CSC 320 - Lecture 20

#quantum-computing #classical-computing

Classical Computers

At low level, we manipulate bits - write 0s and 1s according to very simple instructions.

- Limitations:
    - Some problems cannot be computed using classical computers
        - Undecidability of the Halting Problem.
    - Other problems cannot be computed fast enough; some we don't know how fast we can solve them (i.e., $P = NP$).

Quantum Computing

Quantum Computing leverages nature to represent and manipulate information.

Getting up to Speed with Nature's Imagination: Quantum Computing leverages nature to represent and manipulate information.

- **Applications**. Simulation of nature far beyond what is possible with classical computing.

In contrast to classical computers, quantum computers make use of certain quantum mechanical effects to manipulate data: Superposition, Entanglement, and Interference. Quantum computer requires hardware that enables quantum mechanical effects. How to program a quantum computer is quite different from programming a classical computer.

Two Big Quantum Computing Promises

- Solving classically intractable problems faster.
- Simulating nature or physical systems effectively.

Taking the Quantum Leap

- www.ibm.com/thought-leadership/institute-business-value

Quantum Algorithms Are Different

- Inherently different from common, recipe-like step by step instructions.
- No peaking in between individual algorithmic steps.
- Final result is obtained at the end of the computation through **measurement**.
- No cloning theorem.
- Quantum Computation: Generalization of Probabilistic Computation.

Quantum Algorithms Use...

... properties of qubits, such as:

- **Superposition**. $\alpha|0\rangle + \beta|1\rangle$, $\alpha, \beta \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 = 1$.
  - Measuring qubit/quantum state results in either 0 or 1.
    - 0 is measured with probability $|\alpha|^2$
    - 1 is measured with probability $|\beta|^2$

How Do Quantum Algorithms Work?

- Initialize quantum systems
- Prepare quantum states
- Run the algorithm
- Measure

A quantum algorithm controls the probabilities of a quantum system with which each answer is likely to be measured.

What Can Be Done And What Can't Be Done?

- **No-Cloning Theorem**. Quantum states cannot be copied.
- **Quantum Teleportation**: Transmission of quantum information from one location to another between the sending and receiving location, with help of classical communication and (pre-)shared entangled qubits.

https://www.space.com/37506-quantum-teleportation-record-shattered.html

Deutsch-Jozsa Algorithm: What's In The Box?

Problem. Given an **unknown oracle function** f that is possible to be probed (that is for a given input, one is returned the function's value), and of which we know that it can have one of only two forms.

Task. Decide using a few probes as possible: of which type is f?

- Classical Algorithm: Requires $O(2^n)$ probes.
- Quantum Algorithm: Only one probe!

Time to solve problem

Type of scaling					
Classical algorithm with exponential runtime	10secs	2mins	330years	3300years	Age of the universe
Quantum Algorithm with polynomial runtime	1min	2mins	10mins	11mins	~24mins

Grover Search: Finding The Needle In The Haystack

Unstructured Search:

- Classically: $O(N)$
- Quantumly: $O(\sqrt{N})$

Entanglement. A pair of qubits is **entangled** when the quantum state of each cannot be described independently of the quantum state of the other.

Quantum Computers

They work with *qubits* (not bits). Qubits can be in *superposition* (bits can't be). Qubits can be *entangled* (bits can't be).

To know the result of a quantum algorithm / program one needs to measure to obtain classical bit information. Quantum Circuit.

Note. Universal Quantum Computer is more powerful than Turing Machine.

https://www.ibm.com/quantum-computing

How Good Are Quantum Computers Today?

- Today, quantum computing is in the NISQ era...
  - NISQ: noisy intermediate-scale quantum
- NISQ devices are error prone...
  - Decoherence
  - Interference
  - Other Quantum Noise

- **Ultimate Goal.** Universal faul tolerant quantum computers.
- Today (and future): development of hybrid quantum-classical software and (new!) integrated quantum-classical hardware.

Qubit Technologies Underlying The Hardware Of Quantum Computers

- Superconducting Qubits
- Trapped Ion Qubits
- Quantum Photonic Systems
- Silicon Quantum Computers

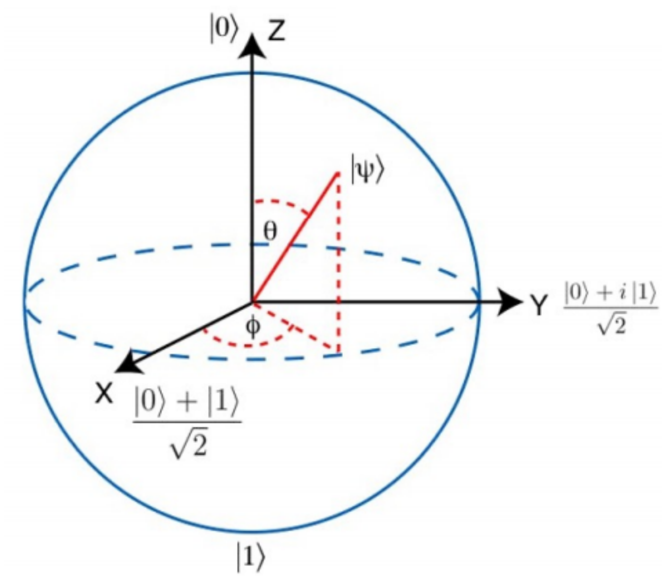
Qubit: Basic Unit of Quantum Information

- Qubit: two basic states, usually written as $|0\rangle$ (zero-ket) and $|1\rangle$ (one-ket).
- A qubit can be...
  - **Quantum State**: Mathematical representation of a qubit.
  - in state $|0\rangle$ or $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$
  - in state $|1\rangle$ or $|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$
  - in a linear combination of both states... where $\alpha, \beta \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 = 1$.

$$\alpha|0\rangle + \beta|1\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Bloch Sphere

- Unit Sphere.
- Antipodal Points: Pair of mutually orthogonal state vectors.
- Point on Surface: Pure state; used for pure state quantum computation.



Quantum Circuit

Computational routine consisting of coherent quantum operations on qubits: ordered sequence of quantum gates, measurements (and resets).

You can try it out on IBM Quantum Composer: https://quantum-computing.ibm.com/composer/files/new

Quantum not (X) gate: $X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

Hadamard (H) gate: $H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

qiskit.org/documentation/qc_intro.html

Bell States: Special Entangled States

There are four famous entangled states called the Bell States.

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \qquad \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$\frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \qquad \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

Hybrid Quantum Computing Challenges & Opportunities

- **Address Complex Problems**
  - Optimization problems
  - Machine learning
  - Risk optimization in financial services
  - Cybersecurity, encryption, decryption
  - Transportation and logistics
  - Real-time optimization
- **Simulating Nature**
  - Molecules, atoms, enzymes
  - Chemistry, biology, material science applications
  - Pharmaceuticals, healthcare, precision health
  - Ammonia for fertilizers in world's food supply, nitrogen fixation
  - Photosynthesis - plants are quantum computers
- **Simulating Molecules**
  - Classically: only approximation possible
  - Good and large enough quantum computer: exact simulation
    - Within a few years we hope to be able to exactly represent larger molecular energy states in a quantum computer.

Will Quantum Computing Replace Classical Computing?

- You'll still need your laptop.
  - Quantum computers will not replace classical computers.
  - Integrated quantum-classical computing in the cloud will be the norm.
- Quantum Advantage
  - Superposition, entanglement & interference allow us to explore an enormous set of possibilities to find answers.

Next - Resource To Get Started

- Qiskit Textbook: https://qiskit.org/textbook/
- Quantum Country: https://quantum.country
- https://qplaylearn.com

Quantum Software Development Kits

You can start tonight!

Innovative digital tools are needed for developing and testing algorithms, writing software and programming the devices.

A new breed of quantum programmer is needed to study and implement quantum software.

Courses In Quantum Computing At UVic

- Physics: 2nd year (de Sousa)
- Computer Science: 4th year/grad topics course: Quantum Algorithms and Software Engineering (Stege/Muller)
- Chemistry (Paci)

Note. Quantum computing can be entered by people from a variety of backgrounds.

Previous Lecture

Lecture19