Quantum Computing

Quantum Information Processing & Quantum Computers

– Dillon B. & Kayla S.

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Intro

Keywords

- Quantum Mechanics
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- Qubit(s)
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- Quantum Computers
- System Stack
- Quantum Parallelism
- Quantum Coherence/Decoherence
- Quantum Error Correction

Recurring Themes

- Classical vs. Quantum
  - Efficiency
  - Simultaneous vs. Sequential
- Mathematical vs Conceptual understanding

Introduction

WHAT?

Quantum computing is a revolutionary approach to computation that leverages the principles of quantum mechanics to process data/information (Feng et al., 2023). In other words, Quantum computing exploits quantum-mechanical effects to more differently and efficiently execute a computation (Abhijith et al., 2022)

WHY?

It is important for the computer science community to understand these new developments since they may/will radically change the way we consider and apply computation in our lives

OBJECTIVES

We will begin with a brief history of quantum computing then segue into discussing the fundamental principles underlying quantum computing and how they form the basis for quantum information processing and the development of quantum computers. Towards the end, we will offer some topical examples of real-world quantum computing technologies and events

1959 -1980

- To learn about the present, we must first examine the past

- In 1959, Richard Feynman gave the talk, “There’s plenty of room at the bottom: An Invitation to Enter a New Field of Physics” at CalTech
    - https://radfiz.org.ua/files/mag02/medu/Bionanotech_dragan/There's%20Plenty%20of%20Room%20at%20the%20Bottom_Feynman.pdf

- From 1960-1980, there were some rumblings about using quantum mechanics to solve computing problems that classical systems cannot, Alexander Holevo, Charles H. Bennett, Roman S. Ingarden, Yuri Manin

1980s - 1990s

- **Paul Benioff - 1980**
  - https://www.researchgate.net/publication/226754042_The_computer_as_a_physical_system_A_microscopic_quantum_mechanical_Hamiltonian_model_of_computers_as_represented_by_Turing_machines
    - Paper describing a quantum mechanical model of a computer
- **Richard Feynman 1981-1982**
  - Gave talk “Simulating physics with computers” in 1981, published in 1982 https://radfiz.org.ua/files/mag02/medu/Bionanotech_dragan/There's%20Plenty%20of%20Room%20at%20the%20Bottom_Feynman.pdf
  - Essentially, he observed that certain quantum mechanical effects cannot be simulated efficiently on classical computers (Kanamori & Yoo, 2020), meaning we need to develop quantum hardware devices to solve these types of problems
  - “nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.”

1980s - 1990s Continued

- **David Deutsch - 1985**
  - He published a paper outlining and formalizing a concept for a universal quantum computer capable of simulating any physical process if given enough resources https://www.cs.princeton.edu/courses/archive/fall04/cos576/papers/deutsch85.pdf
- **Peter Shor - 1994**
  - It wasn't until 1994, when Peter Shor surprised the world by describing a polynomial time quantum algorithm for factoring integers [Shor 1994; 1997], that the field of quantum computing came into its own (Rieffel, 2000)
  - More algorithms developed, more on that later

Helpful Tips for the Upcoming Concepts

- Think of **computation** as the process of manipulating the states of a physical system to solve problems (Kanamori & Yoo, 2020)
  - In classical computers, transistors manipulate electrical currents to process information encoded as bits, 0 or 1
- A fundamental concept in **Quantum Computing** is the use of microscopic objects as the medium to process digital information, e.g. photon, electron, ions, etc. (Kanamori & Yoo, 2020)
- Think of quantum mechanics —> Quantum algorithms/computing —> Quantum technologies as **system stack** (Resch & Karpuzcu, 2019), involving the evolution and integration of theory, like quantum mechanics and algorithms, to practical solutions, like hardware devices
- When you perform measurements on identically prepared **quantum systems** multiple times, you get a statistical distribution of outcomes.

02

Principles & Fundamentals

Qubit (a.k.a Quantum Bit)

- The **qubit** (short for **“quantum bit**”) is the fundamental information carrying unit used in quantum computers. It can be [**conceptualized**] as the quantum mechanical generalization of a bit used in classical computers (Abijith et al., 2022)
- **Quantum computing** involves the use of **qubits** to process information
  - Similar to bits, 0 or 1, in classical computing
  - One-bit information (i.e., zero or one) can be encoded using two [independent and mutually exclusive] states of a microscopic object (Kanamori & Yoo, 2020)

- A **quantum computer** solves a problem by setting **qubits** in initial **states** and then manipulating the **states** so that an expected result appears on the **qubits** (Kanamori & Yoo, 2020)
- Unlike a **classical bit**, the **state** of a **qubit** cannot be measured without changing it (Abijith et al., 2022)

Mathematics of a Qubit

- Here's a **quantum mechanical** description of a **qubit** using dirac notation
  - The state of a qubit can be expressed as a vector $|\psi\rangle$
    - $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, $|\alpha|^2 + |\beta|^2 = 1$, basis states $|0\rangle$ => 0 and $|1\rangle$ => 1
  - $|\alpha|^2$ is the probability of getting the state $|0\rangle$ ("0") as the result of the measurement on the qubit $|\psi\rangle$ while $|\beta\rangle^2$ is the probability of getting $|1\rangle$ ("1") (Kanamori & Yoo, 2020)
  - **1 Qubit:** $|\phi\rangle = \alpha|0\rangle + \beta|1\rangle$, there are 2^1 basis states, $|0\rangle$ => 0 and $|1\rangle$ => 1
  - **2 Qubits:** $|\psi 1\rangle \otimes |\psi 2\rangle = [\psi 1{,}0\psi 2{,}0\ ,\ \psi 1{,}0\psi 2{,}1\ ,\ \psi 1{,}1\psi 2{,}0\ ,\ \psi 1{,}1\psi 2{,}1\ ]^T$, there are 2^2 basis states
  - **3 qubits:** $|\gamma 1\rangle \otimes |\gamma 2\rangle \otimes |\gamma 3\rangle = |000\rangle + |001\rangle + |010\rangle + |011\rangle + |100\rangle + |101\rangle + |110\rangle + |111\rangle$, 2^3 basis states

- With *n* qubits, you have 2^n possible basis states (possible states a qubit can be measure in). This is a big deal!

Superposition

- In a **mathematical sense**, **superposition** refers to the fact that any linear combination of two quantum states, once normalized ($|\alpha|^2 + |\beta|^2 = 1$), will also be a valid **quantum state** (Abijith et al., 2022)

- **Conceptually**, quantum superposition suggests that when a physical system has multiple potential configurations or arrangements or states, its most comprehensive state can be described as a combination of all these possibilities (Logunova, 2023)

- When a quantum computer prepares ***n*** **qubits** in a **superposition state** as its input, 2^n possibilities can be processed simultaneously from just a linear number of **qubits**. This is a significant advantages of **quantum computers** over **classical computers**

Qubit Examples

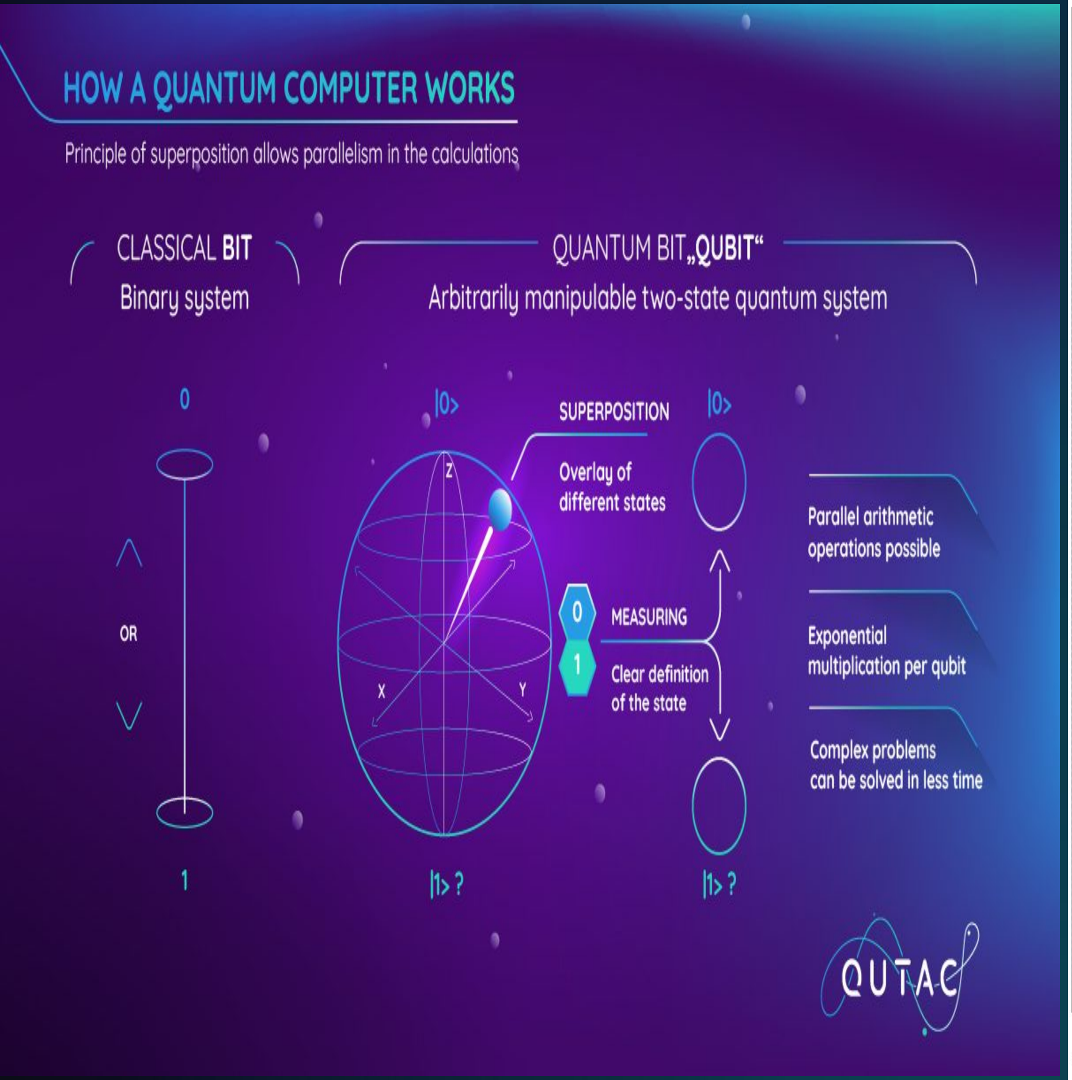
- **Superconducting Qubits**
  - Constructed using superconducting materials, like aluminum and/or niobium
  - A superconducting qubit is typically a tiny loop or line of metal that behaves like an atom—an inherently quantum object (Wright, 2023)
  - The temperatures must be kept extremely cold by an auxiliary apparatus around the quantum processing unit
  - Superconducting materials exhibit quantum properties when they are subjected to extremely cold temperatures

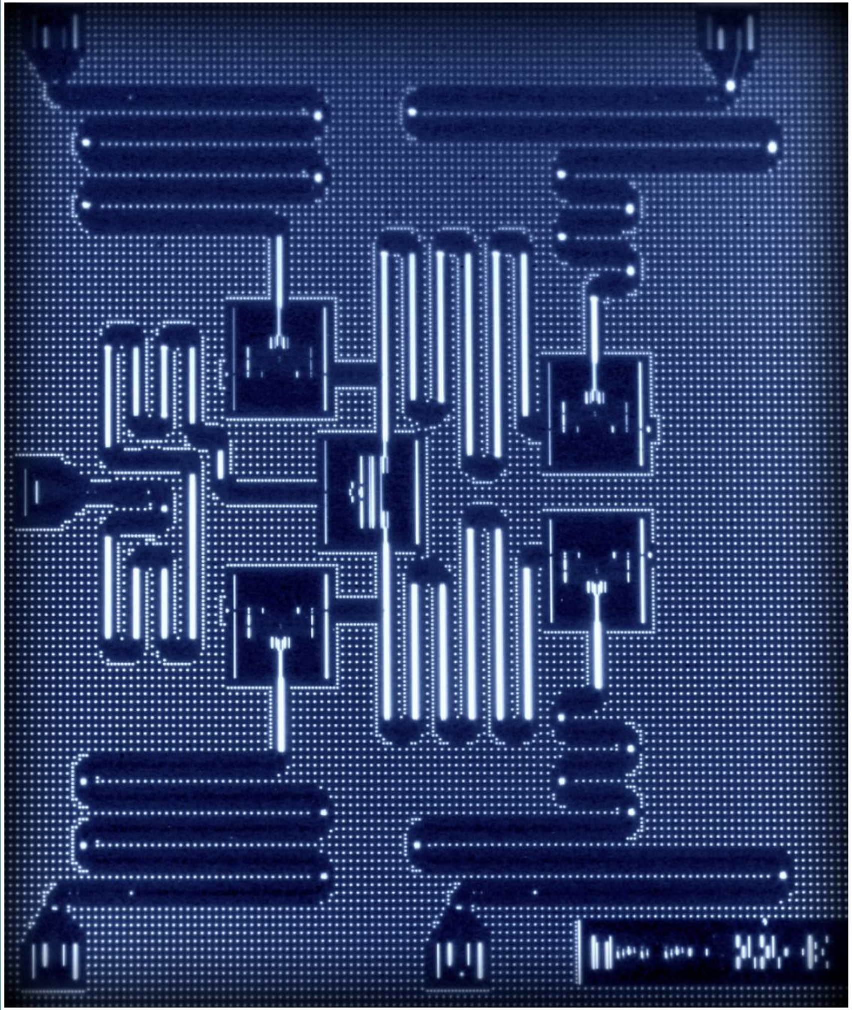
- **Trapped-ion qubits**
  - a charged atom or molecule that behaves like a tiny bar magnet
  - A chip houses the ions and traps them using electric fields in the voids between its tiny printed circuits. The lasers shoot through the windows of the vacuum chamber, cooling the ions and operating the qubits (Wright, 2023)
  - Scalability problem. Each chip can contain at most a few tens of ions without the interactions among them becoming too complex to control. Reaching millions of qubits will require moving ions between modules, a feat scientists have yet to reliably achieve (Wright, 2023)
  - Built into an ion-trap quantum computer
  - IonQ

Qubit Examples Continued

- **Neutral-atom qubits**
  - They can perform a few calculations per second—comparable to trapped-ion quantum computers but more than 1,000 times slower than a superconducting-qubit system (Wright, 2023)
  - A neutral-atom quantum computer is like a charged-atom one, but light rather than electricity holds the atoms in place. To make the light traps, scientists shine a laser through a lens above a chamber containing neutral atoms. The lens splits the incoming beam into a multitude of light spots, each of which can hold an atom in place. The same splitting occurs for other laser beams, which are used to operate the qubits.

- **Nuclear Magnetic Resonance (NMR)**
  - Qubits are implemented using nuclear spin-1/2s in a static magnetic field. The two states of spin up and down represent the 0 and 1 of the qubit, respectively (Fang et al., 2023)





Layout of IBM's five superconducting quantum bit device from 2015. (Credit: IBM Research)

Entanglement

- **Conceptually**, entanglement is a physical phenomenon that occurs when the **states** of a **quantum system** become correlated with each other, regardless of physical distance.
  - When you measure an entangled qubit, its entangled qubit brethren's states will be determined instantaneously without any direct interaction between the them.
- **Mathematically**, the **states** of a **quantum system** that cannot be expressed as a tensor product of its i**ndividual states** are called **entangled states**. (Abhijith J., et al., 2020) or the state of entangled qubits is described by a joint quantum state that cannot be factored into independent states for each qubit.
  - $|\psi\rangle = 1 \sqrt{} 2 (|000\rangle + |111\rangle)$
  - $|\Phi\rangle$=1/sqrt(2)($|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle$)

- In an **entangled** system of **qubits**, the collective **state** of the all **qubits** is a **superposition** of different possible configurations. Each **qubit** in the **entangled** system contributes to the overall **superposition,** allowing the system to represent multiple possibilities simultaneously.

Quantum Parallelism/Parallel Processing

- In **classical computing**, parallel processing typically involves performing multiple computations simultaneously to **speed up** information processing.
  - Think of a GPU built with many CPUs to perform task/data processing for graphics or machine learning algorithms more efficiently than a standard CPU

- Similarly, **quantum computing** exploits the physical phenomena of entanglement and superposition to process large amounts of possibilities in parallel.
  - The entanglement ensures that the states of the qubits are interconnected, so when one qubit is manipulated or measured, the entire entangled state is affected

- **Classically**, to achieve an exponential decrease in time requires an exponential increase in the number of processors, and hence an exponential increase in the amount of physical space needed. However, in **quantum systems** the amount of parallelism increases exponentially with the size of the system. Thus, an exponential increase in parallelism requires only a linear increase in the amount of physical space needed (Rieffel, 2000)

Quantum Parallelism Continued

- *While it's true that measurement collapses the **superposition state** to a specific outcome/output, the quantum speedup occurs during the computation itself, i.e. when the quantum computer explores and processes a large number of possibilities in parallel/simultaneously. The final measurement provides a probabilistic result, yes, but all the algorithmic efficiency comes from how it utilizes **quantum parallelism** during the computation phase of the problem.
- In other words, **quantum parallelism** enables **quantum computers** to process multiple combinations of states in parallel. While a classical computer would need to process each possible combination **sequentially**, a quantum computer can explore many combinations **simultaneously**.

Quantum Gates & Circuits

- A **quantum gate** is an **operation** that transforms one **quantum state** into another. Quantum computing performs certain transformations by performing a series of quantum gate operations on quantum states (Fang et al., 2023)
    - Quantum computers operate by encoding information in qubits and encoding algorithms into quantum gates (Fang et al, 2023),
        - cNOT, SWAP, others
    - In classical computers, algorithms are encoded in logic gates using boolean logic
        - AND, OR, NOT

- Think of a **quantum circuit** as **series of operations (quantum gates)** using quantum mechanical principles to manipulate a **quantum state**
    - Different technologies uses different techniques, like microwave pulses or shining light

Quantum Circuits Continued

- In a **quantum circuit**, the intermediate states are likely to be in a **superposition state**. If the **superposition state** is measured, the quantum state is corrupted and becomes one of the two [independent] base states (i.e., $|0\rangle$ or $|1\rangle$) at the time of the measurement with the probabilities $|\alpha|$^2 and $|\beta\rangle$^2 (Kanamore & Yoo, 2020)

- Because **quantum mechanics** does not allow the system (e.g., **quantum circuit**) to lose information unless the **quantum states** in the system are measured, **quantum gates** must have the same number of inputs as the outputs and must be reversible with no information loss by the gates (Kanamori & Yoo, 2020)
    - If a quantum gate negatively affects a system, then it renders the quantum computation useless. It must perform a pure operation to maintain the integrity of the quantum states within the quantum system...

Challenges

- **Quantum Error Correction**
  - **Decoherence/Coherence**
    - Coherence allows qubits to maintain superposition states and perform quantum operations/the process in which a system's behaviour changes from that which can be explained by quantum mechanics to that which can be explained by classical mechanics (Wikipedia)
    - Decoherence refers to when external influences from the environment corrupt the purity of a quantum state, thereby leading to information loss and errors
    - No-clone theorem, among others
    - As of today, no reliable and cost-effective technique for quantum error correction era has arrived (Feng et al, 2023)
- **The Measurement Problem**
- **Scalability & Fight for the best approach**
  - Different designs of qubits and quantum computing hardware devices a not economically beneficial at scale, (Ion-trap & neutral-atom vs. superconducting qubits)
  - Fault tolerance - as the size of a quantum computer grows, it becomes harder to maintain strong error correction.
  - NISQ era, Noisy Intermediate-Scale Quantum

03

Application and Algorithms

Algorithms and Application

- A quantum algorithm is an algorithm that can only be carried out on a quantum computer that is used to solve a problem by searching the database.

- There are several types of Quantum Algorithms like the Grover Search Algorithm and The Shor Algorithm.

The Grover Search Algorithm

- The Grover Search Algorithm is an algorithm designed to search an unstructured database.

- In mathematics and computer science, there are different ways to classify a problem. A problem is classified as NP-Complete if it is a decision problem that can be verified in polynomial time. Some classic examples of this are the traveling salesman problem and the Hamiltonian path problem. The Grover search algorithm can be used to speed up the subroutine of solving these complex problems.

The Grover Search Algorithm Continued

- The total number of operations in the Grover search algorithm is proportional to sqrt(N)logN which makes this searching algorithm optimal in the sense that no quantum Turing machine can do this in less than $O(\sqrt{N})$ operations

- It is known that this algorithm requires $O(\sqrt{N})$ operations to search an unsorted array of size N, which requires $O(N)$ operations for classical algorithms (Grover, 1996) (Kanamori & Yoo, 2020)

- There are two quantum components to this algorithm
  - The reflection on the mean
  - The inversion of the marked state

The Grover Search Algorithm Continued

- The reflection on the mean:
  - This operation involves reflecting the amplitude of the quantum state about its mean amplitude. It helps amplify the amplitude of the correct solution while reducing the amplitudes of incorrect solutions.

- The inversion of the marked state:
  - This operation involves marking the solution (or solutions) in the quantum state by inverting their amplitudes.

The Shor Factoring Algorithm

- As mentioned earlier, quantum computing entered its modern stage in 1994, when P. Shor ([Sh]) devised the first quantum algorithm showing that prime factorization can be done on quantum computers in polynomial time, that is, considerably faster than by any known classical algorithm.

- The Shor Factoring Algorithm is a way to determine polynomial time (O(n^k))in a given function. Polynomial time is how fast a complex input can be solved.

- In 2001, the first implementation of Shor's algorithm (factorization of 15 = 3 × 5) was realized using nuclear magnetic resonance (NMR) (Vandersypen et al., 2001).

The Shor Factoring Algorithm Continued

- How the Algorithm works is it first starts by selecting a random integer smaller than the number to be factored.

- Then the GCD is found classically. It is then used to determine whether the target number has already been factored accidentally.
  - For smaller numbers, that's a possibility.
  - For larger numbers, a supercomputer could be needed.
  - For numbers that are believed to be cryptographically secure, a quantum computer will be needed.

04

Real World Connections

Real World Quantum Technologies

- Government
  - Different governments have been increasing the funding for quantum computing research and development not only for the advancement of computing technology but also for their national security (Kanamori & Yoo, 2020)
    - Executive summary from U.S. DoD
    - US IT Report Q4 2023 - As U.S. invests in supercomputing, market drivers will cause demand for quantum computing systems to increase
- D-wave Quantum Systems Inc.
  - D-Wave annealer-based quantum computer 2000Q commercially available since 2012 https://www.dwavesys.com/
  - Not universal qc, but intended for optimization problems
    - Nasa uses it to solve their optimization problems for applications such as air traffic control, mission planning and scheduling, machine autonomy, fault diagnosis, and robust system design (National Aeronautics and Space Administration, 2015).
  - D-Wave has announced its 5000-qubit system, which will be released in mid-2020, has been sold to Los Alamos National Laboratory for research purposes (Kanamore & Yoo, 2020)

Real World Quantum Technologies Continued

JPMorgan Chase and Goldman Sachs

- Their research teams have found that quantum computing could significantly reduce the time to calculate option pricing and risk-assessment calculations (Kanamori & Yoo, 2020)

IBM, Google, NASA, etc.

- IBM has been continually working to make their 5-qubit and 20-qubit quantum computers readily available via their cloud service called "IBM Quantum Experience"
- In January 2019, IBM unveiled the first commercial general-purpose multi-qubit gate-based quantum computer called "IBM Q System one" (Kanamori & Yoo, 2020)
- Google claimed their quantum computer had demonstrated "quantum supremacy," stating it went beyond ordinary digital computers (Preskill, 2012) However, IBM claimed that Google's quantum computer did not reach quantum supremacy because the same task could be done with an ideal algorithm on a classical computer in 2.5 days (Kanamori & Yoo, 2020)

Real World Quantum Technologies Continued

- Azure Quantum - Microsoft
  - provides Internet cloud access to their quantum computer simulators and the real quantum hardware supplied by Honeywell, IonQ, and QCI (Kanamori & Yoo, 2020)

- Amazon Bracket - Amazon
  - Amazon started a quantum computing service via AWS, called Amazon Bracket, where users can remotely use the quantum computer hardware of the partners: D-wave, IonQ, and Rigetti (Kanamori & Yoo, 2020)

- Intel, Rigetti, and IonQ also have been developing a quantum computer in their laboratories (Gomes, 2022)
  - https://spectrum.ieee.org/quantum-computers-strive-to-break-out-of-the-lab

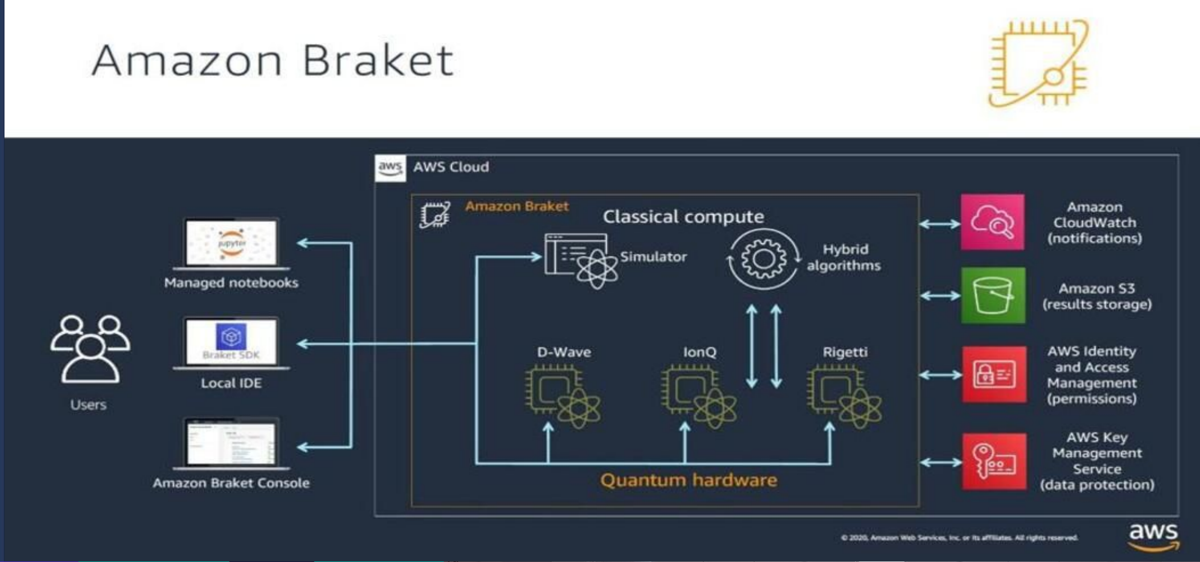
- Substantially different quantum computing devices available thus far (Almudever et al., 2020)

Quantum Programming Languages

- Microsoft has released the quantum development kit (QDK) and the quantum programming toolkit Q# for Visual Studio ("Quantum Development Kit | Microsoft," 2019), which allows users to simulate quantum circuits on a classical computer (Kanamori & Yoo, 2020)

- Qiskit (python)
  - Qiskit is an open-source software development kit for working with quantum computers at the level of circuits, pulses, and algorithms.
  - Qiskit supports both simulation on classical computers and execution on IBM's quantum processors.
  - Users get access to IBM's quantum processors via the cloud-based IBM Quantum Experience platform
- Others
  - Cirq (python)
  - Quipper (Haskell)
  - LanQ (C++)
  - Silq (Silq)
  - ProjectQ (Python)


Microsoft
AZURE
QUANTUM


Amazon Braket
AWS Cloud
Amazon Braket
Classical compute
Simulator
Hybrid algorithms
D-Wave
IonQ
Rigetti
Quantum hardware
Managed notebooks
Local IDE
Amazon Braket Console
Users
Amazon CloudWatch (notifications)
Amazon S3 (results storage)
AWS Identity and Access Management (permissions)
AWS Key Management Service (data protection)
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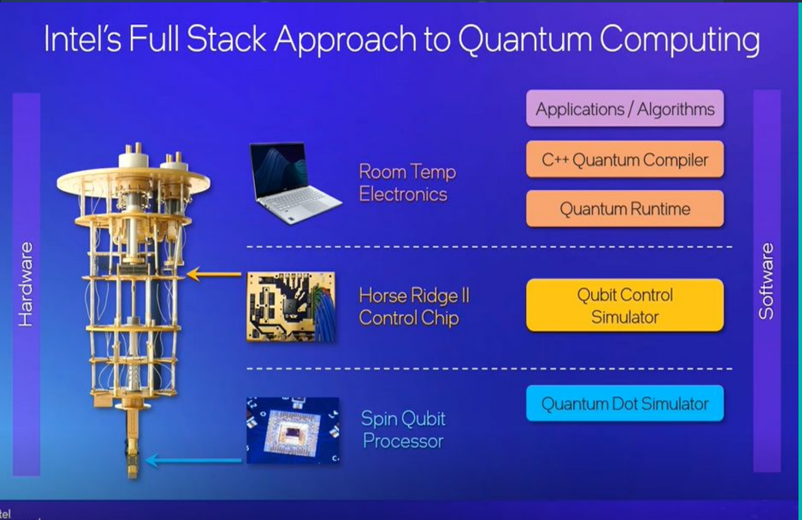
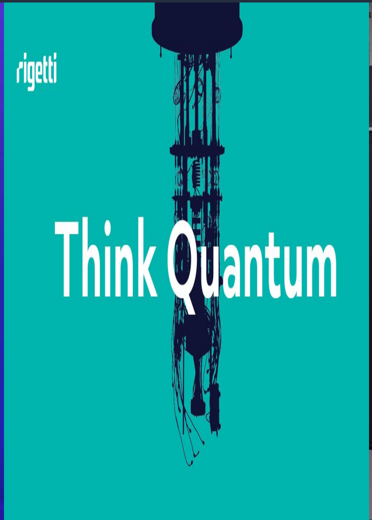
aws


Intel's Full Stack Approach to Quantum Computing
Hardware
Software
Applications / Algorithms
C++ Quantum Compiler
Quantum Runtime
Room Temp Electronics
Horse Ridge II Control Chip
Qubit Control Simulator
Spin Qubit Processor
Quantum Dot Simulator


rigetti
Think Quantum


IONQ
IONQ
IONQ

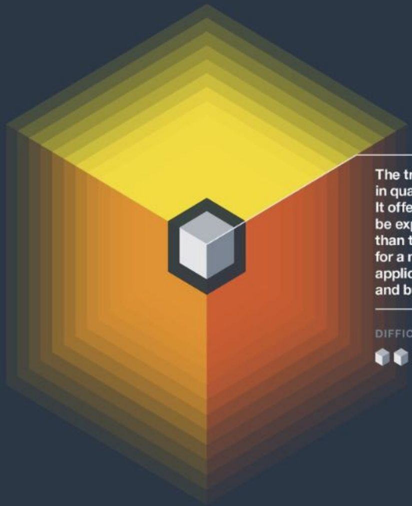
The three known types of quantum computing and their applications, generality, and computational power.

A very specialized form of quantum computing with unproven advantages over other specialized forms of conventional computing.

DIFFICULTY LEVEL

The most likely form of quantum computing that will first show true quantum speedup over conventional computing. This could happen within the next five years.

DIFFICULTY LEVEL



The true grand challenge in quantum computing. It offers the potential to be exponentially faster than traditional computers for a number of important applications for science and businesses.

DIFFICULTY LEVEL

Quantum Annealer

The quantum annealer is least powerful and most restrictive form of quantum computers. It is the easiest to build, yet can only perform one specific function. The consensus of the scientific community is that a quantum annealer has no known advantages over conventional computing.

APPLICATION
Optimization Problems

GENERALITY
Restrictive

COMPUTATIONAL POWER
Same as traditional computers

Analog Quantum

The analog quantum computer will be able to simulate complex quantum interactions that are intractable for any known conventional machine, or combinations of these machines. It is conjectured that the analog quantum computer will contain somewhere between 50 to 100 qubits.

APPLICATIONS
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics

GENERALITY
Partial

COMPUTATIONAL POWER
High

Universal Quantum

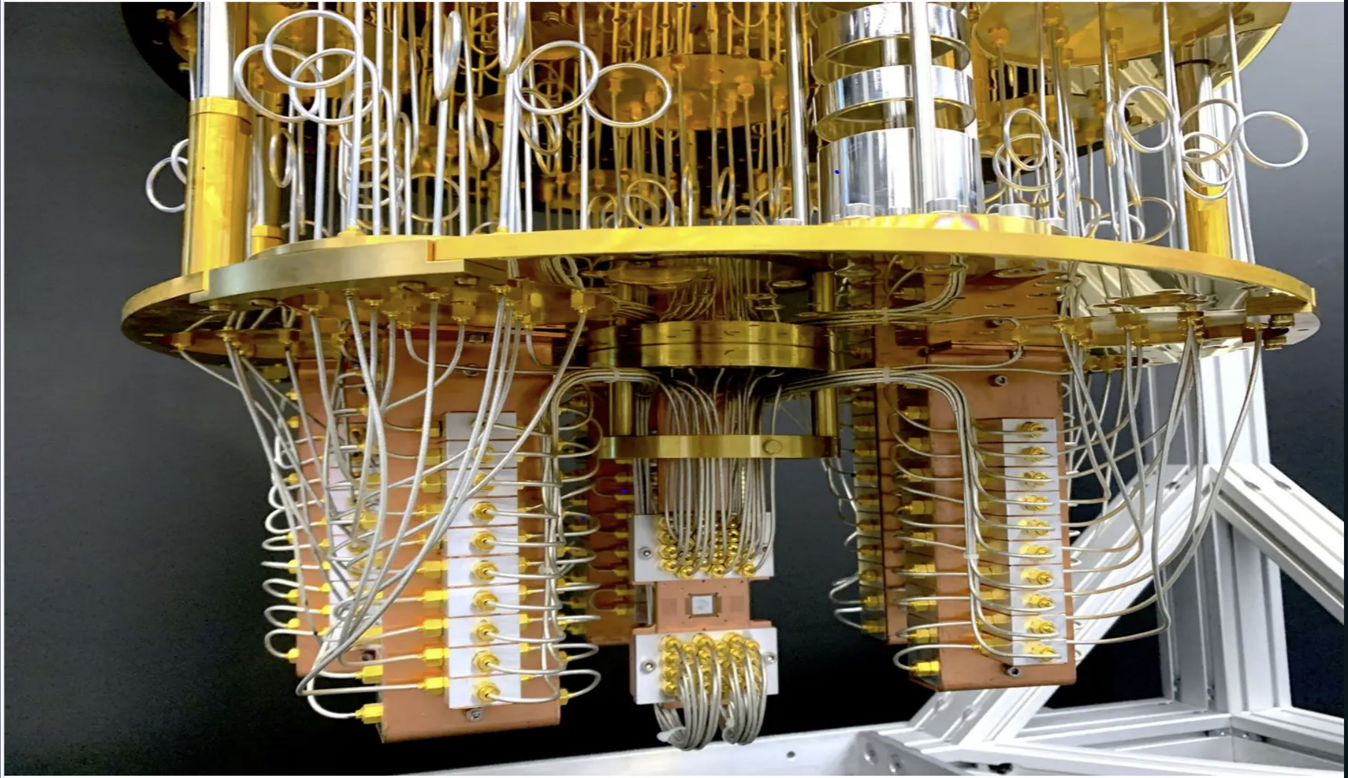
The universal quantum computer is the most powerful, the most general, and the hardest to build, posing a number of difficult technical challenges. Current estimates indicate that this machine will comprise more than 100,000 physical qubits.

APPLICATIONS
Secure computing
Machine Learning
Cryptography
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics
Searching

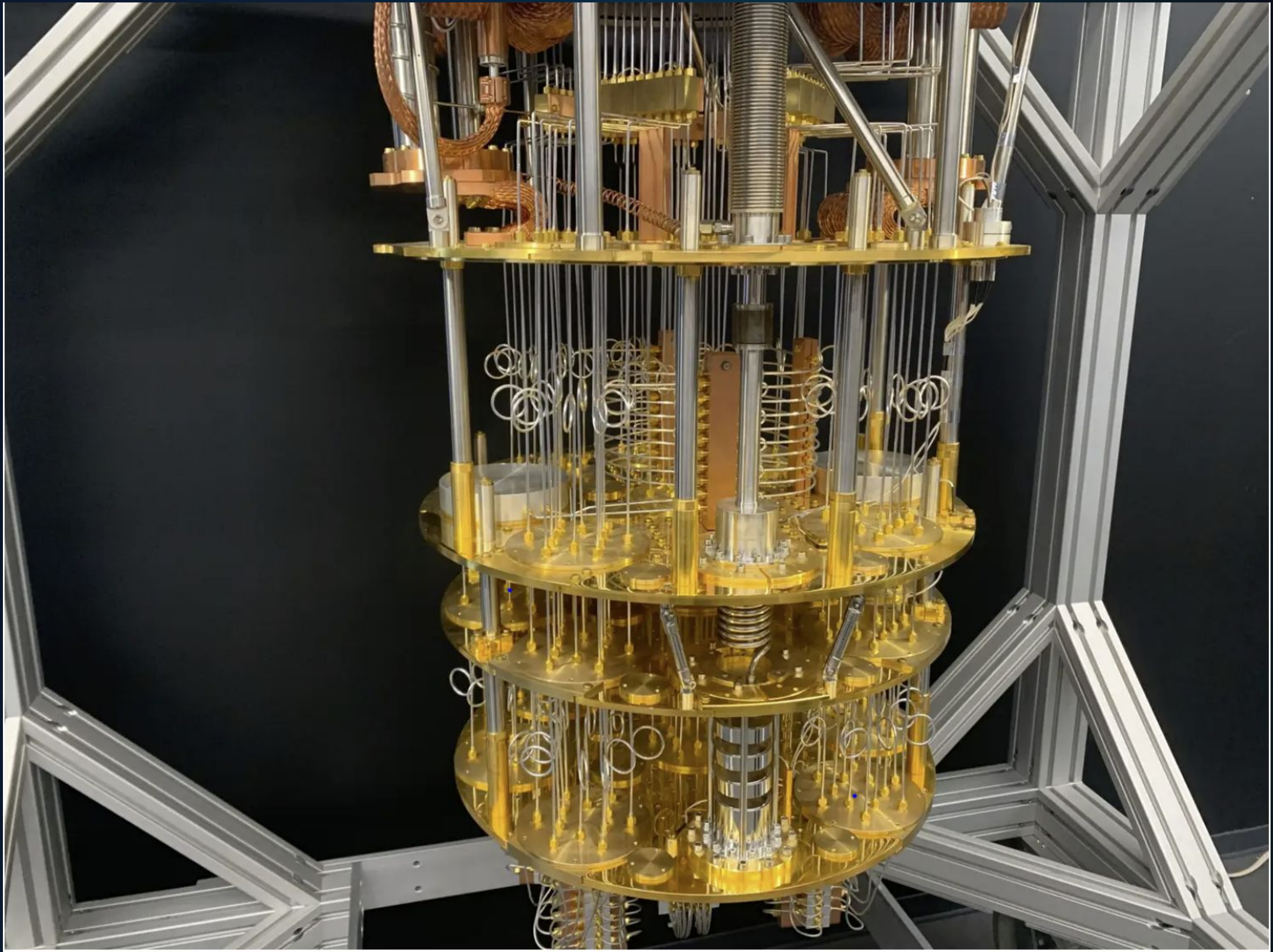
GENERALITY
Complete with known speed up

COMPUTATIONAL POWER
Very High

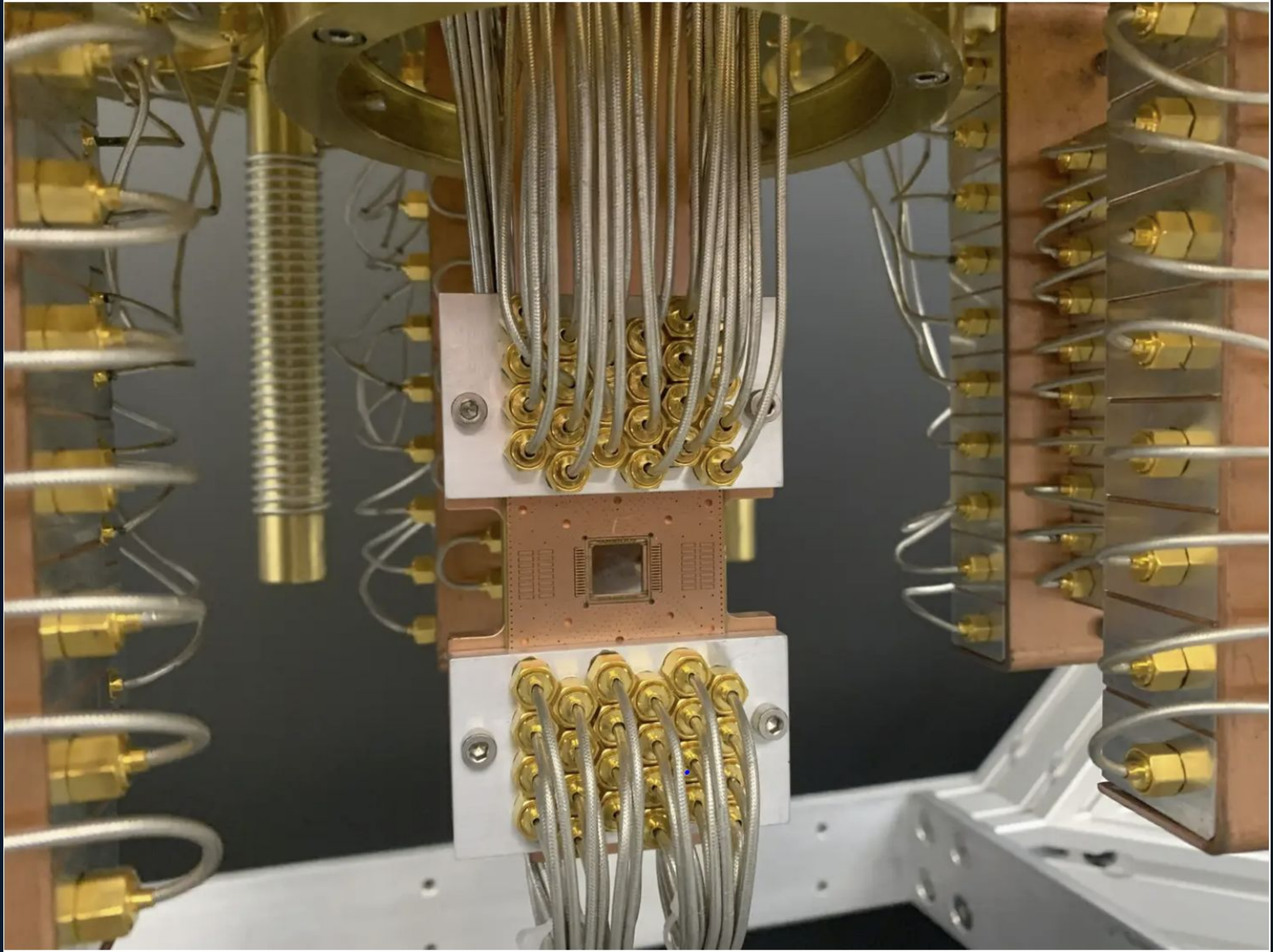
The IBM Quantum System One, released in 2019



IBM takes PopSci inside their quantum computer world. *Charlotte Hu*



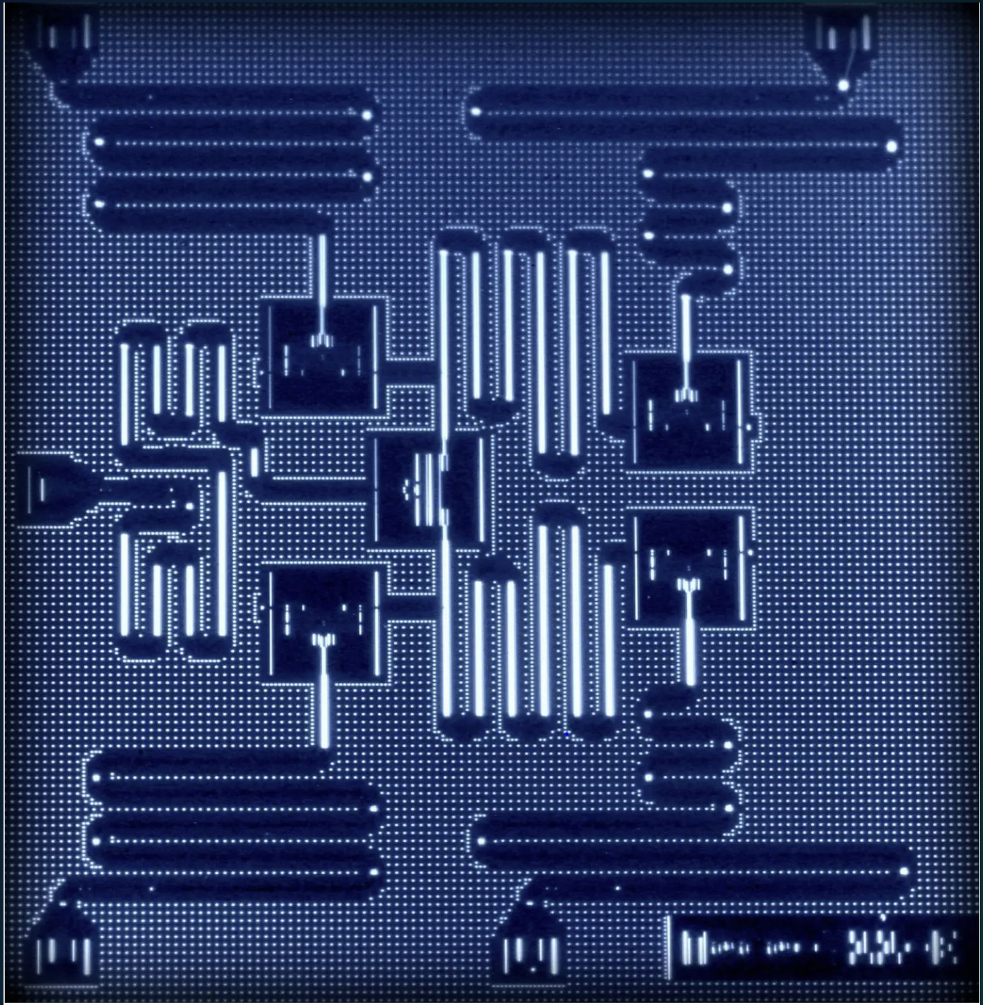
The dilution refrigerator. *Charlotte Hu*



The quantum processor inside the chandelier. *Charlotte Hu*

The control electronics behind the quantum computer. *Charlotte Hu*

The container that holds the dilution refrigerator inside. *Charlotte Hu*



Resonators, seen here, connect the qubits to each other and to the control electronics. *IBM*

05

Conclusion

Conclusion - Introduction and History

- The definition of Quantum Computing is leveraging quantum mechanics for computation.
- Quantum computing is important due to its impact on computer science and daily life.
- Some key historical contributors are Paul Benioff, Richard Feynman, David Deutsch and Peter Shor.

Conclusion - Principles & Fundamentals, Algorithms

- Qubits are a fundamental information carrying unit used in quantum computers
- Quantum Gates are operations transforming quantum states.
- An entanglement occurs when there is a correlation between quantum states
- There are various types of qubits such as superconducting, trapped-ion, neutral-atom, NMR.
- Grover Search Algorithm is optimal for the searching of unstructured databases
- Shor Factoring Algorithm can factor complex scenarios in polynomial time

Conclusion - Real world Connection

- Government involvement in funding for quantum computing.
- Quantum computing in the business sector (JPMorgan Chase, Goldman Sachs).
- Leading companies and institutions in quantum computing (IBM, Google, Microsoft, Amazon, D-Wave).
- Availability of quantum computing services through cloud platforms.
- Different quantum computing languages and development kits.

RESOURCES

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Time for questions?