors, beam splitters, and phase shifters (seen in quantum flytrap simulator)
    - **Key Players:**
        - PsiQuantum
        - XANADU
    - Pros:
        - Can be used at room temperature
        - Compatible with exiting optical infrastructure
        - Uses photonic technology which is well developed
        - Low single photon error rates
    - Errors:
        - Entanglement is difficult (photons are hard to interact with each other)
        - Single photon generation is unreliable
        - Superconducting detectors require cooling to K temperatures
        -
- Trapped Ion qubits
    - Using electromagnetism and lasers to trap and manipulate ions
    - We can encode quantum states into the energy levels of an atom. But atoms are tiny and move around randomly, making them hard to work with.
    - So, we use an electromagnetic field to trap ions (charged atoms) into place
    - There are three key parts to an ion trap: ions, an electromagnetic field, and lasers

- The electromagnetic field is tuned to trap and suspend an ion in free space
- Lasers are then used to change the energy level of the ions (states of the qubits). In other words, the lasers are how we implement gates

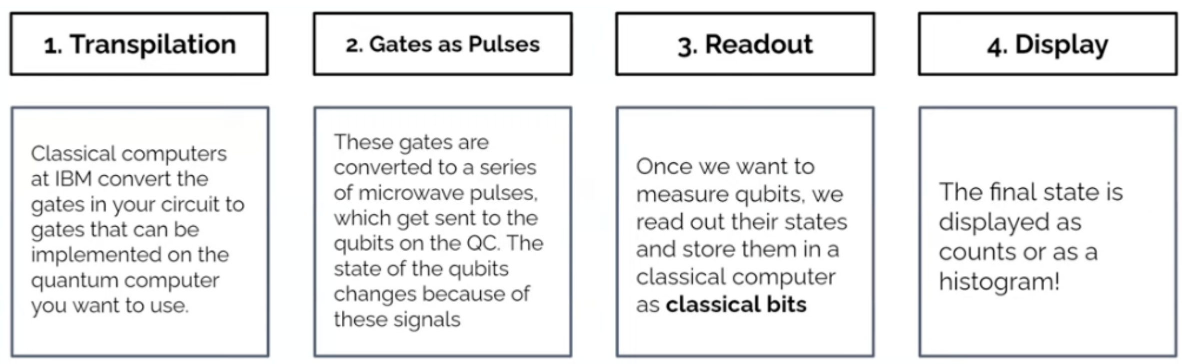


- **Trapped-Ion Qubits: Key Players**
  - ION Q
  - Quantinuum
  - AQT
- Pros:
  - Much more stable than other qubit types. They take a longer time to lose their quantum information
  - Gate are generally very reliable
  - Can operate at room temperature, ad are easier to cool then superconducting qubits
- Cons:
  - They are slower than superconducting qubits

        - After a while (months or longer), the ions can leak away meaning the qubits need to be periodically replaced
        - Controlled a large number of ions is challenged and so scalable to many qubits will be difficult
- Topological Qubits
    - A scientific and engineering challenge with a potential major payoff
    - This is a fundamentally approach to qubit design
    - Proposed in theory but have not yet been demonstrated in practice. They are still being developed today
    - This is in stark contrast to more traditional qubits. Topological qubits are very difficult to engineer
    - The payoff: Scalable qubits that are nearly error-=fee (ultimate goal)
    - The study of anyons is a field of mathematics called topology. Theoretically, we can braid these anyons to store and manipulate quantum information in a way that is nearly error-free
    - This is the approach of Microsoft (big gamble)
        - Possibility of a future-proof quantum computer is worth the wait
        - The qubits of today are not going to be the basis of the quantum computers tomorrow
        - Today's qubits are not going to make a commercial scale quantum computer

Running Circuits

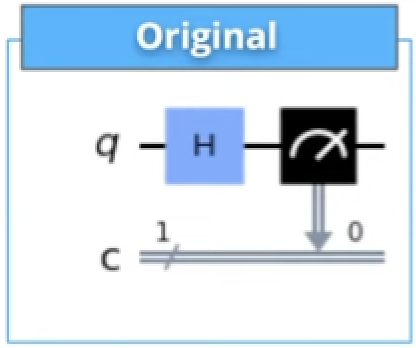
What physically happens when you press “run” when coding on quantum hardware?

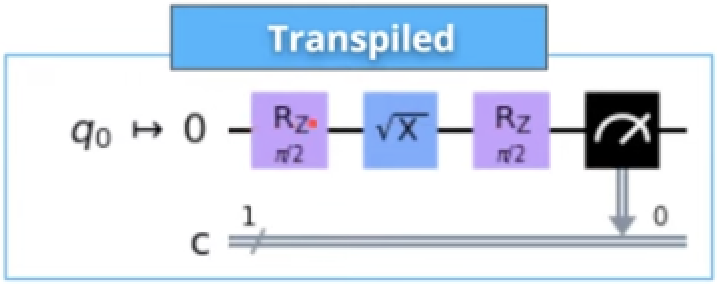


Step 1.

The circuit is translated into gates that can actually be implemented on the hardware you want to use:

- Sometimes the gates you want to use in your circuit cannot be directly implemented on the quantum computer you want to use
- In this case, the gate is your circuit are converted to gates that the computer can implement, so that the end result of the circuit is the same
- As an example, here’s how an hadamard gate gets implemented on the ibm_nairobi:





- The transpiled circuit can look very different on different types of quantum computing hardware

Step 2.

After transpilation, your circuit is ready to be implemented on the hardware. The gates in your circuit get converted to a sequence of energy pulses - different gates are implemented as pulses of different duration and energy

Different pulse have different shapes and involve different amount of energy

Step 3 + 4:

Readout: This is when we transition form quantum to classical computing. Once we want to measure qubits, we read out their states and store them in a classical computer as classical bits

Display: This is when the result of your measurement is shown on your computer, often with histograms or counts

To summarize, here's what happens when you run a circuit on quantum hardware:

1. **Transpilation:** Your code gets sent to IBM's servers. Classical computers convert the gates in your circuit to gates that can be implemented on the quantum computer you want to use.
2. **Applying gates as Pulses:** These gates are converted to a series of microwave pulses, which get sent to the qubits on the quantum computer. The state of the qubits changes because of these signals
3. **Readout**: Classical computers **measure the final state** of the qubits
4. The final state gets sent back to your computer and **displayed** as counts or as a histogram

This works in theory but there are factors and challenges at play that interrupt this computational process: Such example: Errors & Noise

Noise & Errors:

- The environment around the qubit is noisy. There's heat, radiation, stray electromagnetic fields, mechanical vibrations, and other environmental disruptors
- All of this noise can disturb the qubit's state and cause errors in the quantum computer.
- Noise and errors are our primary barriers to engineering useful quantum computer

Noisy qubits lead to noisy data. As we scale up the number of qubits, there errors can compound and significantly impact the outcome of our computation

Noise in States, gates, and Measurement - We see noise and errors appear in each stage of the quantum circuit model

Two type sof Noise:

1. Relaxation
2. Decoherence

Qubits naturally don't want to stay in one place.

Qubits want to be in their lowest energy state, which tends to be what we choose for "0" state

Noise from the environment cause qubits to relax form the “1” state to the “0” state

You can think about this like a cup of coffee that gets cold when it is left out

Qubit Decoherence:

- Suppose you prepare your qubits in the “+” state to conduct an experiment. You check back later and find that your qubits are no longer in a superposition state
- Your qubits have lost their coherence
- decoherence is the loss of the quantum information stored in qubit states (loss of phase, will be discussed later)

Measuring Qubit Decoherence	**Qubit decoherence happens over a typical time scale, known as T_2.** Like T_1, researchers are working to increase T_2 time.

Noise in Gates:

- We apply gates by supplying the qubit with just the right energy to transfer it form its initial state to its final state.
- However, there can be errors in the exact energy given to the qubits. We may accidentally supply too much or too little
- This can cause gate errors - the final qubit state is not what we want it to be because of errors in how the gate was applied. these errors will concatenate

Gate Fidelity:

- Tis what gate errors are measured through. Fidelity is a measure if how reliable the gate is -if you applied the same gate 100 times, how many times would it produce the right final state?
- Gate errors can compound - if one gate makes an error and you have lots of gates in the q-computer, the errors will propagate

Noise in Measurement:

To measure qubits, we have to temporarily “open them up” to the environment, so that we can measure their state. This leaves them vulnerable to errors, known as measurement or readout errors

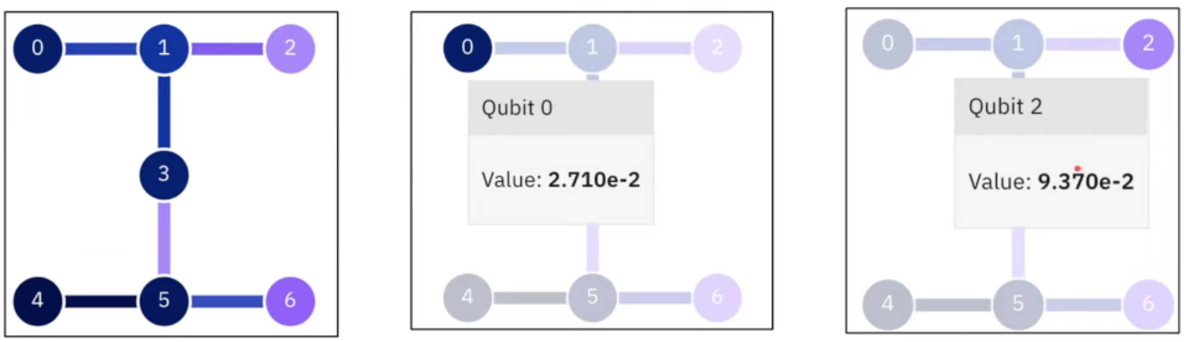
Measuring qubits is a very tricky balancing act, and is at the heart of quantum computing

- One one hand we want to isolate our qubits so that they are not affected by noise
- However we can't isolate them so much that they can't be measured when we want to.

A common way to quantify readout errors (measurement errors) is how often they occur

0.01 would be 1 incorrect readout in every 100 runs

- This will change for different qubits being measured in different states



What cna we do about Errors?

1. Reduce noise by reducing noise form the environment
2. Correct errors by changing how information is encoded in qubits - this is known as quantum error correction

Error correction is a general set of techniques for making computation work correctly even if there are errors. This is a crucial part of both classical and quantum computing

QEC is a about protecting quantum computers form errors, often relying on quantum properties since classical approaches don't tend to work

- QEC is vital to creating fault-tolerant quantum computers

Quantum Error Correction;

- We need some way to encode quantum information in way that correct errors as they happen, potentially including measurement that is not too destructive

    - If done using classical computer method, the entire quantum computation would collapse
- These encoding are called quantum error-correcting codes
- QEC is a huge field that is vital for accomplishing the long term goals of Quantum Computing

The Quantum hardware Landscape

what does hardware look like in today’s quantum reserach and industry landscape?

Di Vincenzo’s Criteria:

- Proposed in 2000 by David Di Vincenzo
- A 5-point hardware wishlist for quantum engineers
- Represent the ideal standard for quantum hardware

1. Well characterized and Scalable qubits
2. Initialize Qubits
3. Long coherence times’
4. Universal set of gates
5. Efficiently measurable

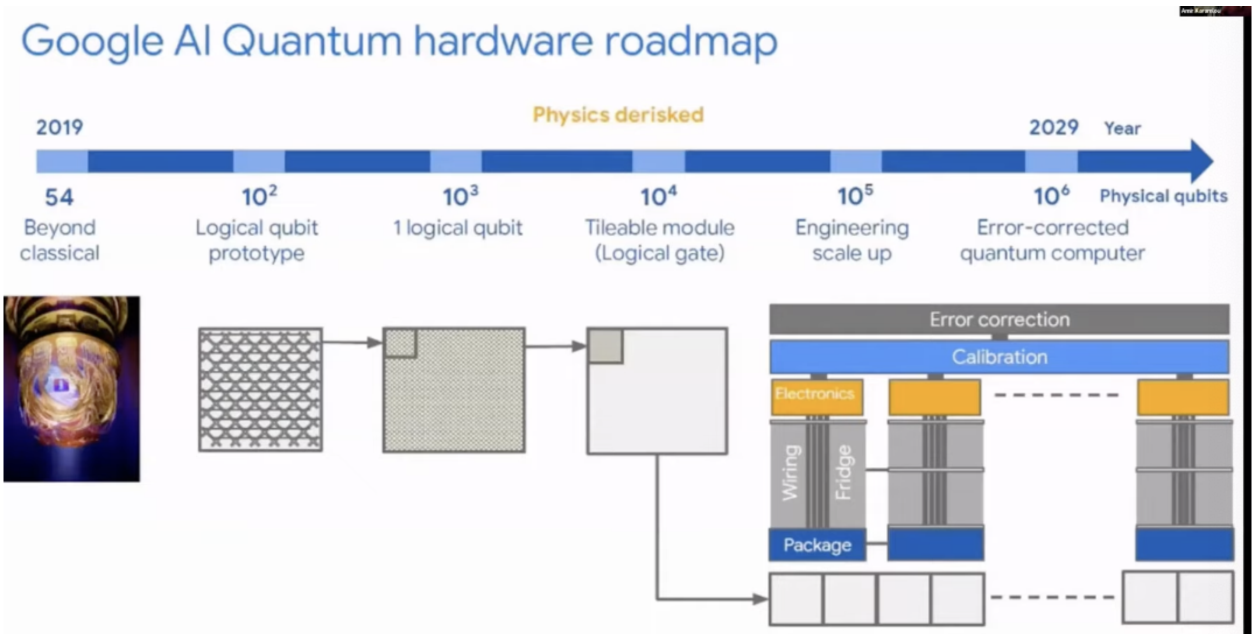
To achieve the 5-points of Di Vincenzo’s Criteria, we need:

- More Qubits (more scalable)
    - How many more qubits do we need?
    - Logical Qubits:
        - Representations of qubits that we use for programmings
    - Physical Qubits
        - Actual, physical materials (ins, photons, superconductors) we use to process quantum information
    - To correct for errors, we need to implement multiple physical qubits per logical qubit in a quantum algorithm

- Example: Shor's error correction code: 9 physical qubits to 1 logical qubit

- Better Quality Qubits (less Noise)
  - Goal is to design quantum devices that can correct for the noise and be fault-tolerant
  - **Quantum threshold theorem:**
    - There exists a certain threshold for error rates below which we can achieve truly fault-tolerant computation., With enough error correction we can achieve this rate

Sample Roadmap (Google AI):



The Quantum Startup Landscape:

Roadmap Key Terms & Metrics:

- Number of Qubits
    - How many qubits is this company projecting? Is it impressive by industry standard?
- Gate Fidelity
    - How reliable are gate operations on these qubits?
- Error & Reliability Metrics
    - What is the rate of errors when information is processed in these qubits
- Physical Qubit Architecture
    - How are the qubits arranged and connected physically?
- Timeline
    - How realistic does this timeline sound base don my knowledge of current quantum technology and what other companies are projecting?

When should you believe the roadmap and press release hype?

1. Is there a significant number of qubits in this projection?

2. How good are these qubits? What is the error rate? Where is the error rate? Is it clearly disclosed, or is it buried in the fine print (is it even there?)