Seminar 12

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Class	Quantum Computing Fundamentals
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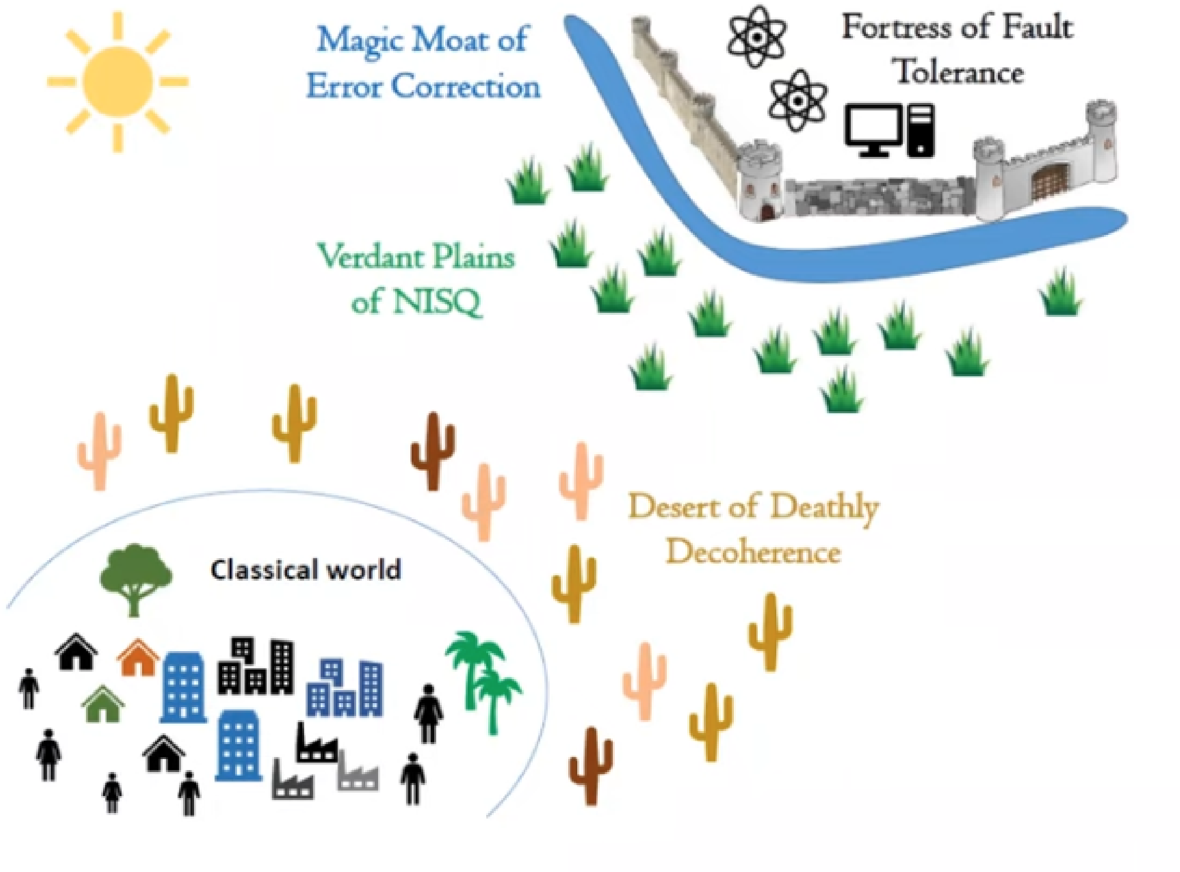
Materials	

Quantum Computing: Past, present, & Future

Week 11 | December 11, 2022

- How did these concepts play a role in the development of quantum computers?
- What challenges and considerations are at play for quantum computing today? What investments and advancements are being made?
- What does the future hold for quantum computing?

General Idea:



Past: How did we get here?

- The path to quantum computing in non-linear. Many things were happening at the same time that led to the rise of quantum computing.
- To make sense of how quantum computing came to be:
  - How did the need for quantum computation arise?
  - What early tech led to the development of quantum computing?

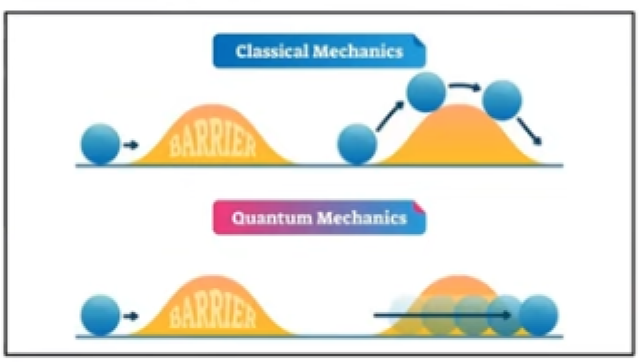
Moore's Law & The Opportunity for Quantum Computation

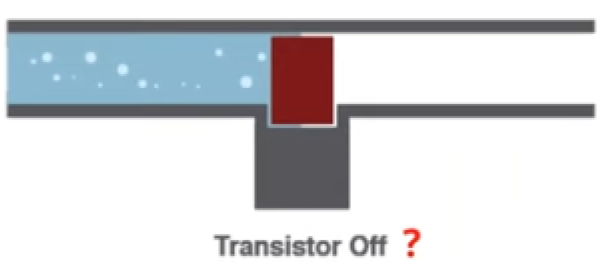
The Physical Limits of Classical Computation:

- Classical bits are made of transistors. You can think of transistors as tiny switches - they stop or allow the flow of electricity (electrons)
- Each computer chip has billions of these transistors.

- To improve computing technology, we want to fit more and more of these transistors on a chip.
    - More transistors = more computational power
    - To fit more transistors onto a chip, we have had to make the transistors smaller
    - This is the basis of Moore's Law - since the 1970's,, the number of transistors on a chip has doubled roughly every 18 months
    - The problem: We have now reached a scale where the transistors are only a few nms wide. In this nano-world, quantum effects can apply

We are approaching the limits of classical physics in our transistors. If the transistor is too small, the electrons can tunnel through the barrier. Tunneling is when the quantum particles end up on the other side of barriers that they could not cross classically. This affects computation: a 0 is not really a 0 anymore since current might still flow. We can't even determine exactly when this will happen because it is a quantum effect.



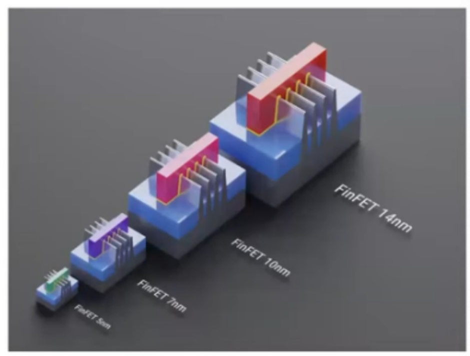


Why are we approaching this limit?

- To get more transistors in a computer, we can either increase the size of the chip or decrease the size of the transistors
- Here's why decreasing transistor size is better:
  - Operating smaller "switches' takes less energy and produces less heat
  - They are usually made of silicon which is increasingly hard to come by and expensive
  - Smaller transistors means less time to send signals between different bits, leading to even more powerful computation

What kinds of computations require this shrinking and packing of transistors?

- We are asking more and more of our computers in our everyday lives. (Streaming, gaming, 3D design)
- AI and Machine Learning (and their hardware demands) are on the rise!
- Many simulations require extensive computing power, such as for modelling climate change, new medicines, quantum physics, and more.

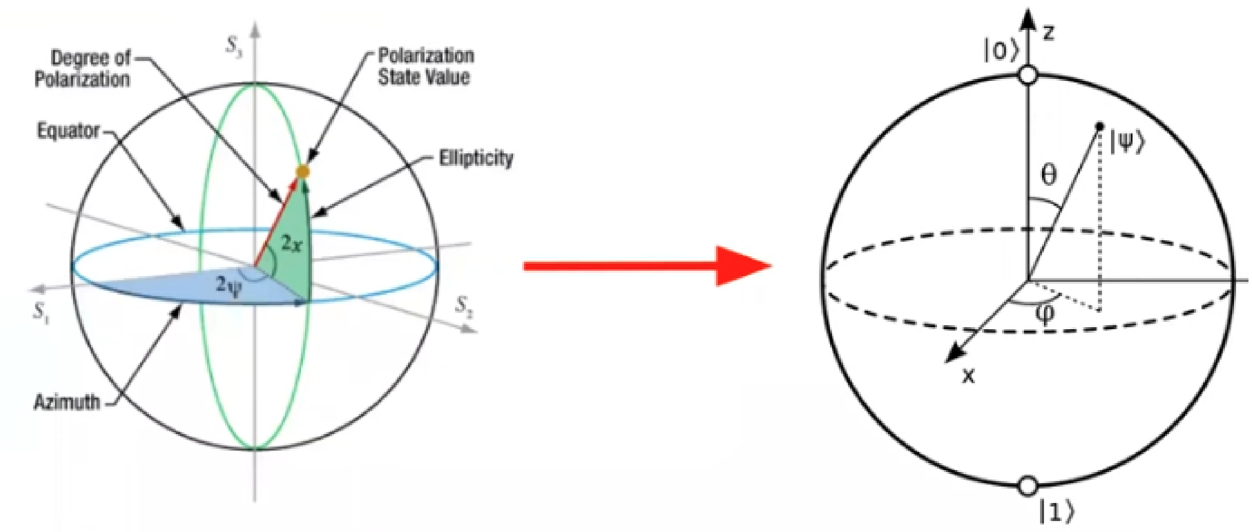


Technologies that laid the groundwork for quantum computing:

- Quantum computing formed form many other technologies and fields that had been developing, including ones that had never been connected to quantum physics before. These technologies and fields were already laying the groundwork for quantum computing today before anyone realized it,
  - Information Theory, Optics, Photonics, Superconductors
- 1911 - Discovery of Superconductivity
- 1957 - A Full Theory of Superconductivity
- 1962 - Enter: Josephson Junctions (led to development of SQUID - the superconducting quantum interference device)

Predecessor to Bloch Sphere:

Poincare Sphere: Developed in 1892 to describe polarization of light (classically) and used heavily in the optics community.



Turing Machine:

Developed by Alan Turing in 1936 to provide a theoretical universal framework for describing computation and used heavily in information theory and computer science

Quantum Turing Machine:

Developed initially by Benioff in 1980 and Deutsch in 1985 to generalize a Turing machine to include quantum properties.

Hamming Code:

Developed in 1947 - this was the first major classical error corrections scheme and used heavily in information theory and computer science

Present: NISQ Era Computing

Today, we are in the NISQ Era of quantum computing. Our goal is to move beyond NISQ to fault-tolerant quantum computing.

- NISQ - Noisy Intermediate-Scale Quantum devices: Today's hardware is noisy, but that doesn't mean they are unusable!
- NISQ is a term coined by John Preskill in 2018

    - Noisy: Subject to substantial errors
    - Intermediate-Scale: Limited in size (# of qubits)
- Fault-tolerant: systems that can run arbitrarily large circuits (number of qubits and gates), even with the presence of faults/errors

Two General Problems Scientists are Tackling:

1. How do we go from NISQ devices to fault tolerant devices?
2. Can we do anything meaningful with NISQ devices themselves or are they just a stepping stone to fault tolerant devices?

What We Have (NISQ or Near-Term)

- Limited number of qubits (50-433)
- Limited qubit connectivity (only allowing single qubit gates in many cases or require complex sets of gates to do something simple)
- Lots of noise, causing errors
- Limited error correction -> limited number of gates (circuit depth)

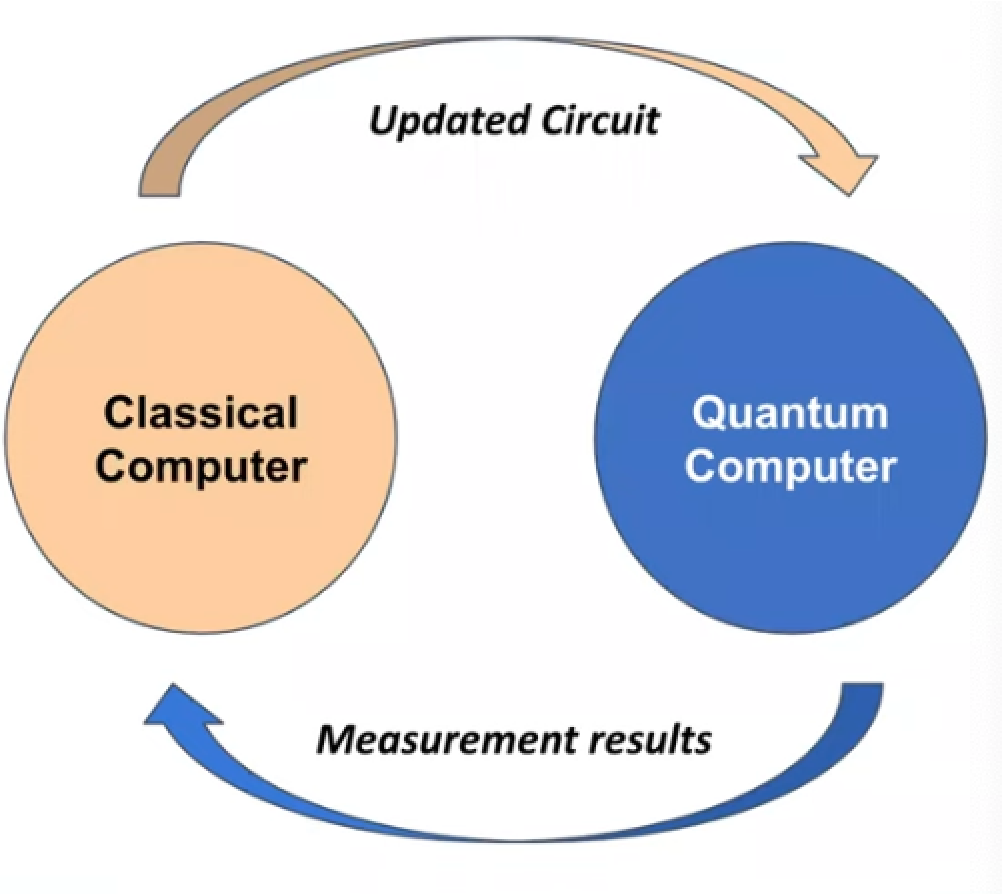
What We Need (Fault Tolerant)

- Errors below a certain threshold using error correction: Quantum Threshold Theorem
- No limitations on the number of qubits
- No limitations on the number of gates (more circuit depth)

NOTE: We have effectively achieved this in classical computing.

How can we use NISQ Hardware?

Our ultimate goal is to have quantum computers that can solve some problems alone. We are not there yet! To still get something out of this, we bring in classical computers!



The Hardware Workflow:

1. Classical Computer: Send instructions to Quantum computer
2. Quantum computer: Runs your quantum circuit
3. Quantum Computer: Sends the results of your circuit to Classical Computer
4. Classical Computer: Figure out how to modify the circuit

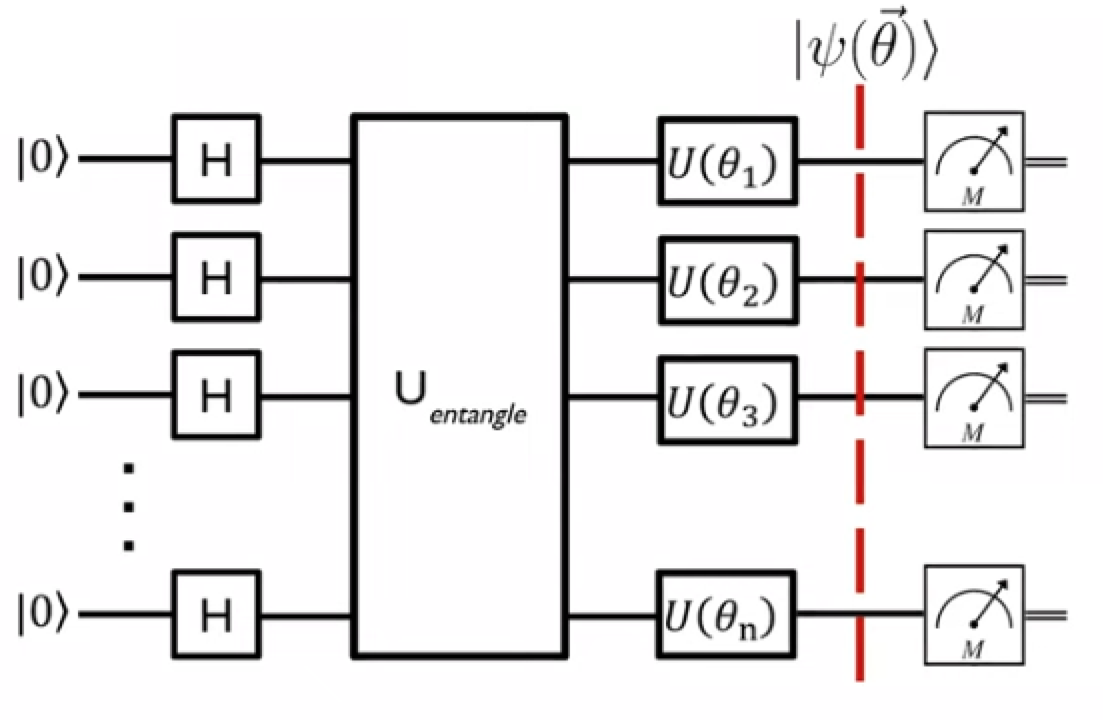
What kinds of Circuits can we run on these devices?

Near-term quantum hardware uses tunable circuits. You have a radio that plays static. We tune our gates like we tune the dials on this radio. Just like we adjust the knobs until we hear clear music, we tune the gates and run these circuits until we get a optimal answer to our problem.

Variational Quantum Circuits:

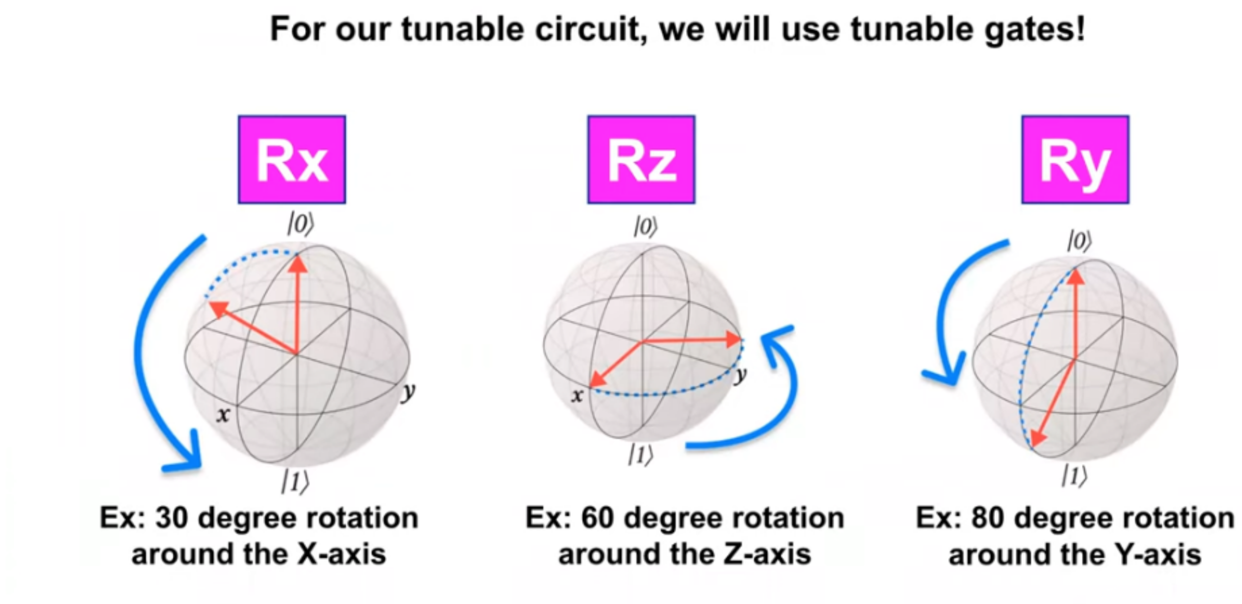
- Hybrid architecture uses “tunable” (variational) quantum circuits

- We have noisy qubits and gates, so we try to compensate by adding tunable parameters'

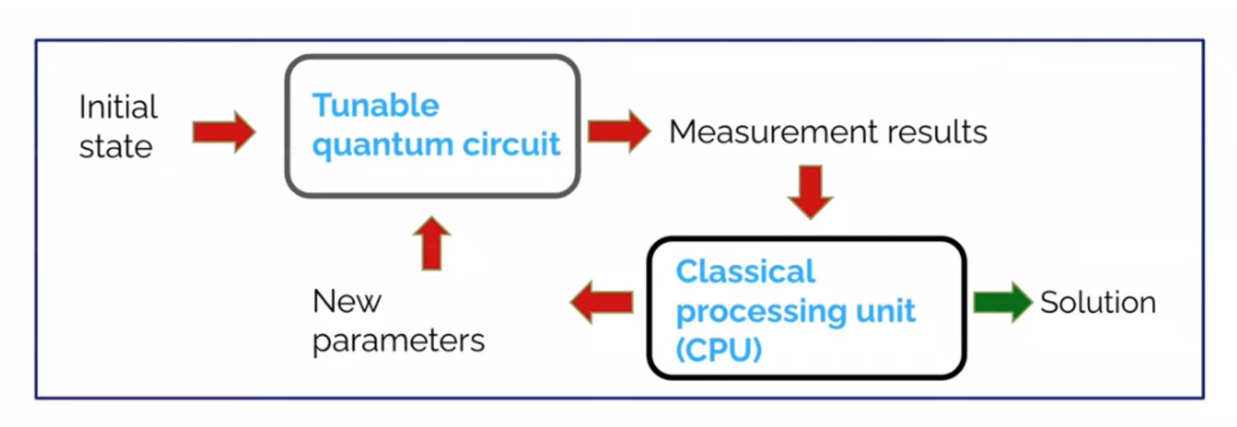


The tunable circuit template is called an ansantz, which has tunable parameters (such as how much to rotate one qubit's Bloch sphere around each axis). The quantum computer runs the circuit with one set of parameters, then the classical computer looks at the result and tunes them accordingly.

For our tunable circuit, we will use tunable gates!



In other words…



- This is considered a heuristic approach, where we use a rule of thumb or general idea to do a good enough job but not necessarily the best oner
- Not every ansatz (template circuit) is created equal
- The art of variational quantum-classical algorithms is coming with good ansantz

The Prominent NISQ Algorithms:

- Quantum Approximate Optimization Algorithms (QAOA)
    - Used for combinatorial optimization

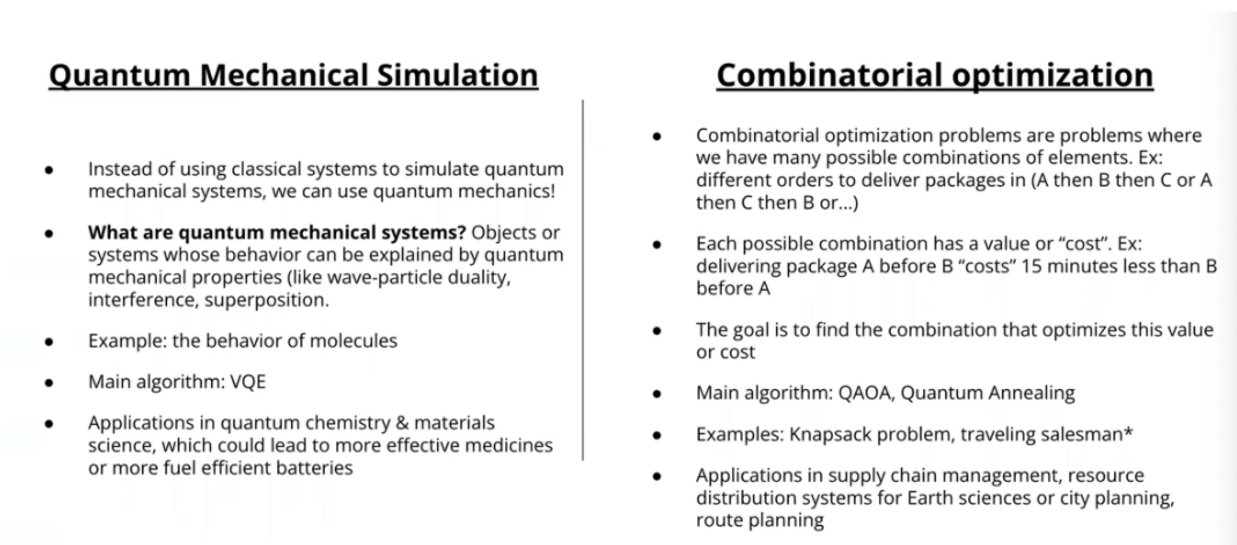
- Variational Quantum Eigen-solver (VQE)
    - Used for continuous systems (chemistry simulations)

Can we do anything meaningful with NISQ devices?:

- Some definitions of quantum advantage are to demonstrate success in processing a real-world problem faster on a quantum computer than on a classical computer
- It’s difficult to determine if we have proven quantum advantage with NISQ technology
- However, these devices and algorithms could still be useful for problems that involve simulation, combinatorial optimizations, or producing randomness

Some examples of types of problems we believe NISQ devices might be helpful for include:

1. **Quantum Simulation**
2. **Combinatorial Optimization**
3. Numerical Solvers (singular value decomposition, nonlinear differential equations
4. Machine Learning
5. Variational Error Correction (variational quantum classifiers, quantum kernel methods, reinforcement learning)
6. Verifying and exploring foundations for quantum mechanics



Real-World Applications of these Problems

Finance: How can asset managers find the optimal portfolio of assets, given the basket of options, a client's budget, and risk-appetite? (McKinsey & Company, J.P. Morgan, Goldman Sachs)

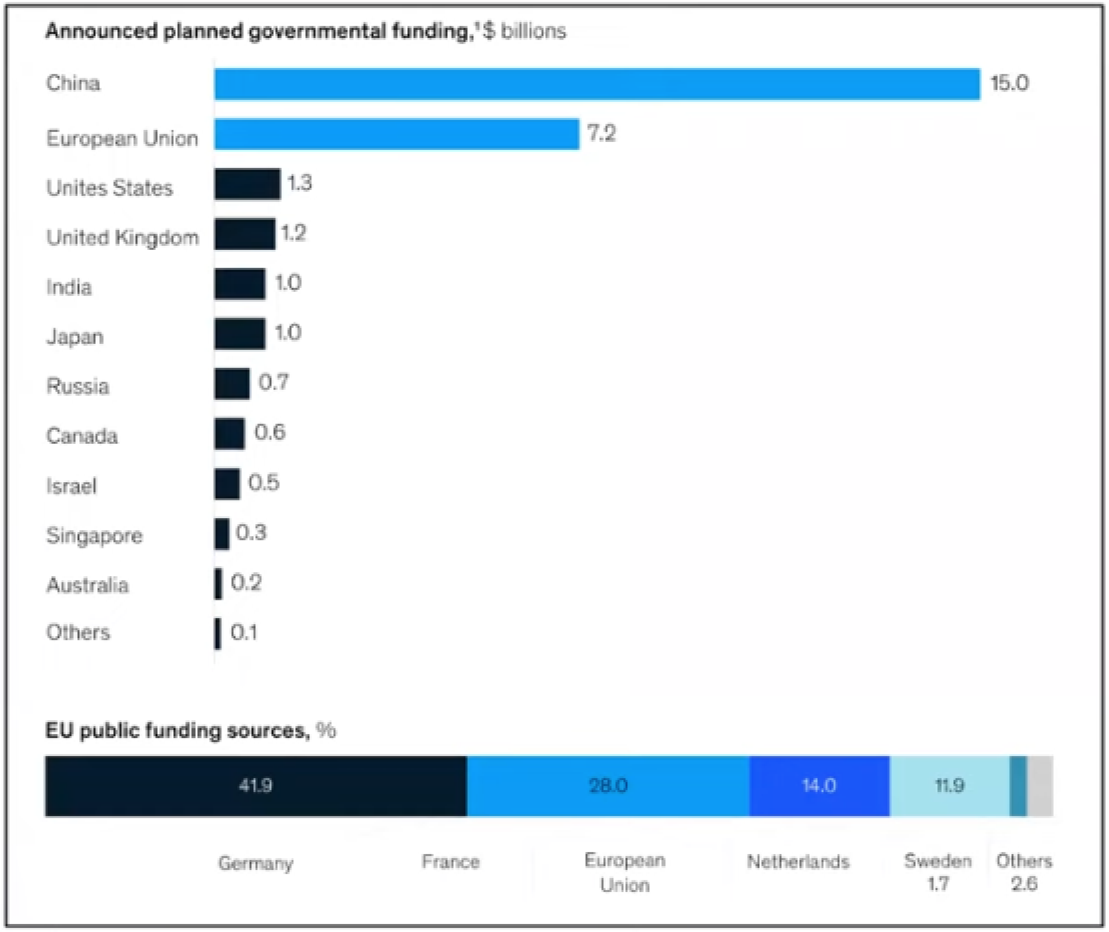
Logistics: Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city? (Amazon, FedEx, UPS)

Case Study: Quantum Machine Learning

The Classification problem: Given labeled data, find a way to predict the label of new data.

What Investments & Advances are we making to achieve fault-tolerance?

The four industries that are predicted to benefit form quantum computing first: pharmaceuticals, chemicals, automotive, and finance. Predicted market value: $90 billion annually by 2040.



Governments are interested in the national security aspect of these technologies and being on the “cutting edge” of tech innovation.

Future Outlook:

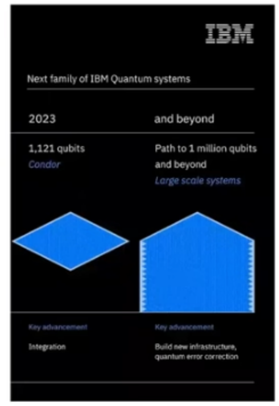
It’s very hard to predict what the future of quantum technology will look like - the most exciting developments will likely be ones we never thought about!

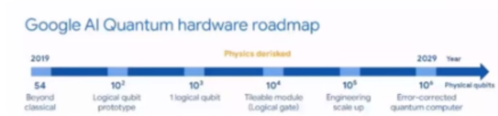
100 qubits: This is where we can start meaningfully exploring error correction. Some companies have already achieved this and others are close behind.

1,000 qubits: This is where we can start meaningfully implementing logical qubits (made up of many error corrected physical qubits). The leaders in quantum hardware project that they will achieve this in the next few years.

1,000,000 qubits: This is when we can likely start to achieve fault tolerance. The leaders in quantum hardware project that they will achieve this by 2030.

In other words, the 2020s are projected to be the last years of the NISQ era.





Some Meaningful Applications (10 Years):

1. Certified Randomness - classical cryptographic schemes
2. Optimization such as machine learning, robotics
3. Quantum Internet

Some Meaningful Applications (50 Years):

1. Fault tolerant quantum computers may be available for sale for companies and governments to use as well as individuals to access through the cloud
2. Cybersecurity requirements may have been altered
3. May see the first uses of quantum algorithms for micro and nano biology applications
4. Quantum internet will likely have been developed out in some areas if Europe and around in other places around the world

Some Meaningful Applications (100 Years):

1. Cybersecurity landscape will likely have ben altered dramatically due in part to the ability to meaningful run Shor’s algorithm
2. Quantum Algorithms will likely be a more standardized tool for developing medicines

3. Fault Tolerant QWQuantum processing units may be available as upgrades to computers much like powerful graphics processing units