CSCI 4140 Superconducting Quantum Computers

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Introduction

- This is the technology used by IBM and Google
- It is the one that tends to get the most attention, mainly due to the large companies involved
- This is far more complicated than ion trap
- Will not go into all of the details, it requires a large amount of physics and math
- Will do a high level overview of how the technology works

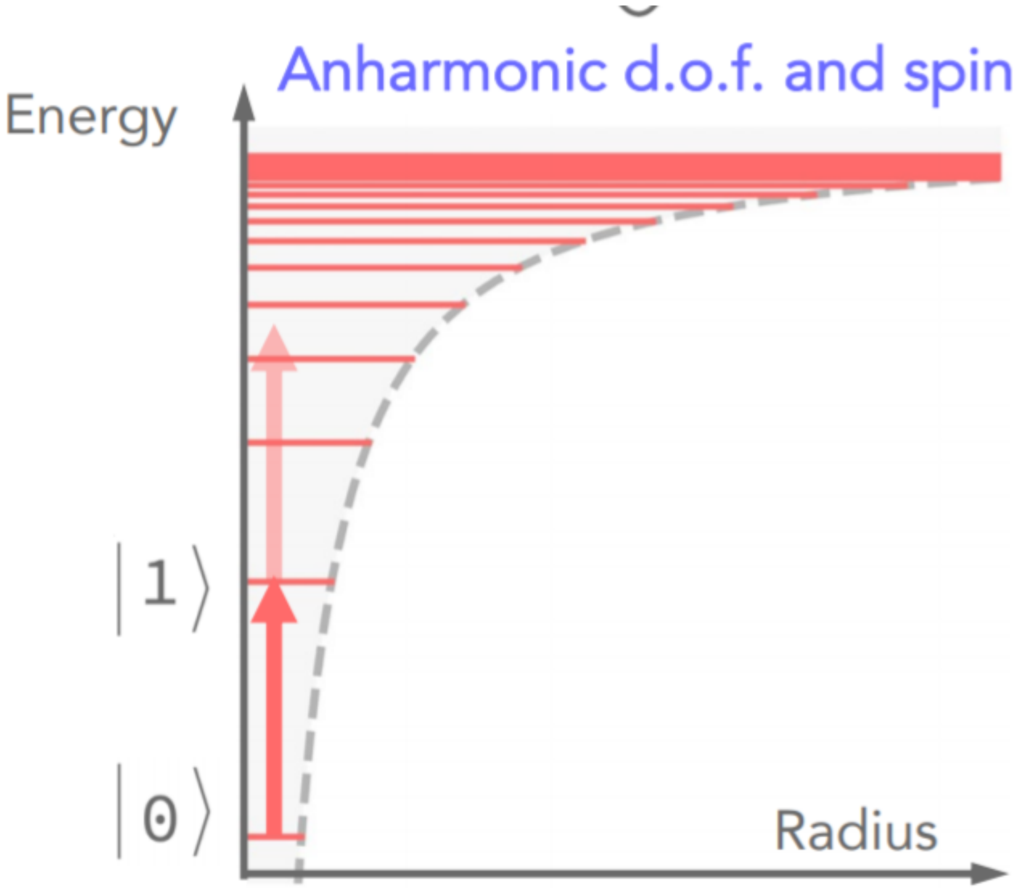
References

- A good source of information is the IBM course on quantum computing, it has extensive notes and videos:
  https://qiskit.org/learn/intro-qc-qh/
- In particular Slatko Minev’s lectures are quite good, but they do get into a lot of technical details:
  https://www.youtube.com/watch?v=eZJjQGu85Ps&feature=youtu.be&list=PLOFEBzvs-VvrXTMy5Y2IqmSaUjfnhvBHR

Basic Idea

- As we’ve seen with ion traps atoms have a fixed number of energy levels and radiation can be used to move between these levels
- Ion traps are based on the idea that each of these transitions requires a different energy level, so it’s possible to select the transition that you want
- This is shown on the next slide
- But, superconducting quantum computers don’t use atoms in this way, they construct electrical circuits the simulate them

Basic Idea

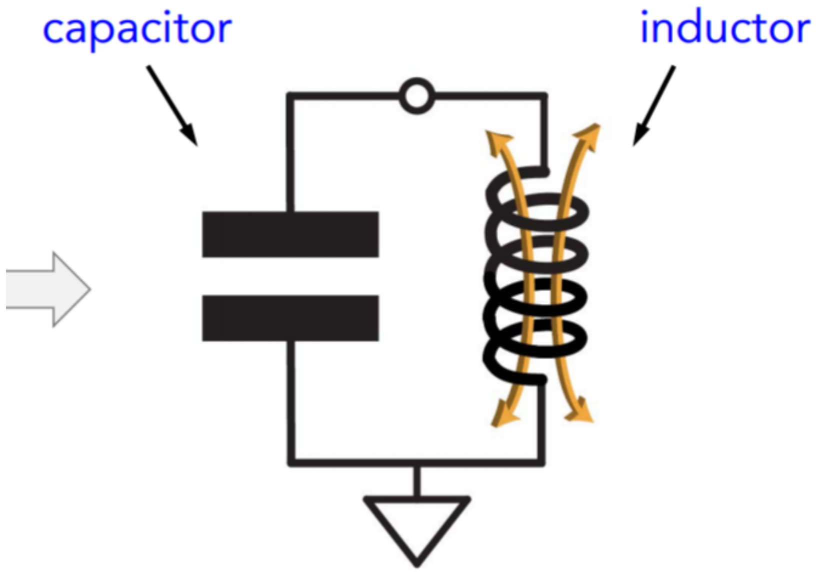


Basic Idea

- If we cool an object to a low enough temperature then quantum effects are the main thing that we see
- This is the idea behind superconductivity, materials that don't conduct electricity very well at room temperature become very good conductors at very low temperatures
- This allows us to construct an electrical circuit that will simulate the transitions we see it atoms
- This circuit is called a transmon

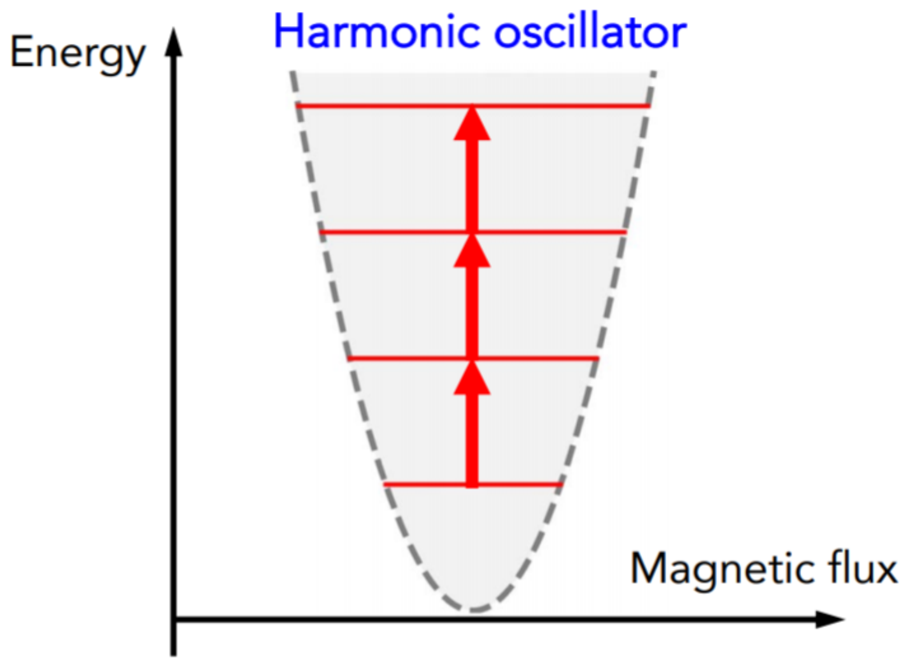
Transmon

- We can easily construct an electrical oscillator with a few simple components, this part doesn't require superconductivity



Transmon

- This circuit respond to a certain frequency and its multiples, called a harmonic oscillator

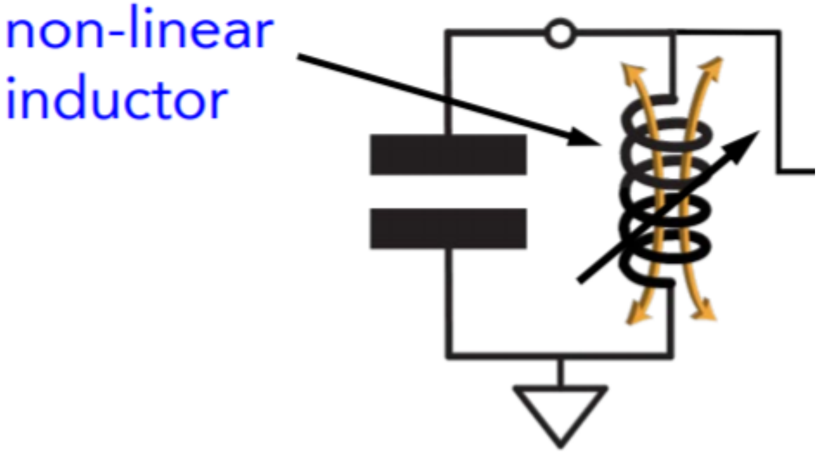


Transmon

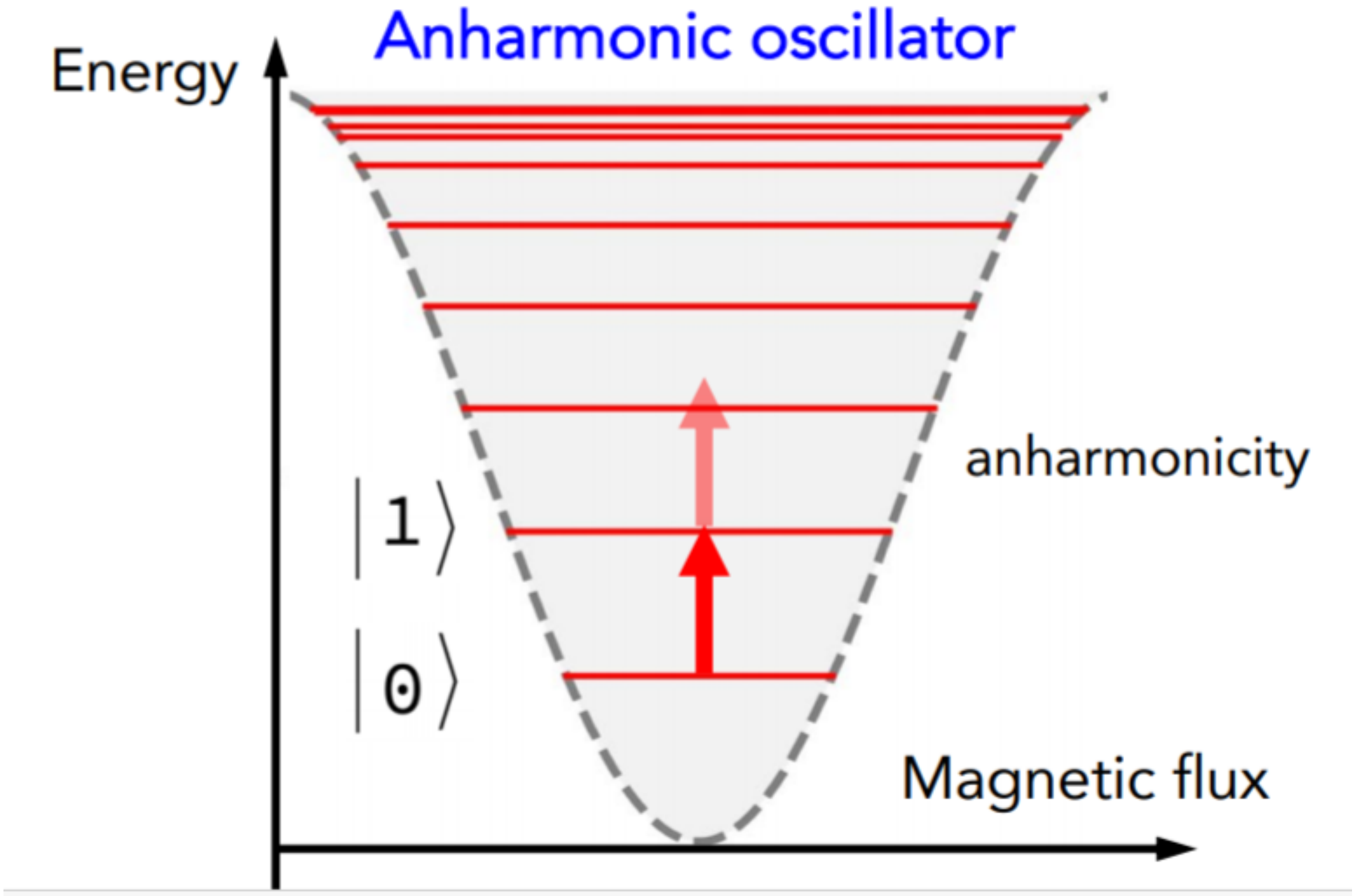
- That’s close to what we want, it has a fixed number of energy levels
- But, there is a problem here, all the energy levels are separated by the same amount
- If we start at state |0> and start pumping in energy to go to state |1> we could also go to one of the higher states
- This isn’t what we want, we want each of the transitions to require a different amount of energy

Transmon

- The solution to this is to change the inductor, so that it changes its value proportional to the amount of energy in the circuit
- This produces a transmon



Transmon



Anharmonic oscillator
Energy
anharmonicity
|1⟩
|0⟩
Magnetic flux

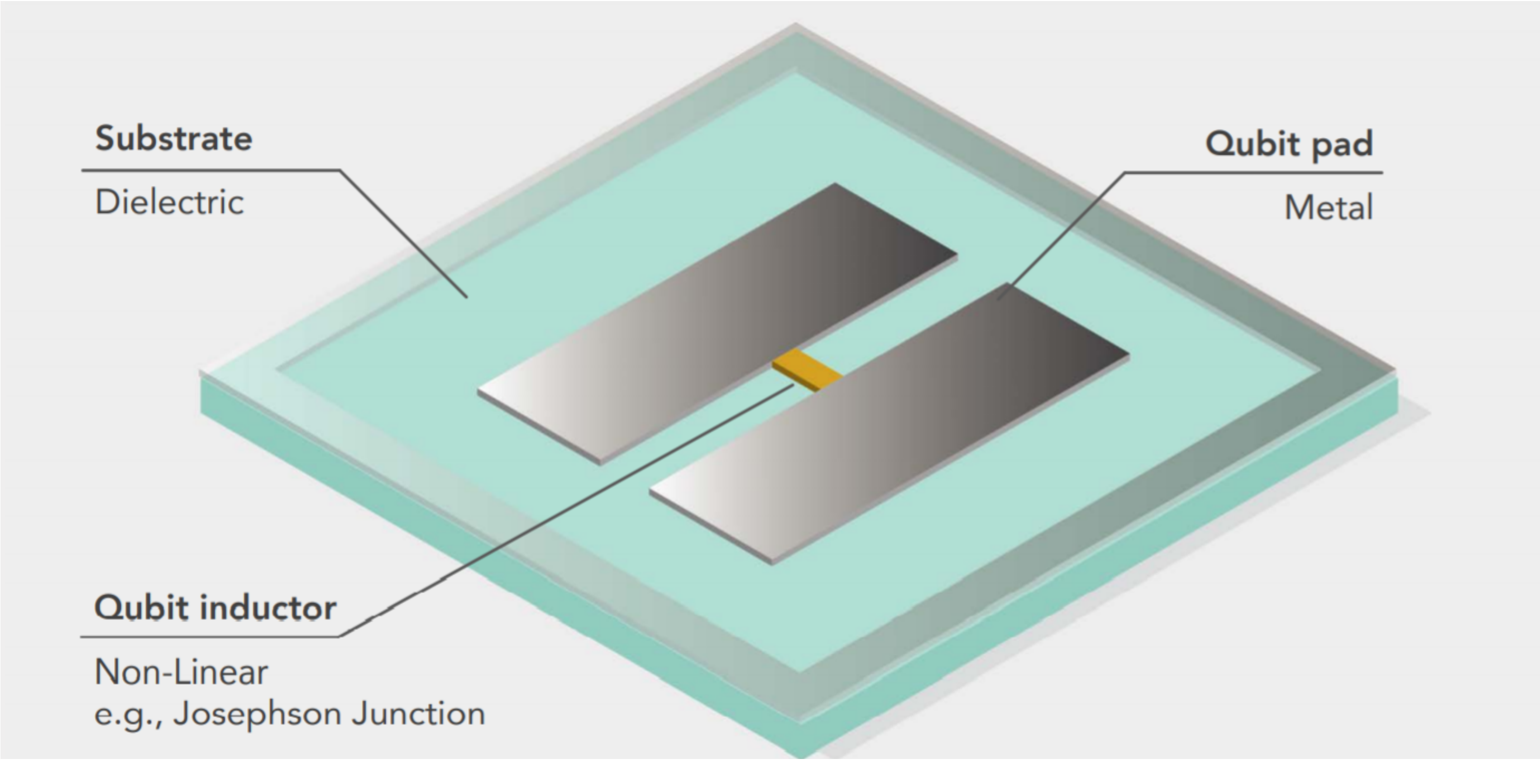
Transmon

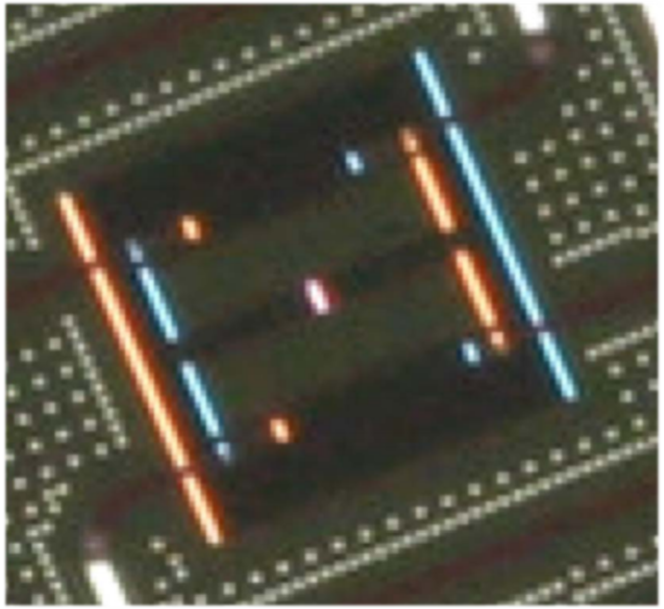
- Now each transition requires a different energy level, so we can control when we get a |0> and a |1>
- Now the question is where to do we get an inductor that behaves like this?
- It turns out that a tunneling Josephson junction does the trick
- This is where superconductivity and the requirement for low temperatures comes in
- Low temperatures also helps with noise, so this isn’t a real problem

Transmon

- A schematic of a transmon is shown on the next slide
- This is fabricated in basically the same way as computer chips and each transmon is quite small, can currently get 65 on a chip
- The two metal pieces form the capacitor and the small rectangle connecting them forms the Josephson junction
- A picture of a fabricated transmon is shown on the next slide

Transmon

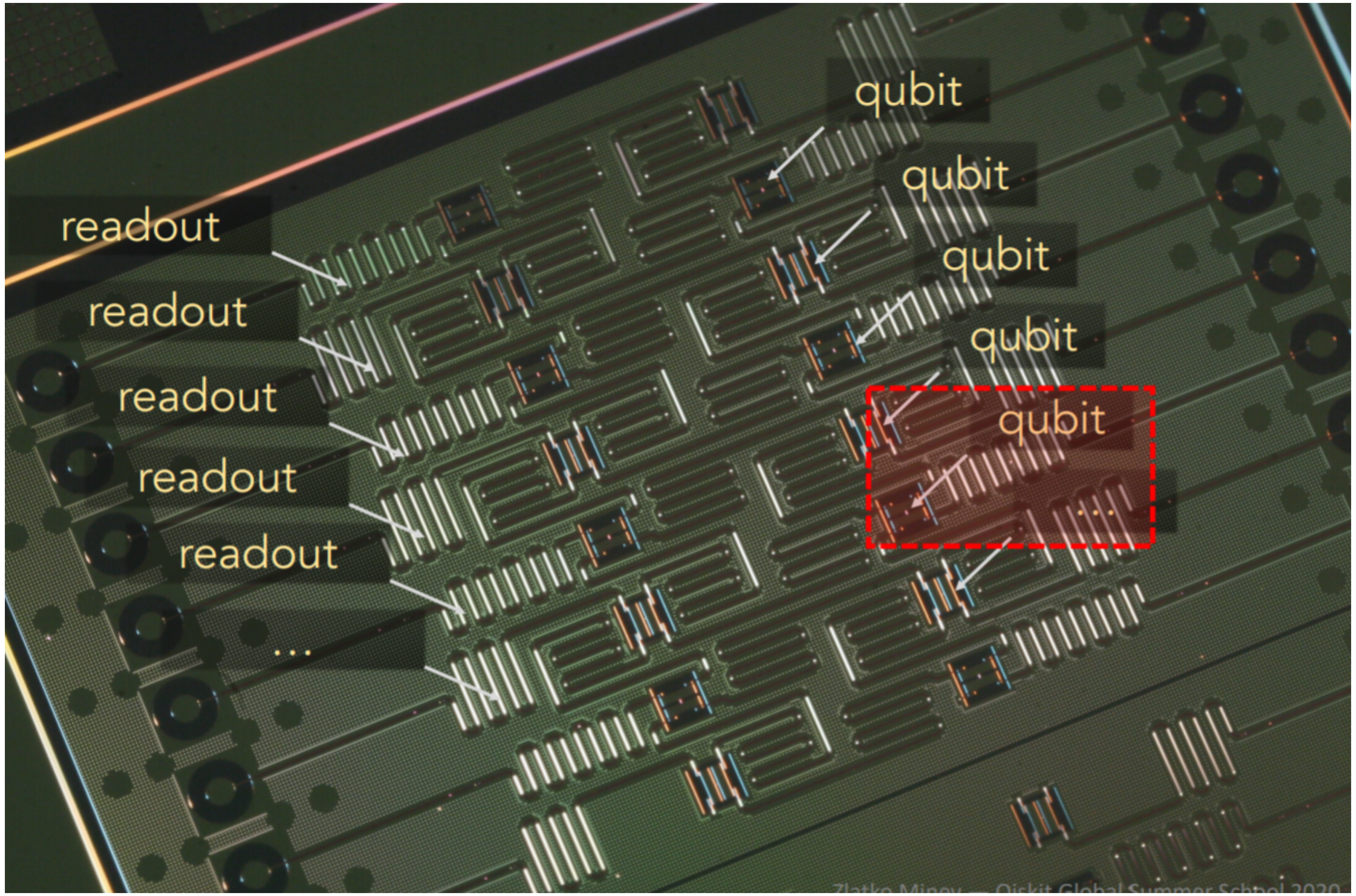

Substrate
Dielectric
Qubit pad
Metal
Qubit inductor
Non-Linear
e.g., Josephson Junction



Transmon

- How do we control a transmon?
- Micro wave energy in the 10Ghz region is used to control them
- Pulses of energy are used to change state and measure the qubit
- This energy is channeled to the qubit over wave guides, the squiggly shaped lines on the chip
- The layout of a typical chip is shown on the next slide
- You can do pulse level manipulation of qubits in Qiskit

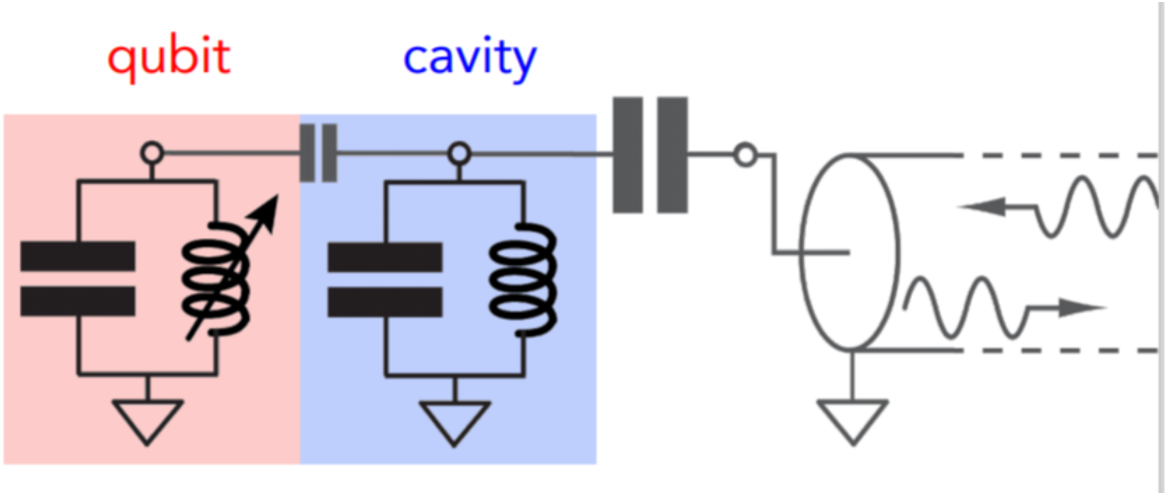
Transmon

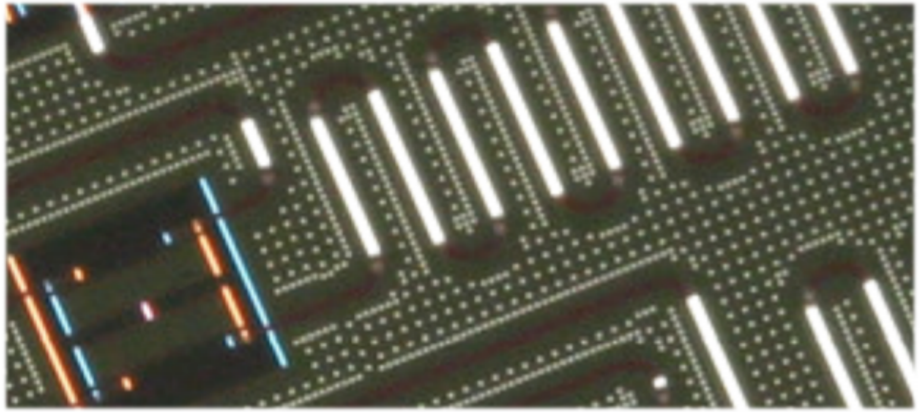

qubit
qubit
qubit
qubit
qubit
readout
readout
readout
readout
readout
...
...

Transmon

- How do we measure the result of a computation
- We go back to our oscillators that are tuned to a particular frequency
- We insert a pulse into the transmon, which causes a transition
- Depending on the qubit state, it will generate a different energy or frequency, one of which will match the oscillator and produce a signal from that oscillator

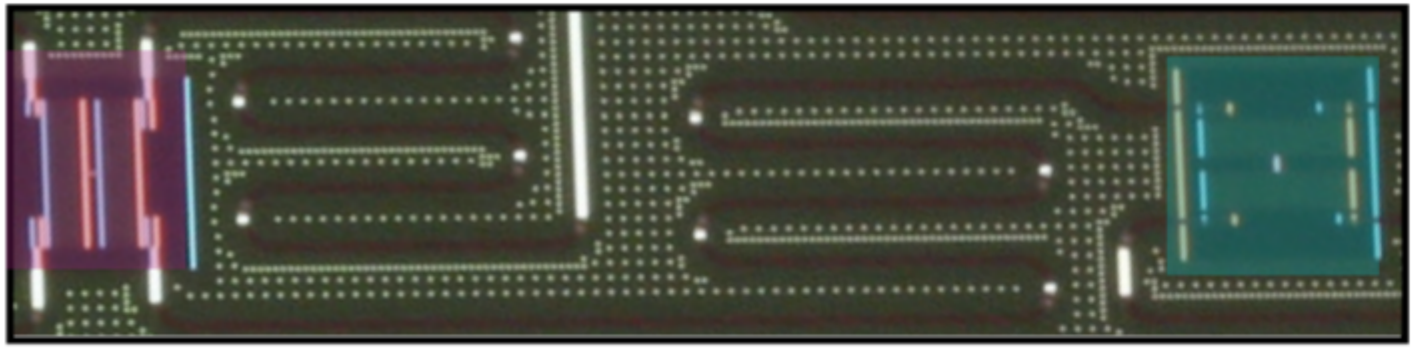
Transmon





Transmon

- Gates: we can get a one qubit gate by using different types of pulses, this is easy to feed to the transmon
- For two qubit gates we need to be able to couple the transmons so they work as a unit, note how they are physically connected with the wave guide



Transmon

- This is one of the problems that we have with this technology, there must be a significant connection between the qubits on the chip in order to perform two qubit gates
- Given the 2D layout, there is a restricted number of interconnections that can be made
- This is one of the barriers to increasing the number of useful qubits on a chip
- Going to a 3D layout may be a solution to this problem

Qiskit Metal

- There is now a part of Qiskit that supports the design of transmon based quantum computers
  - https://youtu.be/C5jDrZgLQ_s
- Information on this can be found at:
  - https://qiskit.org/metal/

Complete System

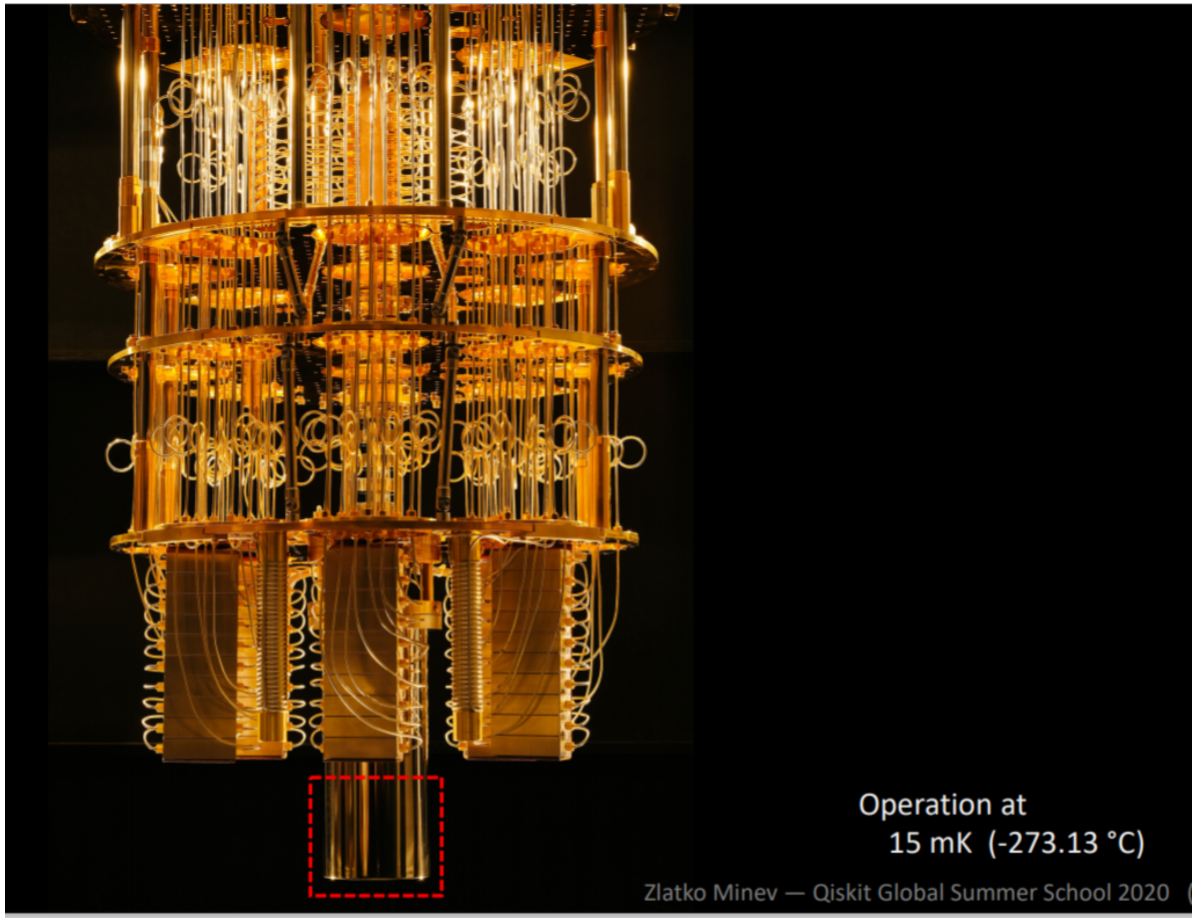
- The chips are small, but the whole system is quite large
- A typical current generation IBM system is shown on the next slide
- The next generation systems are larger, a person can stand inside the cooling system
- This is one of the major cost points for the systems
- There are also a lot of electronics that are used to generate the pulses and decode the measurements

Complete System

Cooling

- We must get as close to absolute zero as we can
- The next slide shows what's inside the cooling system
- The actual quantum chip is at the bottom
- The very top is at room temperature, 300K, the chip at the bottom is at 15mK
- Why is it so big?
- Need to have room for the cooling system, in the middle of the center tier
- Also need room for electronics

Cooling


Operation at
15 mK (-273.13 °C)
Zlatko Minev — Qiskit Global Summer School 2020

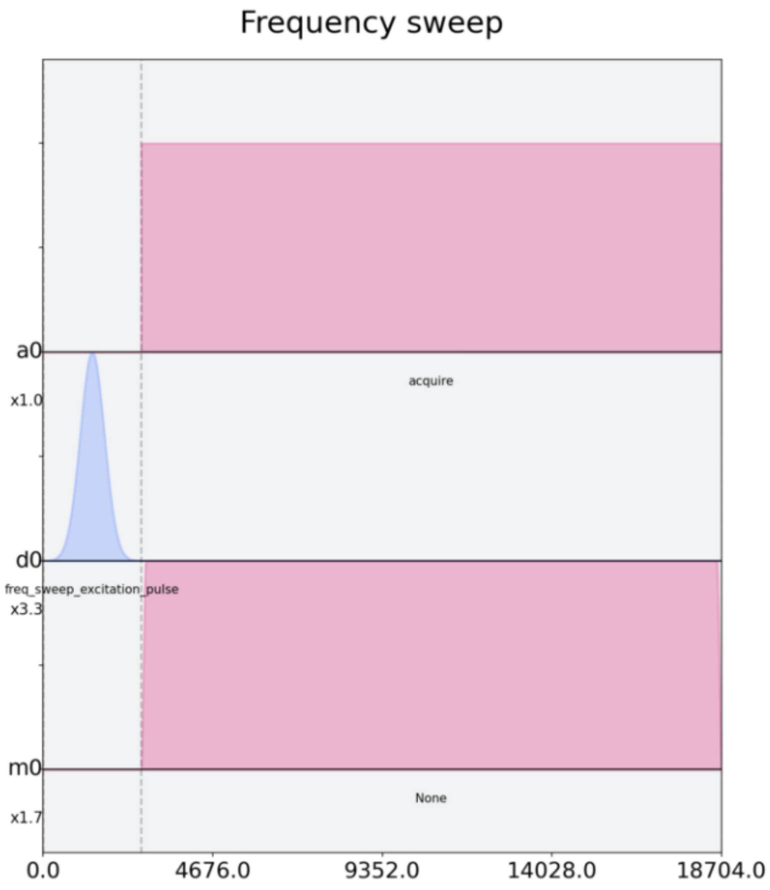
Cooling

- Each of the sub-chambers is at a different temperature, it decreases as you go down, only the very bottom small chamber is at 15mK
- There is a large amount of gold involved
- Gold is a very good conductor of heat, assists the cooling system
- The whole unit shrinks and expands with such a large temperature difference
- There are loops in all the wires to prevent them from snapping when it is brought back to room temperature

Pulse Shaping

- Pulses of micro waves are used to control the qubits, the exact timing and shape of the pulses is important
- A small pulse diagram is shown on the next slide, there are three sections to this diagram
- The top section is the pulse that triggers the measurement, and the bottom is the pulse that controls receiving the measurement
- The middle pulse is used the manipulate the qubit
- This can all be done through Qiskit

Pulse Shaping



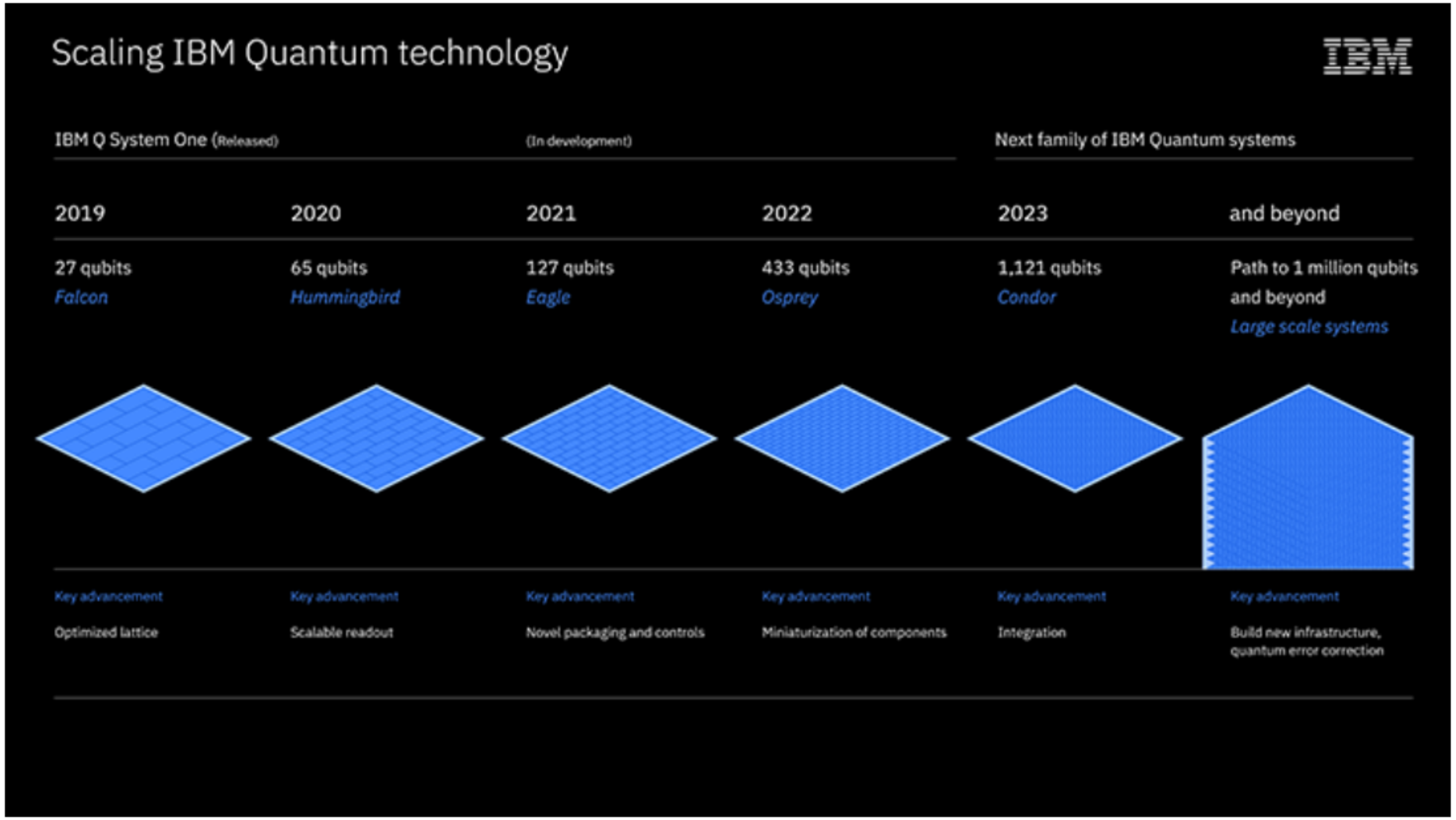
Pulse Shaping

- Recent research shows that the shape and timing for the pulse can have a significant impact on error rates
- Feedback from the system while the pulse is occurring can assist with pulse shaping
- The qubits are frequently calibrated, at least once a day, to determine their performance and response to pulses
- This is used to optimize the control algorithms

IBM Roadmap

- The roadmap for future quantum computers is shown on the next slide
- By 2023 they hope to have over 1,000 qubits
- There is a 65 qubit system in Quebec, this is IBM’s current model
- Next year they plan to have 127 qubits
- There are many engineering challenges, in particular cooling and control, building the transmons is not the major challenge

IBM Roadmap



Scaling IBM Quantum technology
IBM
IBM Q System One (Released)
(In development)
Next family of IBM Quantum systems
2019
2020
2021
2022
2023
and beyond
27 qubits
Falcon
65 qubits
Hummingbird
127 qubits
Eagle
433 qubits
Osprey
1,121 qubits
Condor
Path to 1 million qubits and beyond
Large scale systems
Key advancement
Optimized lattice
Key advancement
Scalable readout
Key advancement
Novel packaging and controls
Key advancement
Miniaturization of components
Key advancement
Integration
Key advancement
Build new infrastructure, quantum error correction

Summary

- Examined the basic ideas behind supercomputing quantum computers
- Introduced the transmon for representing qubits
- Examined how transmons can be controlled and measured
- Presented IBM's roadmap for future quantum computers