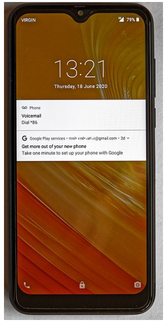
Introduction to Quantum Computing for Everyone

Classical Computing is EVERYWHERE

- ***Hardware***: Laptops, cell phones, servers, microcontrollers, etc.
- ***Software***: Operating systems, apps, web browsers, etc.

Matthieu Riegler

Acabashi

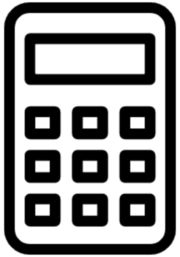


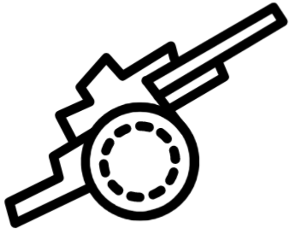
Why do we need quantum computation when the power of advanced supercomputing is at our disposal?

Limits on Classical Computation

- Classical computers solve many day-to-day problems efficiently, or at least faster than a human
- Many complex calculations, however, are still intractable with classical machines and software
    - ***Intractable problems require infinite resources/time to solve!***
- Example problems that are difficult for classical computers include:
    - Modeling natural processes
    - Selecting the ‘correct’ solution from an exponentially large set of potential solutions

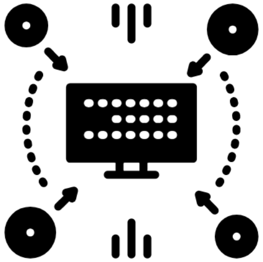
Development of Classical Computers





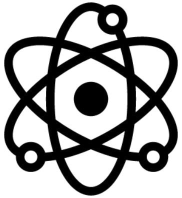
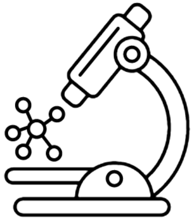
Designed for mathematical calculations

Ada Lovelace envisioned uses like composing music



Grace Hopper made them easier to program

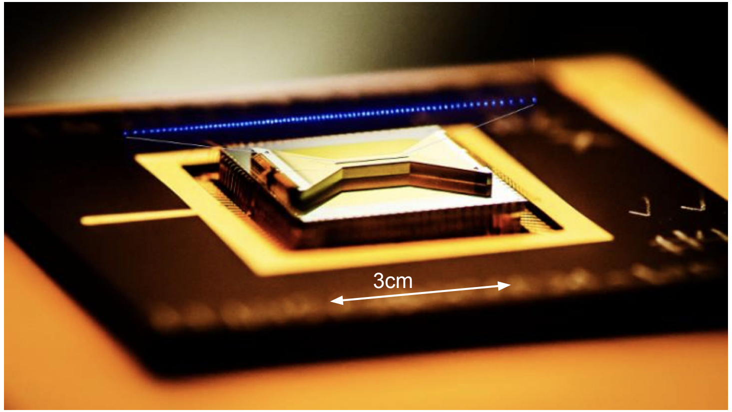
Development of Quantum Computers

Quantum Computers weren’t designed to mimic how humans perform tasks.
They are the products of an observation that there are unique features that can be harnessed for some computations that are lengthy when done like humans.

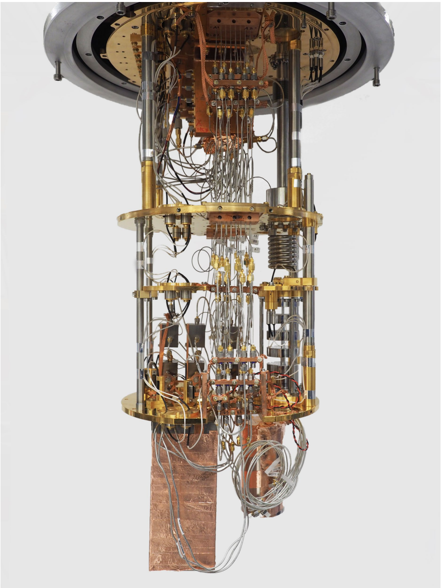
Competing quantum hardware technologies

Emily Edwards and Kai Hudek
Ken Brown STAQ Lab Duke



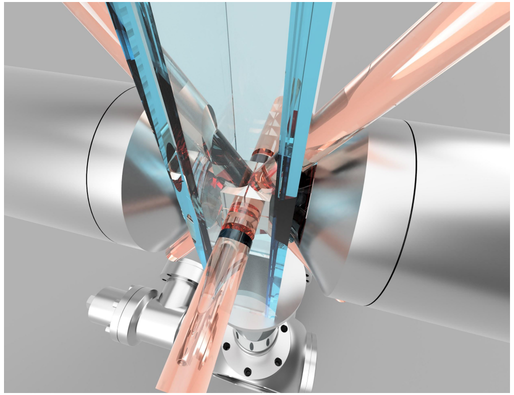
Trapped ion
(inset magnified view of ions $5x10^{-6}$ m spacing)

Yongshan Ding
Dave Schuster Lab UChicago



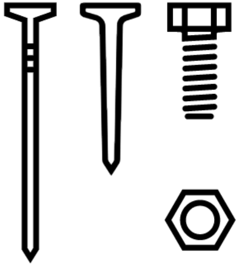
Superconducting

Bernien Lab at UChicago

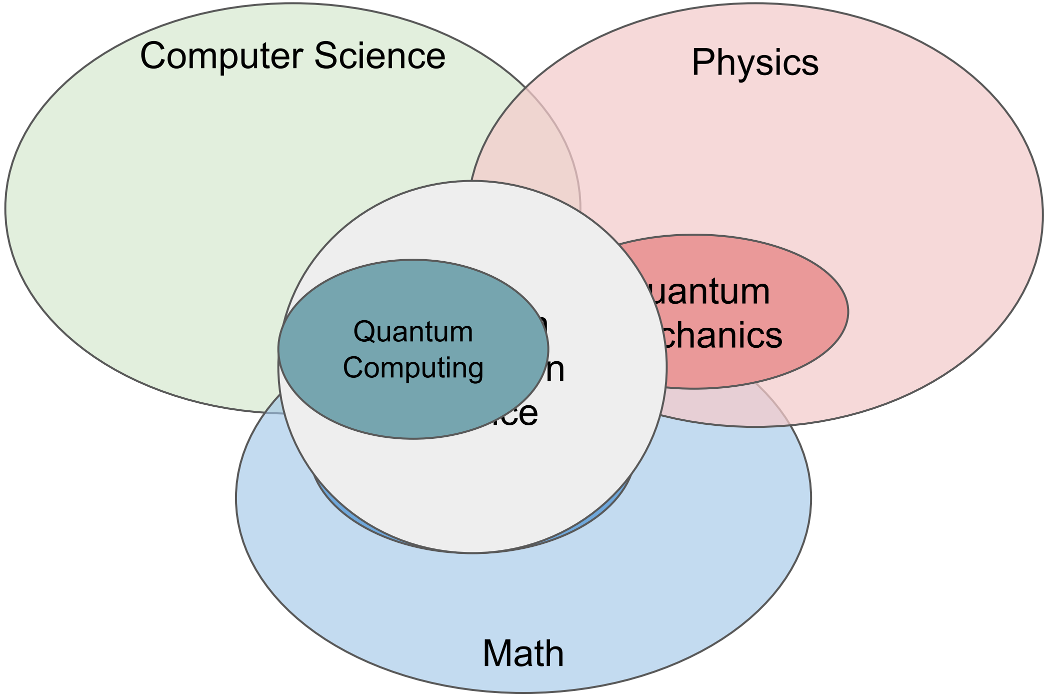


Neutral Atoms

Development of Quantum Computers



Quantum Information Science



Chemistry Simulation

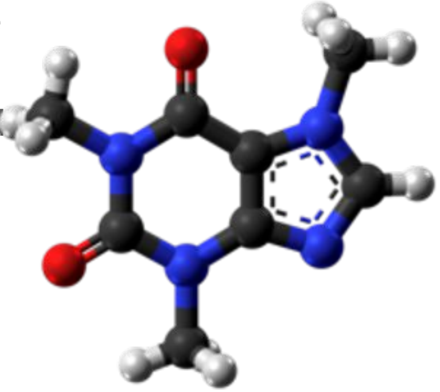
- Simulation of molecules allows for the development of improved chemicals and materials
- Classical simulation techniques are implemented with a 'guess and check' strategy
  - Theorists develop a hypothesis
  - Experiments are outlined and performed
  - Results are analyzed and new theories are developed
- The efficient simulation of atoms and simple molecules is a near-term quantum computing application

Example 1: Quantum Chemistry

- Classical computers have a difficult time representing the information associated with chemical bonds
    - Molecules contain many protons, neutrons, and electrons organized in various configurations
- Caffeine, a 24 atom molecule, would need 10^{48} bits to describe all possible energy arrangements

10,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000

- A quantum computer could hold all this information in 160 qubits!
    - $2^{160} \cong 1.46 \times 10^{48}$



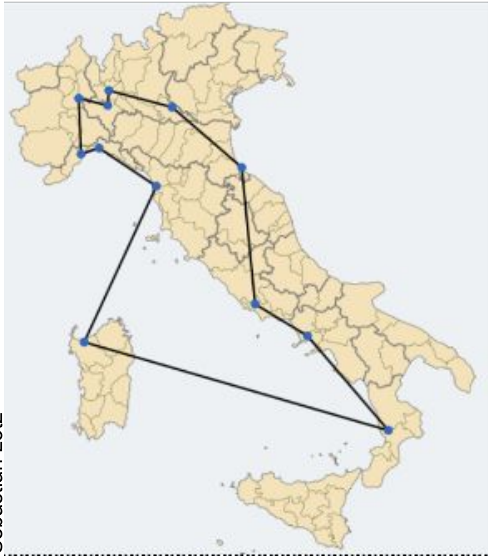
Caffeine - $C_8H_{10}N_4O_2$

Optimization

- Optimization is important for resource maximization
  - Time, energy, hardware, etc.
- Example: UPS optimizes routes for minimal left turns rather than shortest route
  - ***10,000,000 gallons less fuel used and 350,000 more packages delivered per year!***
- Classical optimization involves computationally expensive search algorithms
  - Find a solution that is 'good enough' out of massive number of potential solutions
- Near-term quantum computers are targeted to be well suited for optimization problems

Example 2: Quantum Optimization

- The ***Travelling Salesman Problem*** aims to find the shortest route for round-trip among multiple cities
- Classical optimization involves searching all possible routes
  - Visiting 20 cities: 20x19x18...2x1 ≅ **2,430,000,000,000,000,000 combinations!**
- Quantum computers mathematically model optimization so qubit measurement has a high probability of determining the best route without checking each one
  - Define target solution and route segment costs
  - Encode qubits with search ‘equation’
  - Qubit value converges to ideal route in relatively few algorithm iterations



Sebastian Lotz

Optimum Tour of Italy

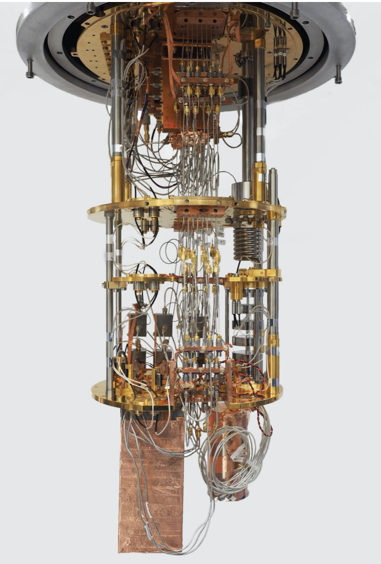
Long-term Quantum Computing Applications

- ***Chemistry:***
  - Battery material discovery
  - Improved fertilizer production
  - Drug discovery
  - Material durability
- ***Optimization:***
  - Financial market analysis
  - Streamlining manufacturing
  - Reduced transportation emissions
- ***Security:***
  - Secure key generation
  - Robust encryption schemes
- ***Machine Learning***
  - Artificial Intelligence
  - Image/audio generation
  - Predictive models

Classical vs. Quantum Devices: State of Art

Carlos Jones/ORNL

Summit Supercomputer
~250x10^{15} Bytes of storage
(1 Byte = 8 bits)



Schuster Quantum Computer (UChicago)
~10s of qubits of storage

Commercial machines reaching < 100 qubits

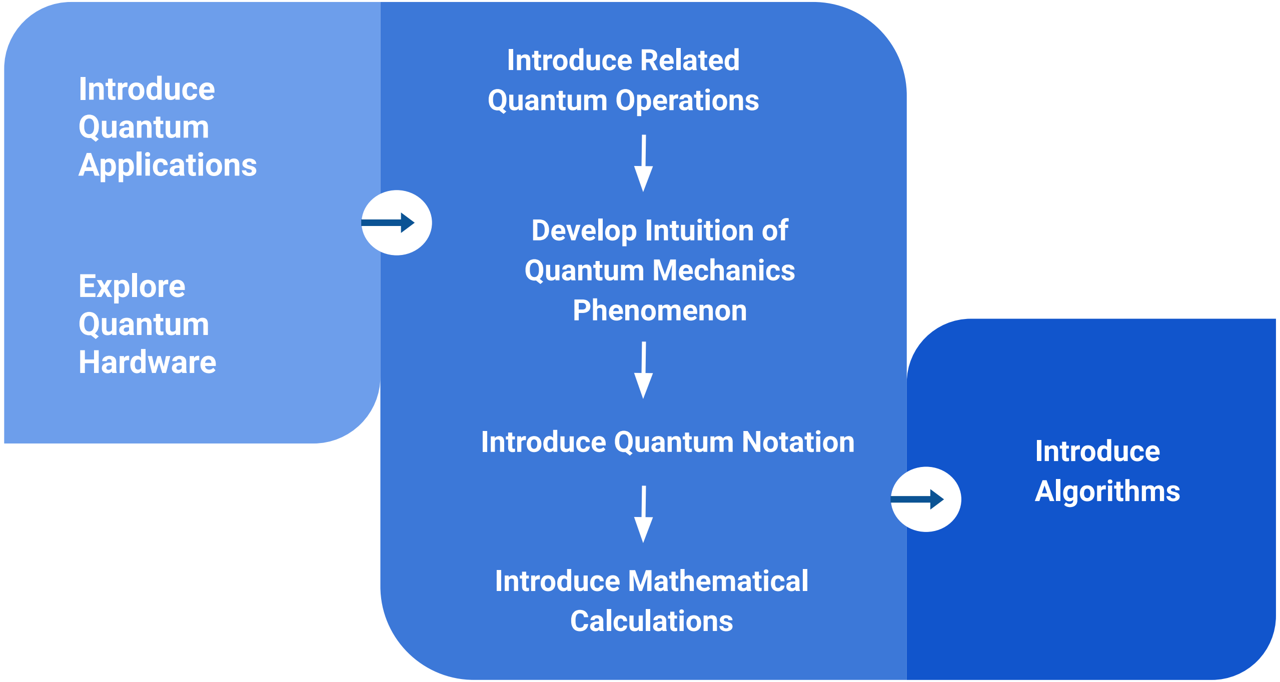
Moving Forward with Quantum Machines

- Many technical challenges to scaling the number of qubits
  - Short lifetime and error prone
  - Devices are sensitive to environment and each other
  - Limitations due to complex hardware and software
- Improved control and hardware will allow for more sophisticated systems and algorithms

Takeaways

- The impact of quantum computing will be widespread, revolutionizing computation for some types of problems
- In this course, you will learn more about why quantum information is different from classical information, and how it will change the world!

1st 4 weeks: Intuitive Introduction



What comes next?

Build skills from operations to circuits (e.g. quantum teleportation) to algorithms

Explore quantum computing concepts via coding

Qiskit - IBM’s software for their quantum computer

Build up further mathematics skills necessary for complex algorithms