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INTRODUCTION TO QUANTUM COMPUTING, SUPERPOSITION AND ENTANGLEMENT

CS202 LECTURE 23

Agenda

Introduction to Quantum Computing

Quantum Mechanics Preliminaries

Quantum Internet Building Blocks

- Quantum End Nodes
- Quantum Communication Channel
- Quantum Repeaters
- Quantum Switch
- Quantum Routers

Some Technological Challenges And Future Directions

Conclusion / Future Outlook

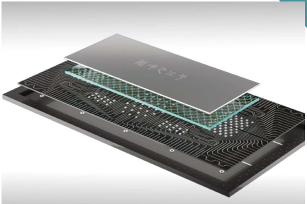
Willow, Google's state-of-the-art quantum chip

- Willow completed a benchmark computation in under five minutes
- 105 physical qubits
- Take today's fastest supercomputers an estimated 10 septillion years (10^25 years) to complete

- Massive difference in performance highlights the potential of quantum computing to tackle problems that are currently intractable for classical computers

Zuchongzhi 3.0 Processor, China's Counterfall to Willow

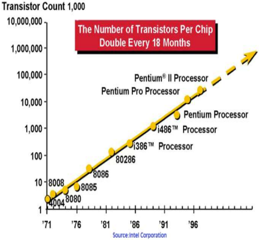
- Same number of qubits as in willow (105 qubits) high operational fidelities.
- **Quantum Advantage:** Demonstrated by completing an 83-qubit random circuit sampling task in seconds, surpassing classical supercomputers.
- **Performance Benchmark:** Achieved one million samples within a few hundred seconds, outperforming Google's Sycamore processor.



Quantum Mysteries

- Quantum mechanics - explain how the universe works at a scale smaller than atoms
- Quantum computing - exploits the quantum mechanical properties of superposition and entanglement to perform computations of complex systems
- Quantum computing handle very large dataset problems with relatively less number of qubits

Why Quantum Computers



- Moore's law slowing down
- Transistor cannot be made smaller due to laws of Quantum Mechanics starts to take over
- Classical computers lag in solving many types numerical problems

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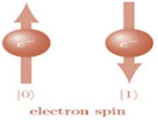
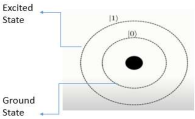
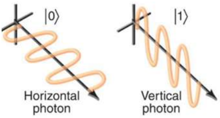
Quantum Mechanics Preliminaries

Quantum Bits

A **Quantum bit (qubit)** is two-level quantum system, such as spin up-down of an electron, ground to exited state of an electron and the vertical-horizontal polarization of a photon







Quantum Bits: Mathematical Representation

- A quantum state can be regarded as the weighted combination of two base states 0 and 1
- State 0 (ground state) written as $|0\rangle$
- State 1(excited state) written as $|1\rangle$ with some probability
- Qubit expressed as linear combination of the basis **superposition** states

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

| > is Ket or Dirac notation

α and $\beta \in C$ are complex numbers, known as probability amplitudes

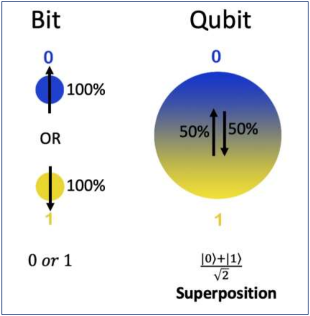
Quantum Bits: Mathematical Representation

Qubit can either be in two states simultaneously

It may be 50% information in ground state or in excited state at the same time. See in next slide

But we don't know, what the state it is exactly in

It collapses to state 0 with probability α^2 and to state 1 with a probability β^2 when measured.


Bit
0
100%
OR
100%
1
0 or 1
Qubit
0
50%
50%
1
$\frac{|0\rangle+|1\rangle}{\sqrt{2}}$
Superposition

Vector Form

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

$$|0\rangle \equiv \begin{bmatrix} 1 \\ 0 \end{bmatrix}, |1\rangle \equiv \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Quantum Mechanics Preliminaries

Superposition & Measurement

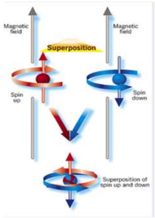


Fig: Quantum Superposition of qubit

- Qubits can have a value of 0 or 1 or both simultaneously by virtue of superposition principle
- When measured it collapses to state 0 with probability α^2 and to state 1 with a probability β^2
- Thus, superposition enables quantum computer to perform parallel computation on a huge scale

Quantum Mechanics Preliminaries

Quantum Entanglement

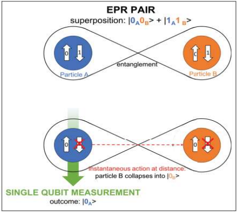


Fig 4 Quantum Entanglement

- ✓ Entanglement - Qubits connected in an entangled state despite of physical separation between them therefore measuring one qubit, one may change the characteristics of the other qubits

- ✓ Combination of superposition and entanglement results in collection of N qubits encoding information in a 2N-dimensional Hilbert space

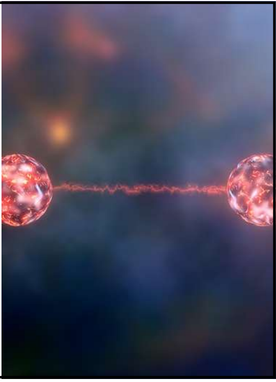
This will enable quantum computers to solve large-scale space problems

What is Quantum Entanglement?

Definition: Two or more particles share a quantum state; measuring one instantly determines the state of the other, regardless of distance

Key Features:

- Non-local correlation (e.g., spin/polarization)
- Measurement of one particle's state instantaneously determines the other particle's state
- No classical signal or medium required
- No faster-than-light classical communication



Reframing Entanglement

Core Idea: Entanglement = Instantaneous transportation of change, not information

Classical vs Quantum Systems:

- **Classical:**

  Information encoded → transmitted → decoded

- **Quantum:**

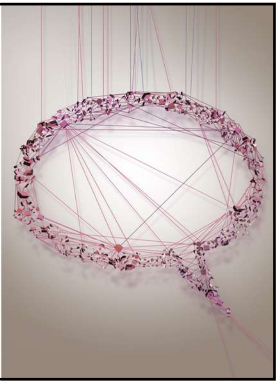
  Change in state of one system → instant mirroring in another

Philosophical Reflections

- **Holistic Interconnectedness:** Universe as a unified system
- **Change as Fundamental:** Dynamic, non-local transformations
- **Beyond Space-Time:** Challenges classical causality
- **Quote:** “The universe is not a collection of objects, but a web of relationships”

Epilogue

- **Summary:** Entanglement redefines "change" as a universal, instantaneous process
- **Impact:** Advances in tech (communication, computing) + paradigm shift in philosophy
- **Final Thought:** "Is reality a tapestry woven by entangled threads of change?"



Quantum Mechanics Preliminaries

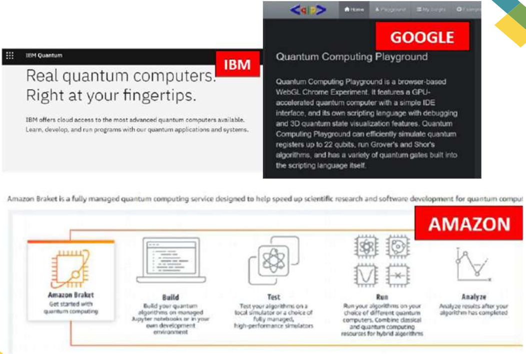
No Cloning Theorem

The qubits can not be cloned

It is impossible to create an independent and identical copy of an arbitrary unknown quantum state

The no-cloning theorem has a time-reversed dual, the no deleting theorem

This prevents the usage of classical error correction techniques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Learn, develop, and run programs with our quantum applications and systems.
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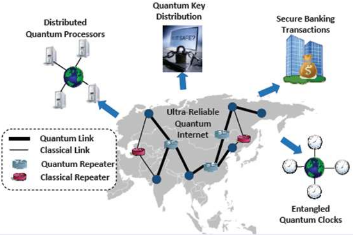
GOOGLE
Quantum Computing Playground
Quantum Computing Playground is a browser-based WebGL Chrome Experiment. It features a GPU-accelerated quantum computer with a simple IDE interface, and its own scripting language with debugging and 3D quantum state visualization features. Quantum Computing Playground can efficiently simulate quantum registers up to 22 qubits, run Grover's and Shor's algorithms, and has a variety of quantum gates built into the scripting language itself.
Amazon Braket is a fully managed quantum computing service designed to help speed up scientific research and software development for quantum comput
AMAZON
Amazon Braket
Get started with quantum computing
Build
Build your quantum algorithms on managed Jupyter notebooks or in your own development environment
Test
Test your algorithms on a local simulator or a choice of fully managed, high-performance simulators
Run
Run your algorithms on your choice of different quantum computers. Combine classical and quantum computing resources for hybrid algorithms
Analyze
Analyze results after your algorithm has completed

Applications: Where are we heading?



Quantum Internet: A global network of heterogeneous quantum processing and communication nodes over large distances, for example for distributed quantum computing, long-haul QKD, QKD and location verification aided secure banking transactions, as well as for quantum clock aided ultra-precise synchronization and navigation.

Quantum Internet : Introduction

- Promising candidate - potential to revolutionize existing wired/wireless communications

- Two major break throughs:
  - Extremely secure communication platform
    - Qubits rely on physical property of photons not vulnerable codes
  - Massive distributed compute power
    - Exploit quantum parallelism

Quantum Internet : Introduction

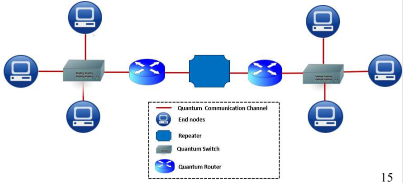
Quantum Internet can:

- Provide access to quantum computers as a **cloud service** (cost-effective solution)
- Support functionalities with no counterpart in classical domain
- E.g., secure communication, blind computing, advance sensing techniques and clock synchronization

Quantum Internet Building Blocks

- ✓Quantum End Nodes
- ✓Quantum Communication Channel
- ✓Quantum Switches
- ✓Quantum Routers
- ✓Quantum Repeaters

Block Diagram Of Quantum Internet



Quantum Internet Building Blocks

Quantum End Nodes

- Quantum end nodes - host which receive, process, store and transmit quantum information
- Based on qubits, nodes are categorized into
  - ***Simple nodes***
    - use single qubit for processing
  - ***Quantum processors nodes***
    - composed of multiple qubits
    - perform advance computational tasks

Quantum Internet Building Blocks

Quantum End Nodes

- Companies and universities struggling to incorporate higher number of qubits on single quantum processor

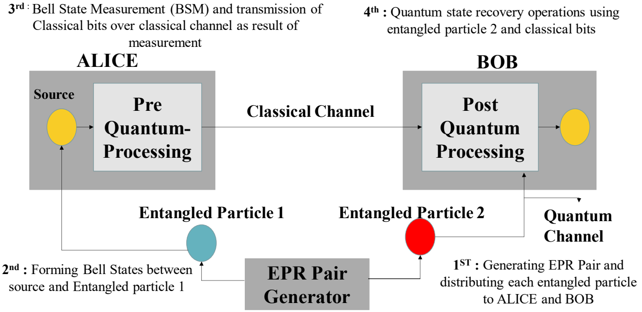
- Some leading players:
  - ✓ **Google** - quantum processor comprising 54 qubits named Sycamore in 2017 ; Willow 2024
  - ✓ **University of Science and Technology China (USTC)** - quantum processor named Zuchongzi comprising of 56 superconducting qubits
  - ✓ **IBM** - 127 qubit processor named as IBM eagle

Quantum Internet Building Blocks

Quantum Communication Channel (QC)

- **Quantum Internet** - requires the transmission of qubits among various quantum end nodes
- **Quantum teleportation (QT)** - reliable transfer of quantum information between distant nodes without requiring the physical transfer of qubits

  - Requires two parallel links for quantum communication
    - **Classical link -** transmits two classical bits from one end node to the other
    - **Quantum link -** responsible for entanglement generation and distribution



Quantum Teleportation

Quantum Teleportation

- **Quantum teleportation** is not straightforward for application, which renders efficient communication and fidelity of the system
- It involves imperfections in its process

- **Decoherence** - imposed by photon loss in environment
- Result of a sequence of operations that are applied for the processing of teleportation

- Thus, the technology opted for quantum teleportation plays a strong part in improving the system fidelity and reducing decoherence

Quantum Communication Channels
(A Comparison)

- Classical information as well as quantum information can be sent through quantum channels
- This channel can be a free space, fiber based or satellite-based channel

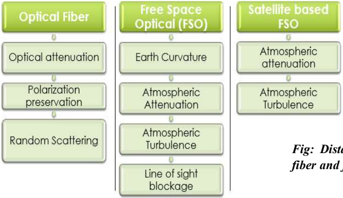
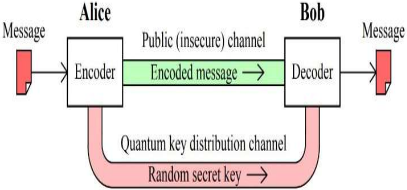


Fig: Distance limiting factors for optical fiber and free space optical channel

Optical Free Space Vs Fiber Channel

- Free space Optical channel offers low losses than fiber optical channel because space has low losses than fiber
- Satellite based channel has application for long distance communication
- In fiber optical channel, achievable key rate scales linearly, which exponentially decay with distance due to absorption.
- Due to this reason, long range communication using fiber optical channel is not preferrable

Quantum Cryptography



Quantum Key distribution (QKD) Schemes

- Ensures secure communication between two distant parties.
- Allow two parties to share encryption keys with security based on physical laws.
- Following are some practical QKD schemes:

1. Overcoming the rate-distance limit of quantum key distribution without quantum repeaters.
2. Fully passive entanglement based quantum key distribution scheme.

Quantum Internet Technical Challenges & Future Directions

1. Decoherence

- ✓ Imperfections caused by adverse impact of environment.
- ✓ Solutions are QECC and Entanglement Purification /Distillation

2. No-Cloning Theorem

- ✓ Restrictions of copy qubits render classical error correction techniques not usable for quantum error correction
- ✓ Specially design QEC techniques are Quantum Reed-Muller codes, QLDPC codes, QCC, QTC, QURC

3. Imperfections due to Entanglement Generation or Distribution

- ✓ Solutions are satellite based FSO and SNSPD for entangled pair detection

4. Wavelength of Division Multiplexing

- ✓ For seamless use of single optical fiber for both classical and quantum channels required for teleportation some variants of wavelength division multiplexing may be used

5. SoftWarization

- ✓ primarily involve network function virtualization and software defined networking

Conclusion & Future Direction

- ***Quantum Internet*** - potential to transform the current internet into decentralized computational powerhouse
- key distinctive features includes ultra-secure communication platform and exponential compute power
- Photonic technology emerged as the key enabler for Quantum Internet
- Some of the projected applications of this promising technology are in the realm of
  - ✓ Quantum Machine learning,
  - ✓ Quantum internet of things (QIoT)
  - ✓ Quantum-Enabled 6G wireless networks

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Part 2 - Quantum Internet Bolsters QML

Quantum Computing/Quantum Internet bolsters ML

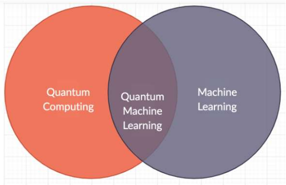
Quantum computers hold the potential to accelerate ML by solving complex problems and generating multiple solutions simultaneously

Promise of more efficient AI performance on complex tasks is a key outcome of leveraging quantum computing for ML

What is QML

- Quantum Machine Learning is a theoretical field that's just starting to develop. It lies at the intersection of Quantum Computing and Machine Learning.

- Main goal of Quantum Machine Learning is to speed things up by applying what we know from quantum computing to machine learning.



What is QML

1. Beyond Bits: Explore the mind-bending possibilities of qubits, which can be both 0 and 1 at the same time.

2. Parallel Pathways: Quantum algorithms tap into the magic of superposition, exploring multiple solutions simultaneously for exponential speedup.

3. Entangled Insights: Unlock hidden connections across vast datasets with the spooky power of entanglement, revealing patterns invisible to classical machines.

4. Revolutionizing the Game: From materials science to drug discovery, quantum machine learning tackles problems once deemed impossible, paving the way for a brighter future.

Classical vs Quantum ML

Aspect	Classical Machine Learning	Quantum Machine Learning
Computational Model	Uses classical bits for computation	Utilizes qubits, taking advantage of superposition and entanglement
Information Representation	Represents information using classical bits (0 or 1).	Leverages quantum states, allowing for superposition of 0 and 1.
Algorithm Execution	Sequential execution of classical algorithms.	Parallel and simultaneous execution of quantum algorithms.
Processing Speed	Limited by classical computing speed	Has the potential for exponential speedup for certain tasks.
Nature of Computation	Deterministic computations based on classical logic.	Probabilistic computations involving quantum interference.
Parallelism	Limited parallelism in classical computation	Inherent parallelism due to superposition and entanglement.

Essence of QI enabled Quantum Machine Learning

- Quantum Machine Learning merges quantum computing principles with classical machine learning techniques to solve complex problems efficiently
- Leverages the inherent parallelism and entanglement of qubits for enhanced computational power
- Machine learning algorithms provide probabilistic results and face computational bottlenecks
- Quantum computers offer probabilistic results due to measurement and potential exponential speedups
- Quantum computers not expected to replace classical computing but can enhance machine learning pipelines

Some Application Areas (Quantum Computing and Machine Learning)

Quantum ML in Healthcare

- ❖**Precision Medicine:** Personalized treatments through quantum data analysis.
- ❖**Drug Discovery:** Accelerating process with quantum algorithms.
- ❖**Genomic Analysis:** Individual genetic profiling with quantum ML
- ❖**Disease Characteristics Analysis:** Understanding diseases better through quantum ML

Quantum ML in Cancer Research

- Efficient problem-solving for drug discovery and genomic analysis
- Predictive models for early detection and personalized treatment

Quantum ML in Finance

- ❖ **Portfolio Optimization:** Maximized returns, minimized risk through quantum analysis
- ❖ **Risk Assessment:** Improved financial risk models with quantum computing
- ❖ **High-Frequency Trading:** Revolutionized trading speed and data processing

Thank You!