Impacts of AI: COMP3800-03
AI and Quantum computing
Wentworth Institute of Technology

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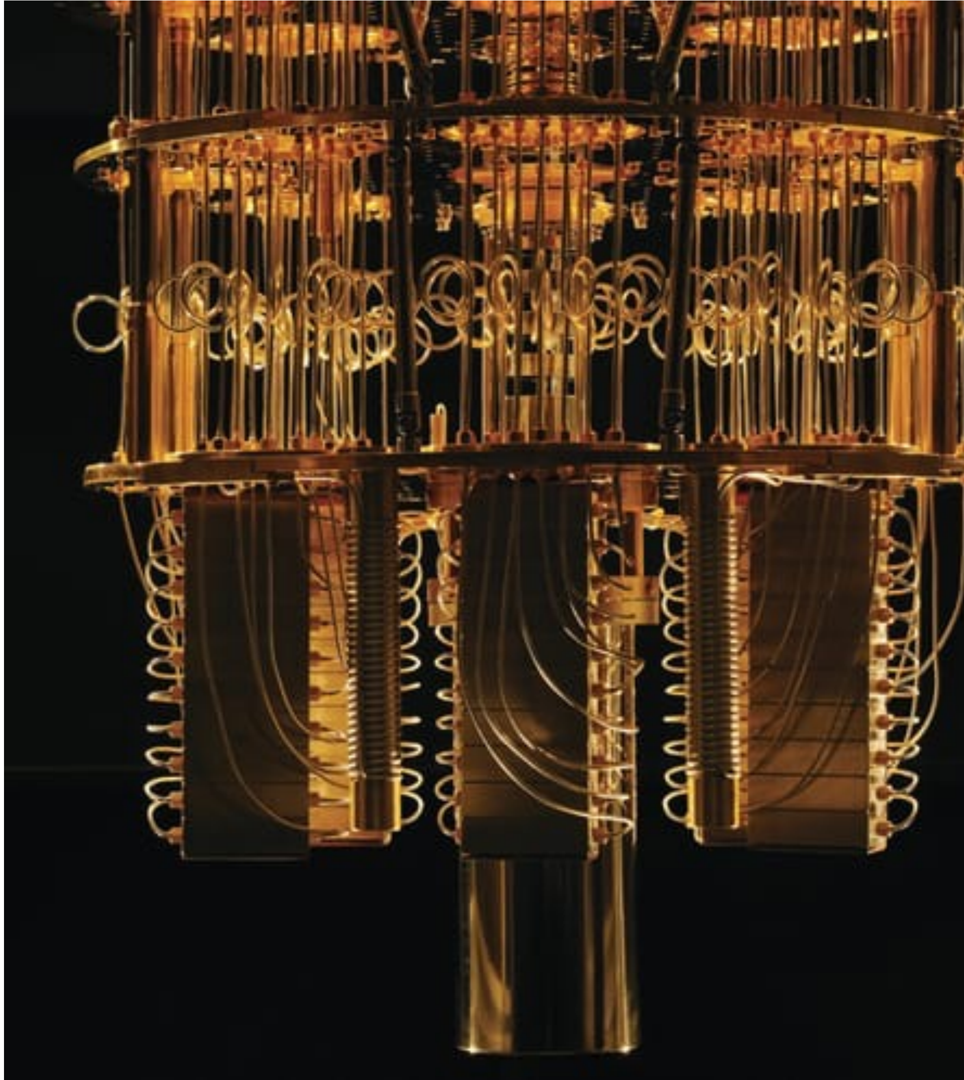
What is Quantum Computing?

- Current computers manipulate individual bits, which store information as **binary 0 and 1 states**

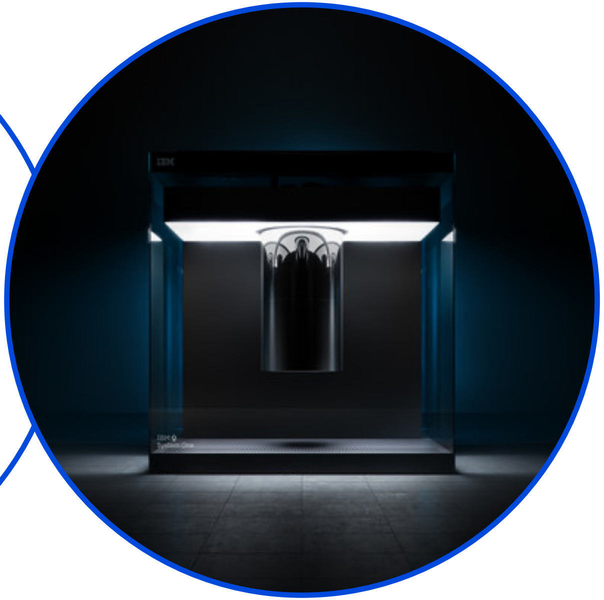
- Quantum computers leverage **quantum mechanical phenomena to manipulate qubits**



A new computing paradigm

***For example,* factoring large numbers into their primes:**

On a conventional computer, this calculation could take **trillions of years**.



On a future quantum computer, it could take **only minutes**.

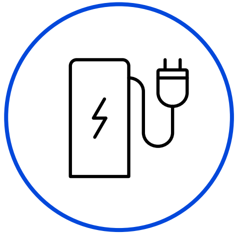
Find the prime factorization of 75; write your answer using exponential notation

Prime numbers.

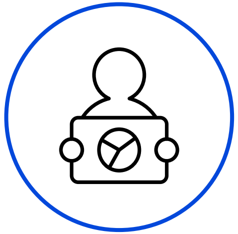
Composite numbers

Companies are hoping Quantum can solve their problems

Potential uses for quantum computing



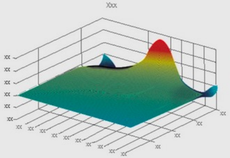
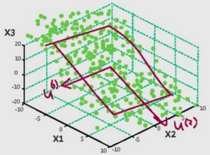
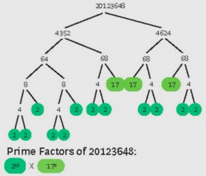
Simulating chemical structures and reactions inside **batteries**, that could improve the range of electric vehicles.



Adjusting **portfolio risk** for investors.

Optimize routes for delivery vehicles, or the movement of parts through factories.

EXHIBIT 1 | Quantum-Advantaged Computational Problems

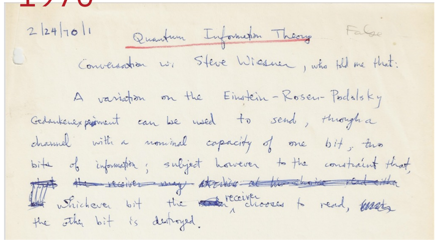
Type of problem		Useful for...	Industry applications include...
	Combinatorial optimization	Minimizing or maximizing an objective function, such as finding the most efficient allocation of resources or the shortest total distance among a set of points (e.g., the traveling salesman problem)	• Network optimization (e.g., for airlines, taxis) • Supply chain and logistics optimization • Portfolio optimization in financial services
	Differential equations	Modeling the behavior of complex systems involving fundamental laws of physics (e.g., Navier Stokes for fluid dynamics and chemistry)	• Fluid dynamics simulations for automotive and aeronautical design and medical devices (e.g., blood flow analysis) • Molecular simulation for specialty materials design and drug discovery
	Linear algebra	Machine learning tasks involving matrix diagonalization, such as clustering, pattern matching, and principal components analysis, as well as support vector machines, which are ubiquitous in applications across industries	• Risk management in quantitative finance • DNA sequence classification • Marketing and customer segmentation
	Factorization	Cryptography and computer security, where the most common protocols today (e.g., RSA) rely on the infeasibility (for classical computers) of factoring the product of two large prime numbers	• Decryption and code breaking (e.g., for governments)

Source: BCG analysis.

Quantum Computing Milestones

1970

Charles H. Bennett may have been the first person to write the phrase "quantum information theory" on February 24, 1970


2/24/70/1 Quantum Information Theory False

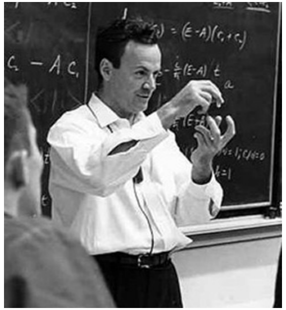
Conversation w. Steve Wiesner, who told me that:

A variation on the Einstein-Rosen-Podolsky Gedankenexperiment can be used to send, through a channel with a nominal capacity of one bit, two bits of information; subject however to the constraint that, ~~the receiver may at his choice read either~~ whichever bit the receiver chooses to read, the other bit is destroyed.

1981

"nature isn't classical ... and if you want to make a simulation of nature, **you'd better make it quantum mechanical"**

– **Richard Feynman**, theoretical physicist



1995

Peter Shor proved his quantum algorithm could crack RSA encryption in minutes, a feat that would take a regular computer the lifetime of the universe to unravel

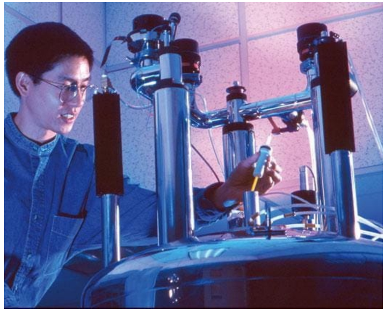
Quantum Computing Milestones

1996

Lov Grover, came up with a quantum algorithm that would allow people to swiftly search unstructured databases. This led to advances in hardware

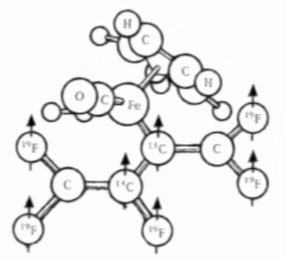
1998

The **first experimental demonstration** of a quantum algorithm



2001

The first execution of Shor's algorithm. The number 15 was factored using 1018 identical molecules, each containing seven active nuclear spins

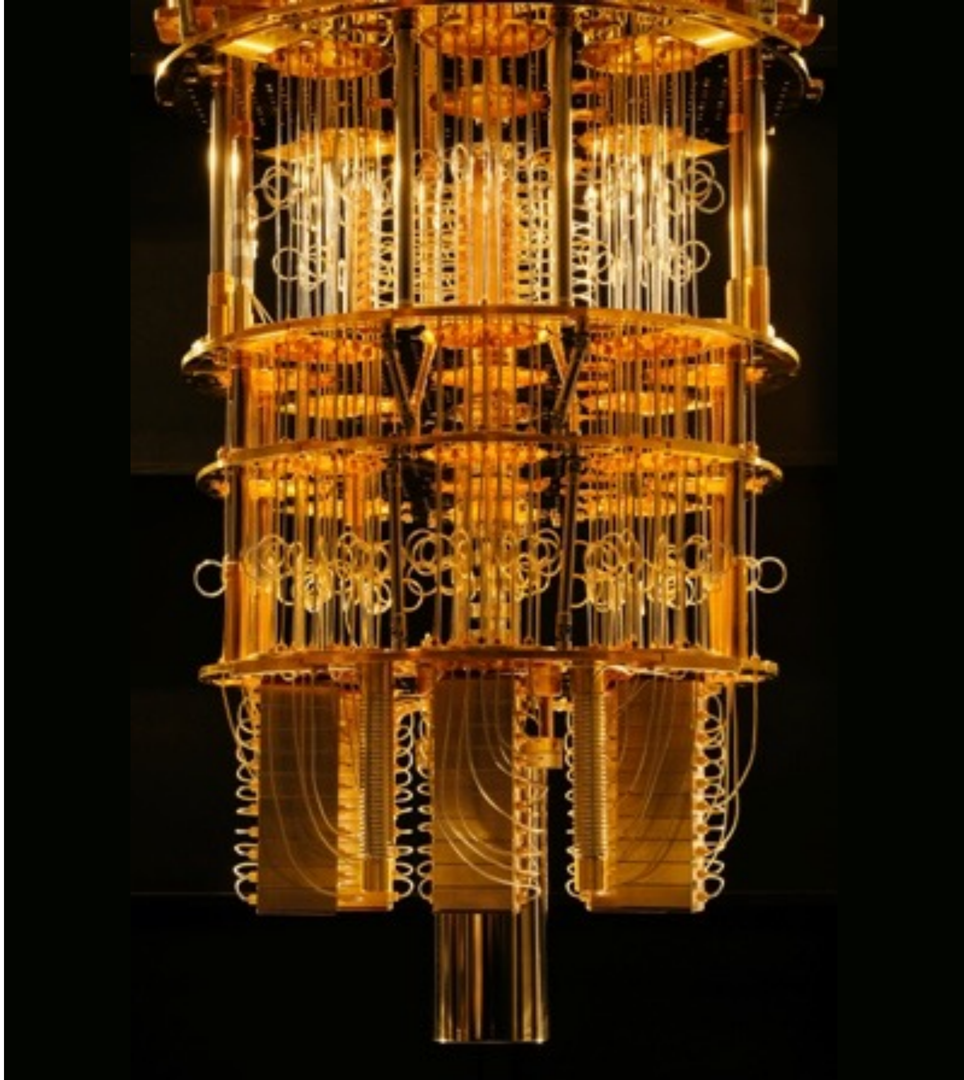


IBM Unveils Groundbreaking Quantum Computing System

Quantum computer systems

Quantum computers leverage quantum mechanical phenomena to manipulate information

Quantum computers rely on quantum bits, or qubits

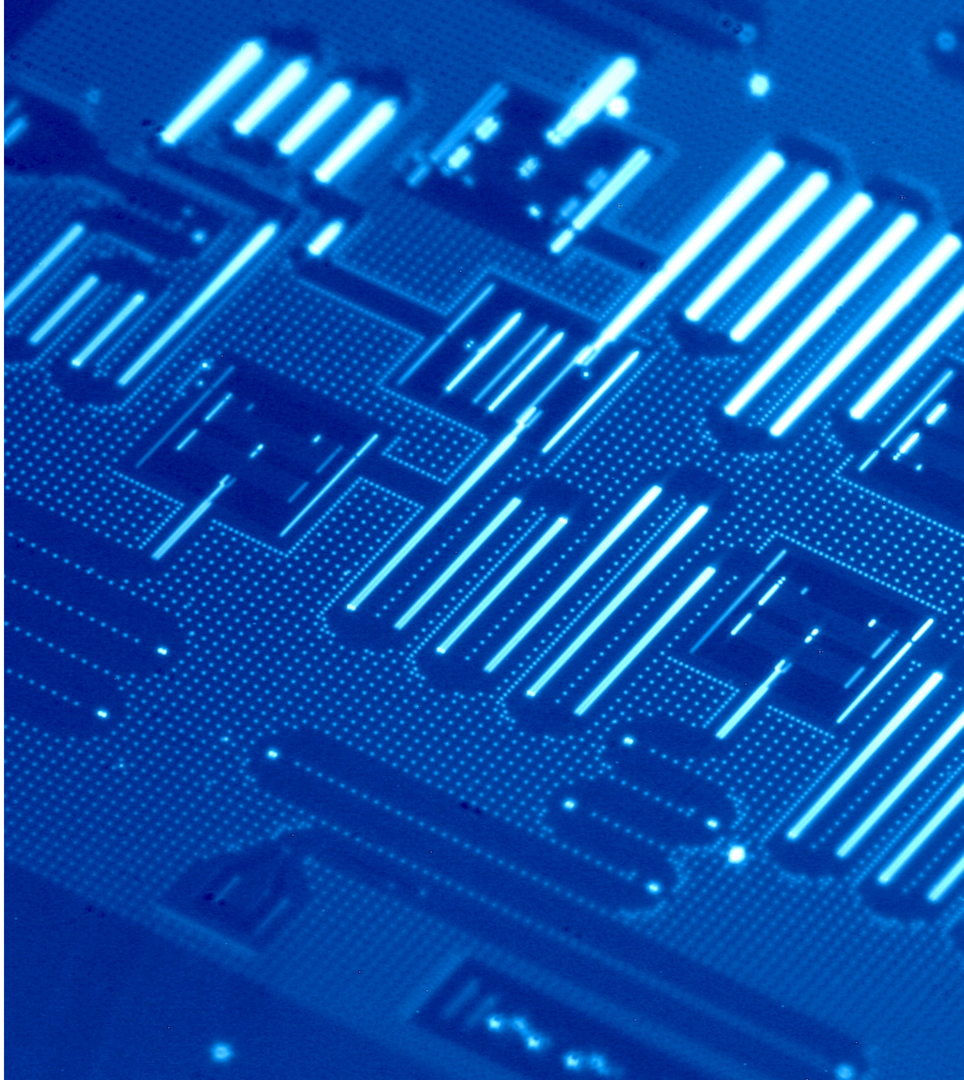


Qubits

In quantum computers, the basic variable is the qubit

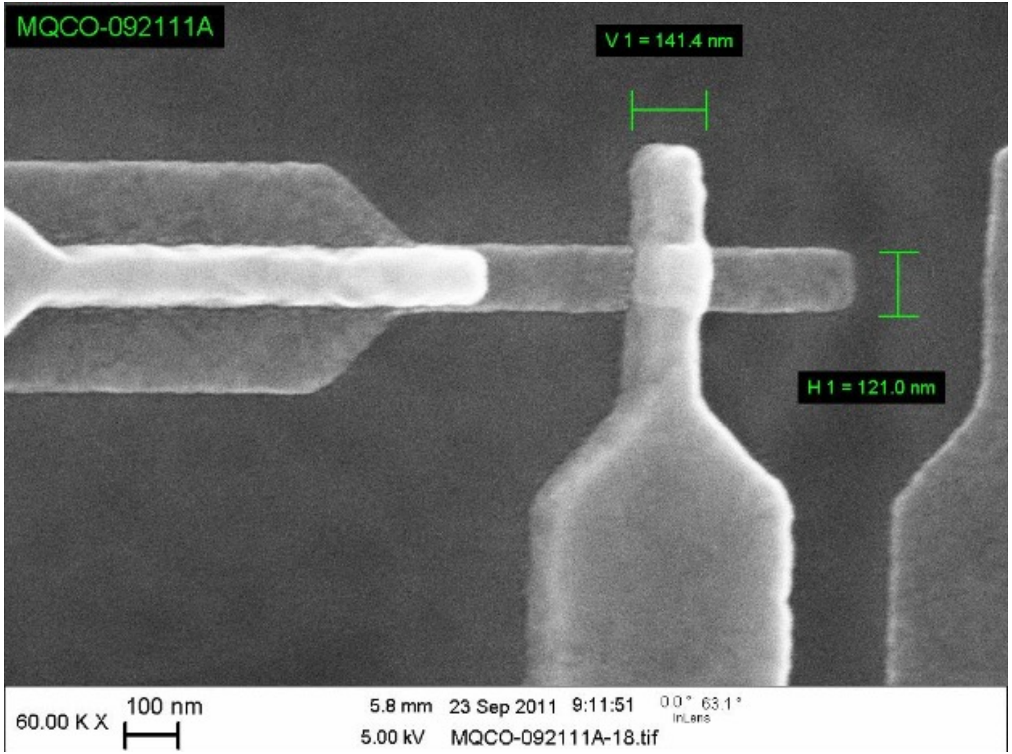
Qubits obey the laws of quantum mechanics

Unlike any classical variable, these cannot be represented by some number of classical bits



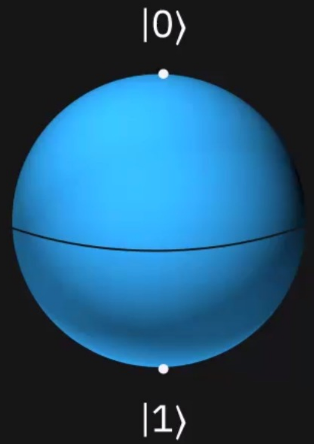
Qubits

- IBM's qubits are more precisely called **transmon qubits**
- The qubit is measured in **nanometers** (one billionth of a meter)
- Qubits themselves are incredibly powerful, yet delicate

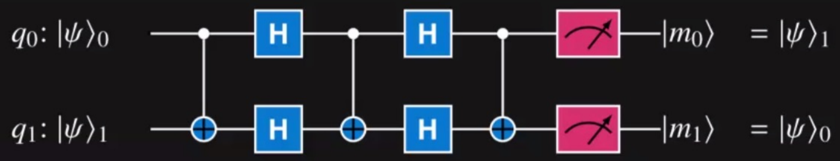


Quantum bits (qubits) and quantum circuits

IBM **Quantum**



A quantum bit or qubit is a controllable quantum object that is the unit of information



A quantum circuit is a set of quantum gate operations on qubits and is the unit of computation

THREE QUANTUM MECHANICAL PROPERTIES

used to manipulate the state of a qubit

Superposition

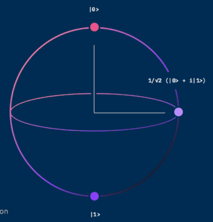


Figure 1:
Superposition

Entanglement

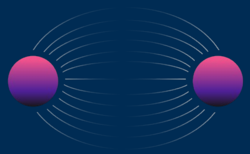


Figure 2:
Entanglement

Interference

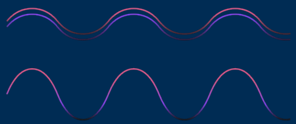


Figure 3:
Positive Interference

Quantum Properties: Superposition

A combination of states we would ordinarily describe independently

Like two musical notes at once

— what you will hear is a superposition of the two notes

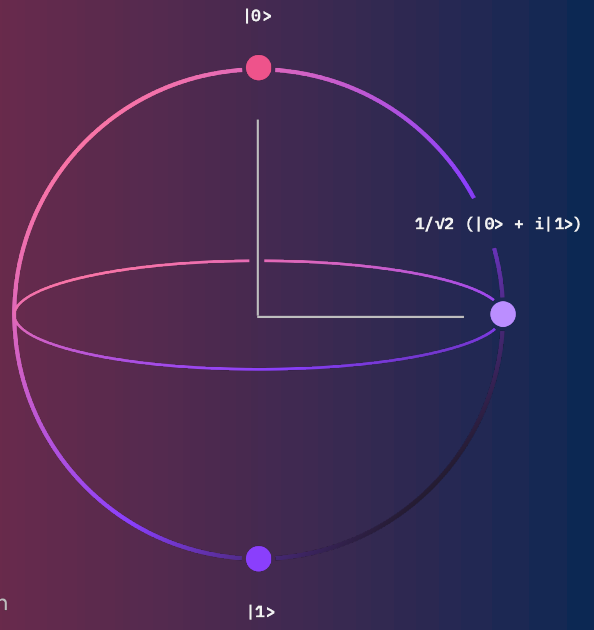


Figure 1: Superposition

Superposition

A **superposition** is a weighted sum or difference of two or more states.

For example, the state of the air when two or more musical tones sound at once.

Superposition

Quantum theory predicts that a computer with **n qubits can exist in a superposition of all 2^n** of its distinct logical states 000...0, through 111...1

Do the coin toss…

A counter-intuitive quantum phenomenon describing behavior we never see in the classical world

Entangled particles behave together as a system in ways that cannot be explained using classical logic

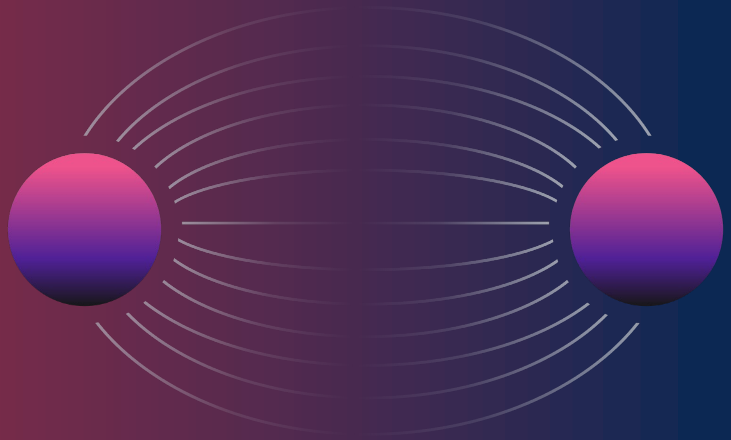


Figure 2: Entanglement

Quantum Properties: Interference

Quantum interference can be understood similarly to wave interference

When two waves are in phase, their amplitudes add, and when they are out of phase, their amplitudes cancel

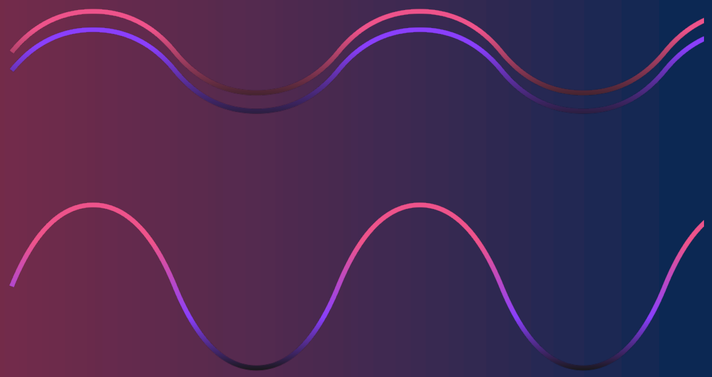


Figure 3:
Positive Interference

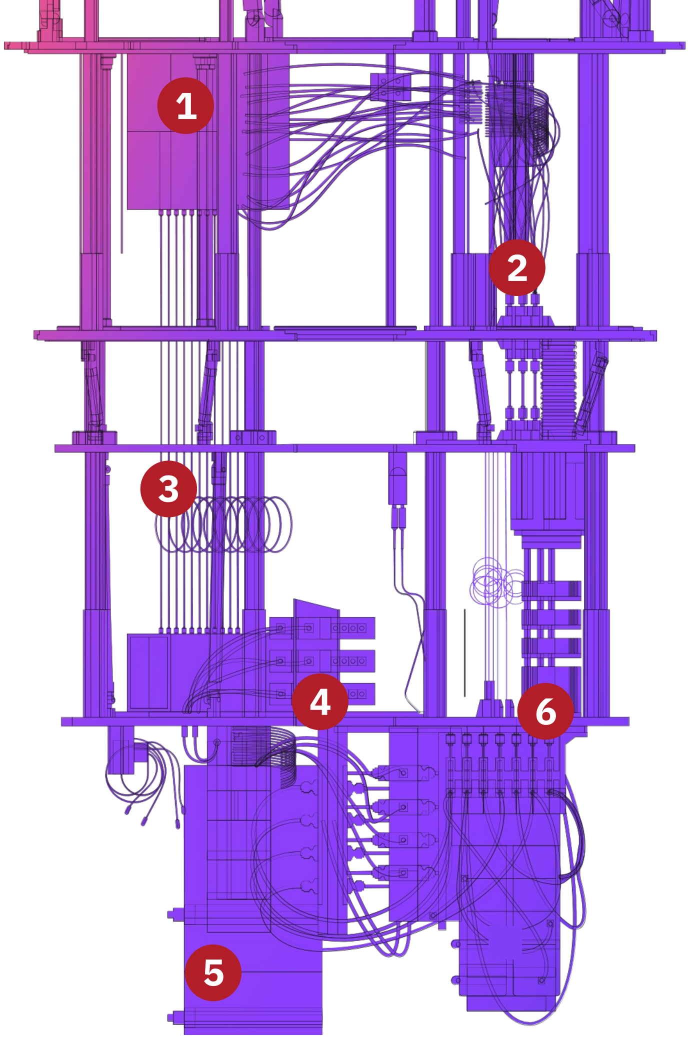
Inside a quantum computer

To work for extended periods of time, **superconducting qubits must be kept very cold**

Quantum computers operate at temperatures close to absolute zero, **colder than the vacuum of space**

Parts of a quantum computer

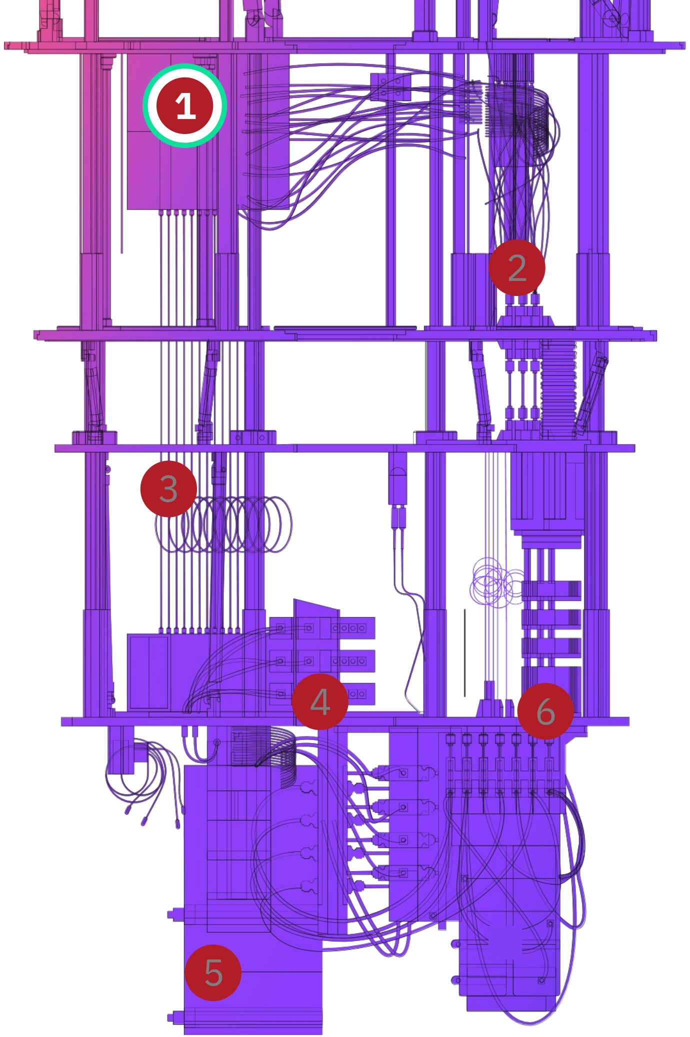
1. **Qubit Signal Amplifier**
2. **Input Microwave Lines**
3. **Superconducting Coaxial Lines**
4. **Cryogenic Isolators**
5. **Quantum Amplifiers**
6. **Mixing Chamber**



1

Qubit Signal Amplifier

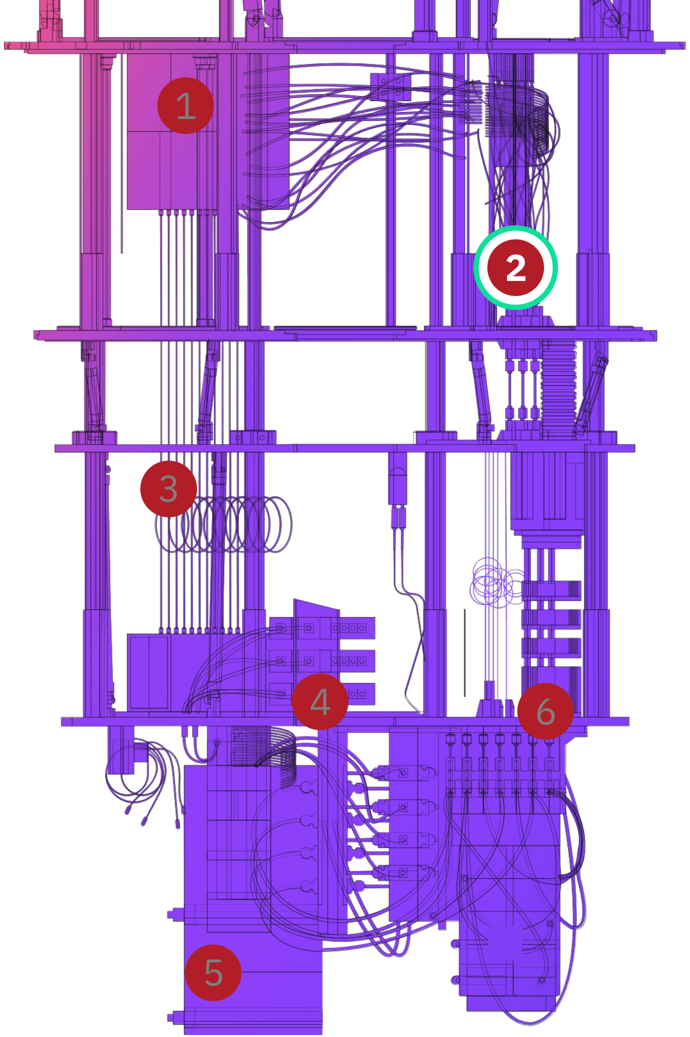
One of two amplifying stages is cooled to a temperature of 4 Kelvin



2

Input Microwave Lines

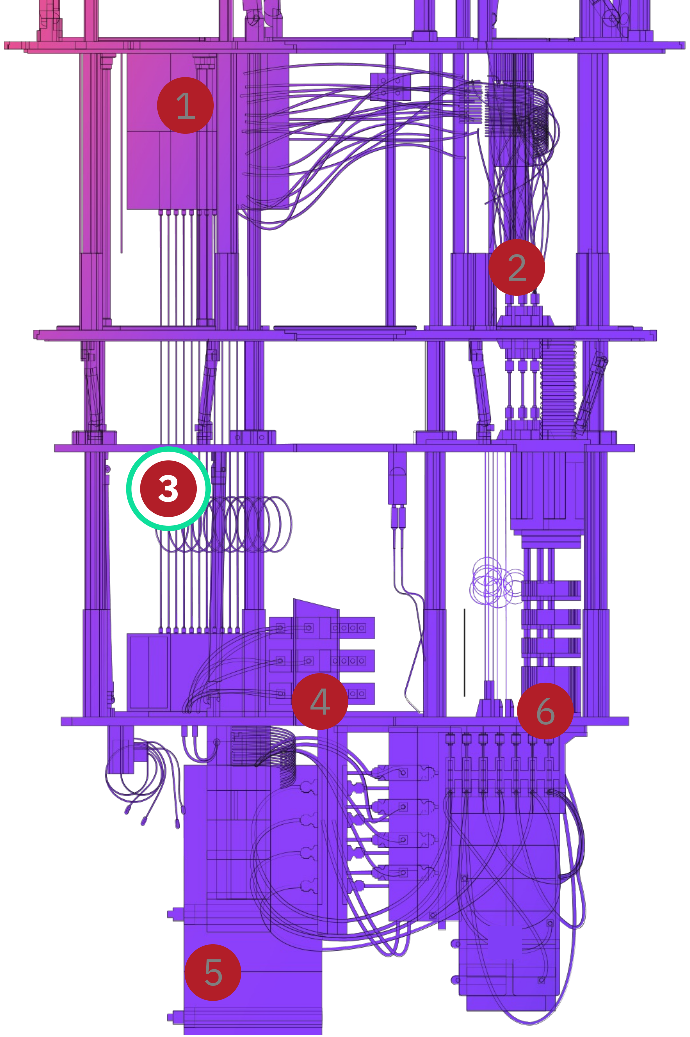
Attenuation is applied at each stage in the refrigerator in order to protect qubits from thermal noise during the process of sending control and readout signals to the processor



3

Superconducting Coaxial Lines

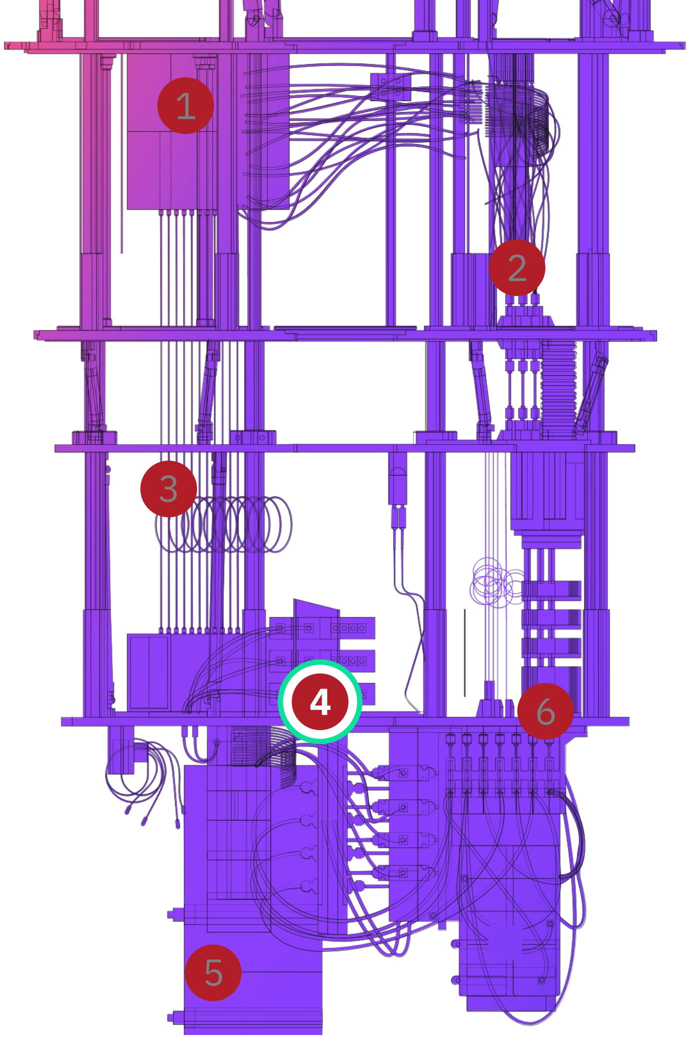
In order to minimize energy loss, the coaxial lines that direct signals between the first and second amplifying stages are made out of superconductors



4

Cryogenic Isolators

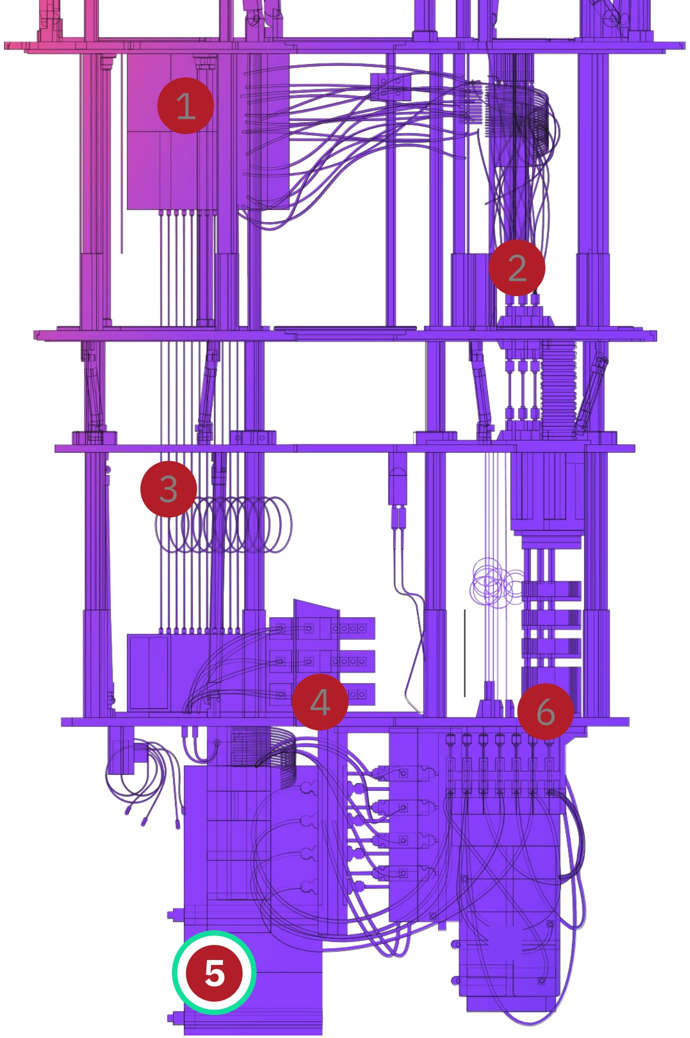
Cryogenic isolators enable qubits signals to go forward while preventing noise from compromising qubit quality



5

Quantum Amplifiers

Quantum amplifiers inside a magnetic shield capture and amplify processor readout signals while minimizing noise

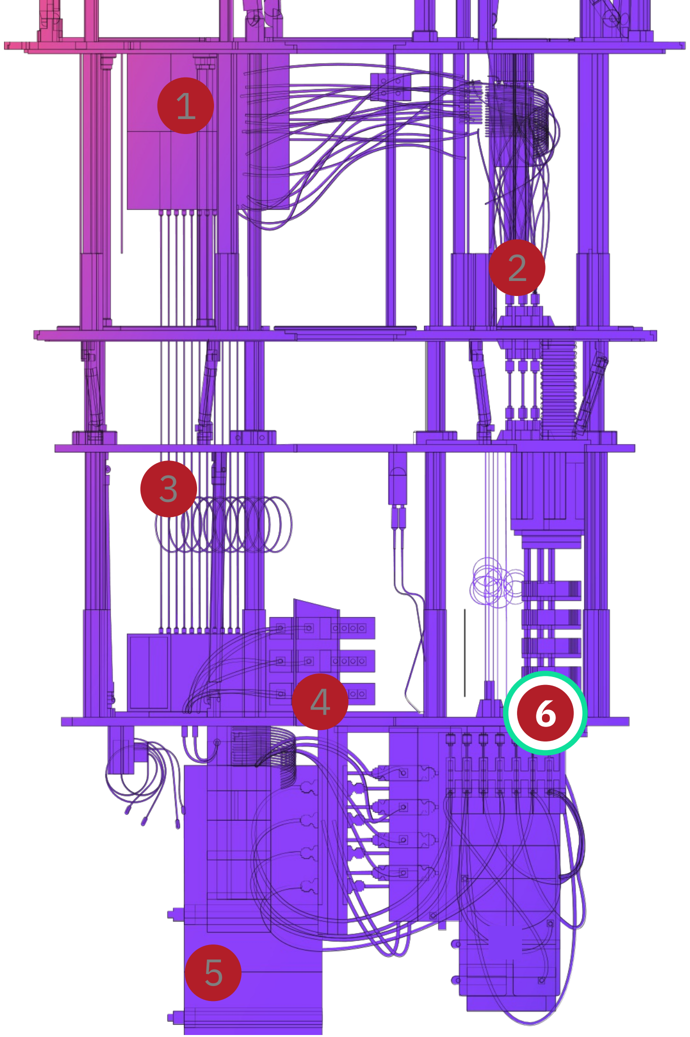


6

Mixing Chamber

This chamber at the lowest part of the refrigerator provides necessary cooling power

It brings the processor and associated components down to a temperature of 15 mK — colder than outer space



Hardware

Sine wave generators
produce continuous tones at qubit and resonator frequencies

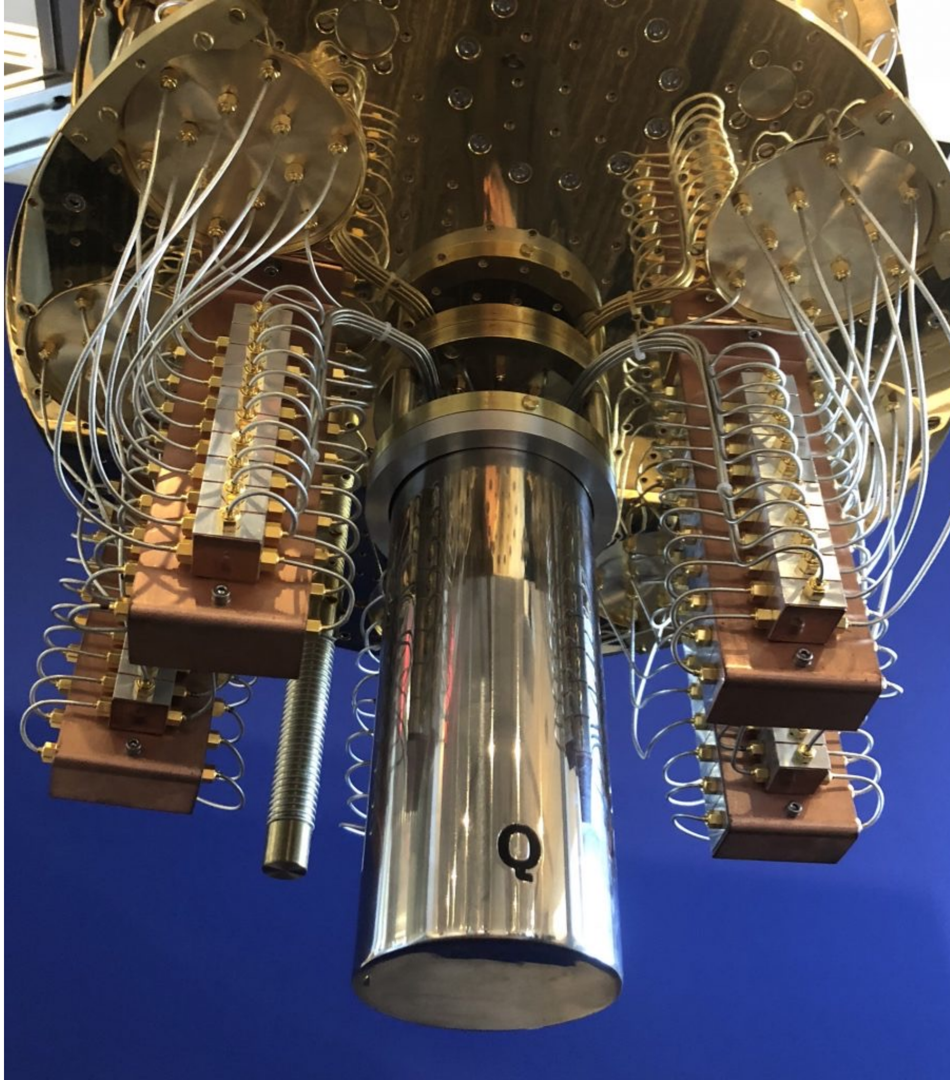
Arbitrary waveform generators
produce programmable pulse envelope sequences

Mixers
multiply the sine wave and envelope signals to generate qubit control/readout pulses

Other hardware:
- amplifiers
- splitters
- coaxial cables
- power supplies
- 10 MHz reference clocks
- digitizers
- computers

Quantum volume

- **Quantum volume** is the measure of error rates and how the system is “wired”
- Quantum volume describes the largest quantum computational space that a device can explore



Refrigeration

- Qubits are kept at an extremely cold temperature of **1/200th the temperature of outer space**
- Qubits are kept this cold to prolong their fragile quantum state

Here a scientist takes a closer look at the cryogenic refrigerator

IBM

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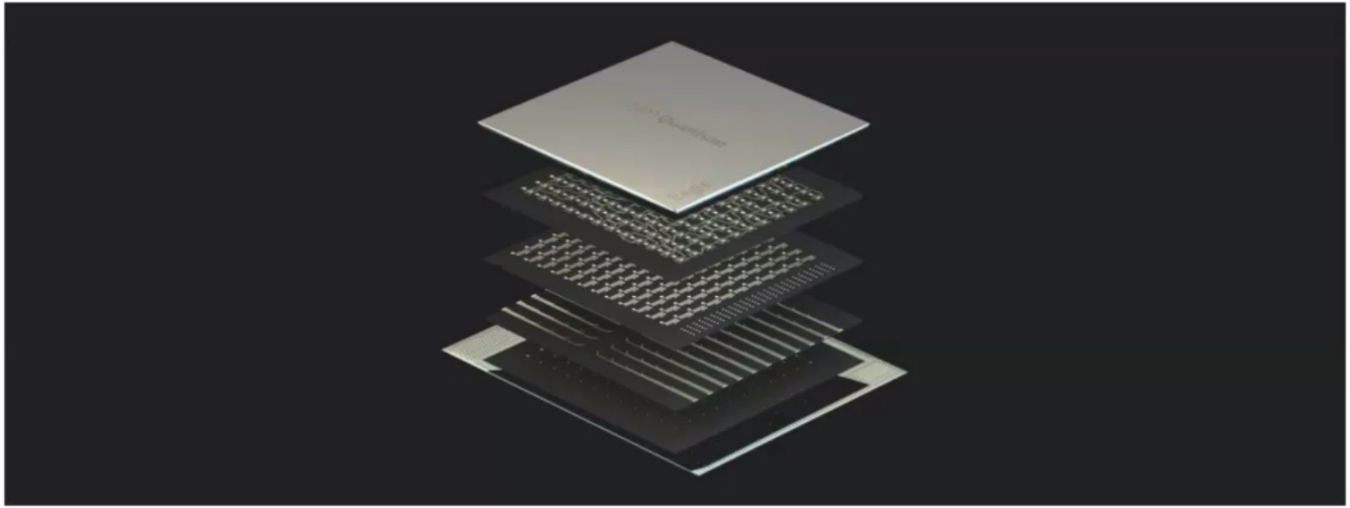
IBM Unveils Breakthrough 127-Qubit Quantum Processor

- Delivers 127 qubits on a single IBM quantum processor for the first time with breakthrough packaging technology

- New processor furthers IBM's industry-leading roadmaps for advancing the performance of its quantum systems

- Previews design for IBM Quantum System Two, a next generation quantum system to house future quantum processors

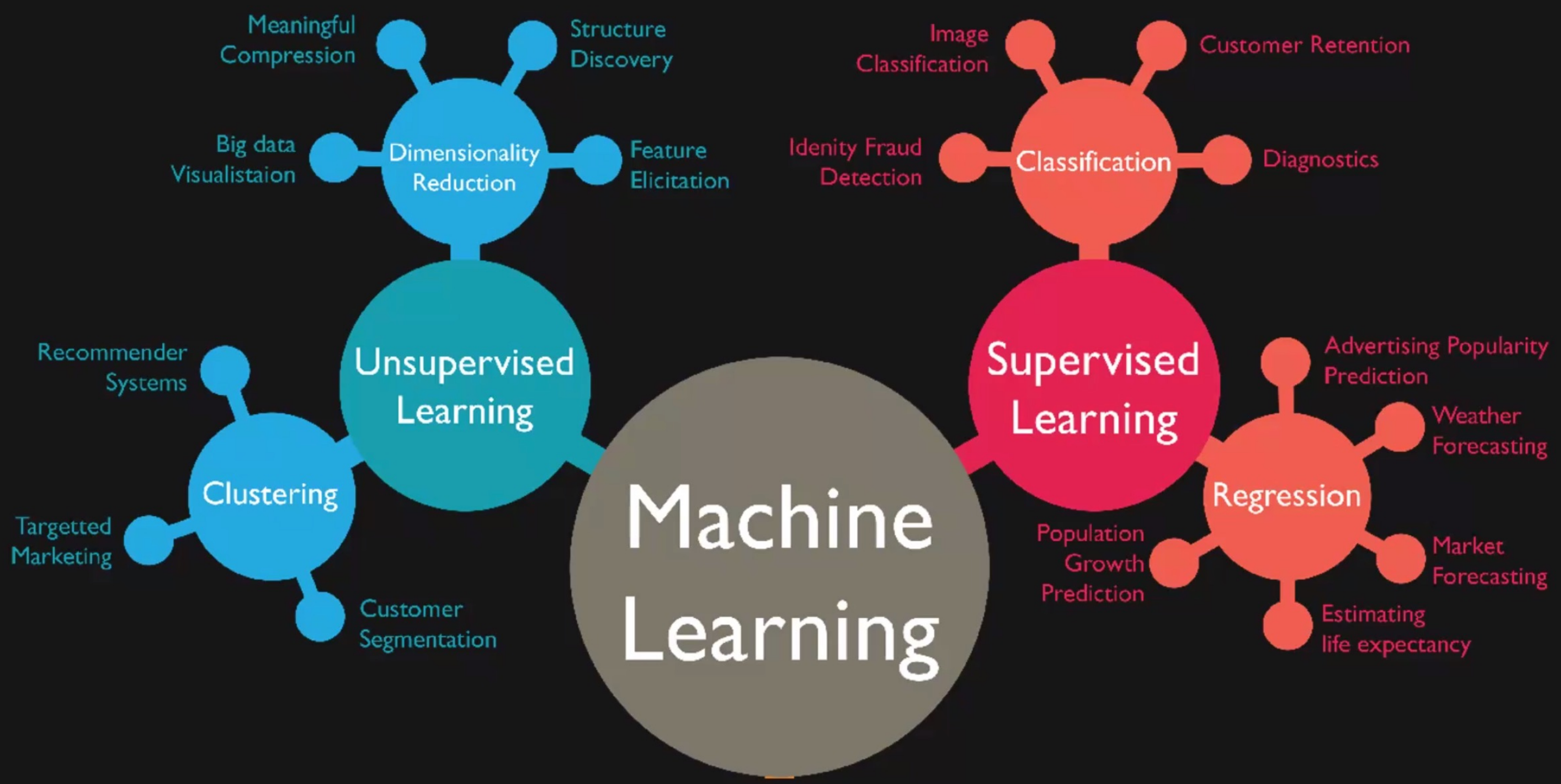
Nov 16, 2021



https://newsroom.ibm.com/2021-11-16-IBM-Unveils-Breakthrough-127-Qubit-Quantum-Processor

Machine Learning

IBM Quantum



Quantum applications span three general areas

IBM **Quantum**

Simulating Quantum Systems

Quantum chemistry
Material science
High energy physics

Artificial Intelligence

Better model training
Pattern recognition
Fraud detection

Optimization / Monte Carlo

Portfolio optimization
Risk analysis
Loans & credit scoring
Monte Carlo-like applications

Development Roadmap

IBM **Quantum**

	2019	2020	2021	2022	2023	2024	2025	2026+
	Run quantum circuits on the IBM Cloud	Demonstrate and prototype quantum applications	Run quantum applications 100x faster on the IBM Cloud	Dynamic circuits for increased circuit variety, algorithmic sophistication	Frictionless development with quantum workflows built in the cloud	Call 1K+ qubit services from Cloud API and investigate error correction	Enhance quantum workflows through HPC and quantum resources	
Model developers					Quantum model services: Natural Sciences, Finance, Optimization, Machine Learning			
Algorithm developers		Qiskit application modules: Natural Sciences, Finance, Optimization, Machine Learning			Prebuilt quantum runtimes		Prebuilt quantum + HPC runtimes	
Kernel developers	Circuits		Qiskit Runtime	Dynamic circuits	Circuit libraries		Advanced control systems	
Quantum systems	**Falcon** 27 qubits	**Hummingbird** 65 qubits	**Eagle** 127 qubits	**Osprey** 433 qubits	**Condor** 1121 qubits	**Beyond** 1K - 1M+ qubits		
IBM Cloud	Circuits		Programs		Models			

Many companies have interest in Quantum

"Quantum computing can take our understanding of nature and chemistry to a granularity that has never been able to be done before because the computations are just too hard"

–Vijay Swarup, VP ExxonMobil

Resources

1. What is IBM Q?
   https://www.research.ibm.com/ibm-q/learn/what-is-ibm-q/.

2. IBM Q Experience
   https://quantum-computing.ibm.com/login

3. https://qiskit.org/learn/