Quantum Computing
The **NEXT** Transformative Technology

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GridLab: Third International Workshop on the Future of Computing

Zakopane, Poland
December 20-22, 2023

Agenda

- Media Hype of Quantum Programming
- Funding and Resource Centers
- Brief Intro of Quantum Programming Technology

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Richard Feynman: Call to QC in 1982

- Richard Feynman
  - Discovered Quarks
  - At CalTech
- Postulated that to simulate quantum systems, you would need to build quantum computers
  - 1982, “Simulating Physics with Computers“

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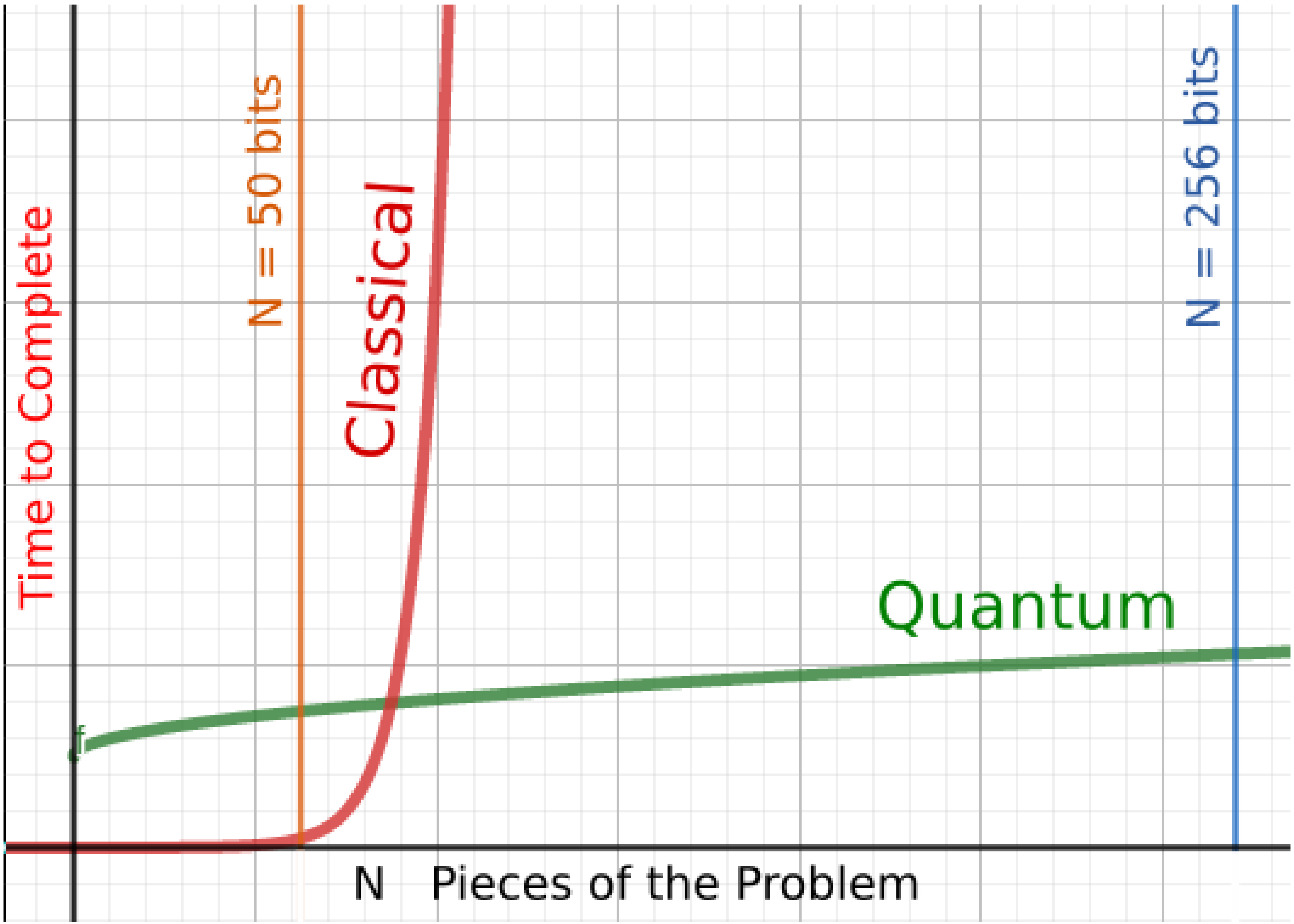
Hype in Quantum Computing

- Scientific American, April, 2021: *"Will Quantum Computing Ever Live Up to Its Hype?"*
- QC hype says it will:
    - Supercharge machine learning
    - Revolutionize the simulation of complex phenomena in chemistry, neuroscience, medicine, economics
    - Newsweek: *"How China Is Using Quantum Physics to Take Over the World"*
- ***But*** quantum computing ***can*** help solve some NP hard problems

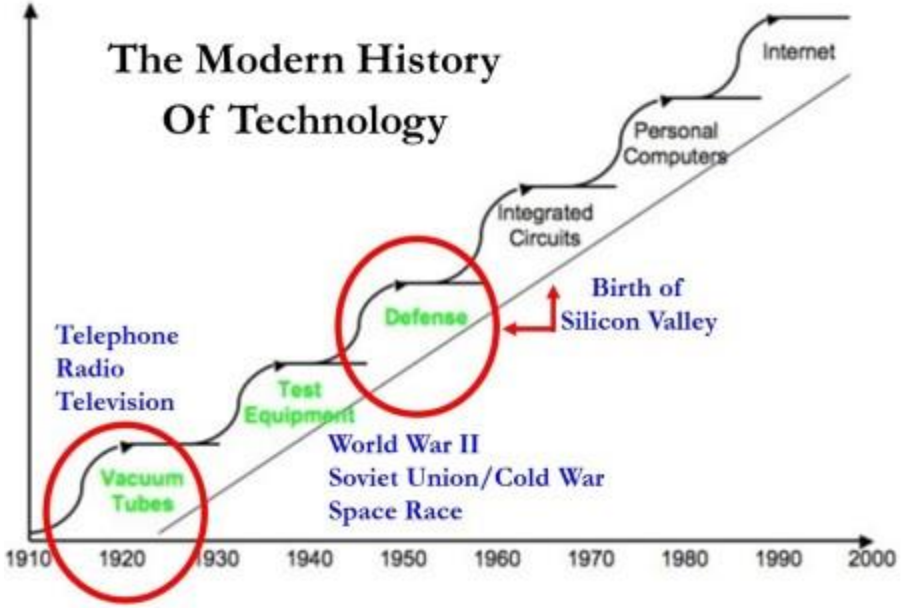


Quantum
vs
Classical

Completion
Time vs
Problem
Size

Quantum Computers at Early Stage

- It’s said that QC is at the stage of Vacuum Tubes
- Quantum hardware has just recently moved into the realm of qubit counts that far outpace quantum simulators.
  - IBM’s Eagle Processor is a 1000 qubit, gate based, superconducting machine
    - Came online in Dec of 2023.
  - QuEra’s Aquila Processor is a 256qubit, dual mode, gate/annealor based, neutral atom processor.
    - Came online in Q3 of 2023



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Best Way to Make Quantum Computers Not Decided

- Type of QCs:
  - Neutral Atom
  - NMR
  - NV Center-in-Diamond
  - Photonics
  - Spin Qubits
  - Superconducting Qubits (IBM)
  - Topological Quantum Computation
  - Trapped Ion

Quantum is National Security Vulnerability

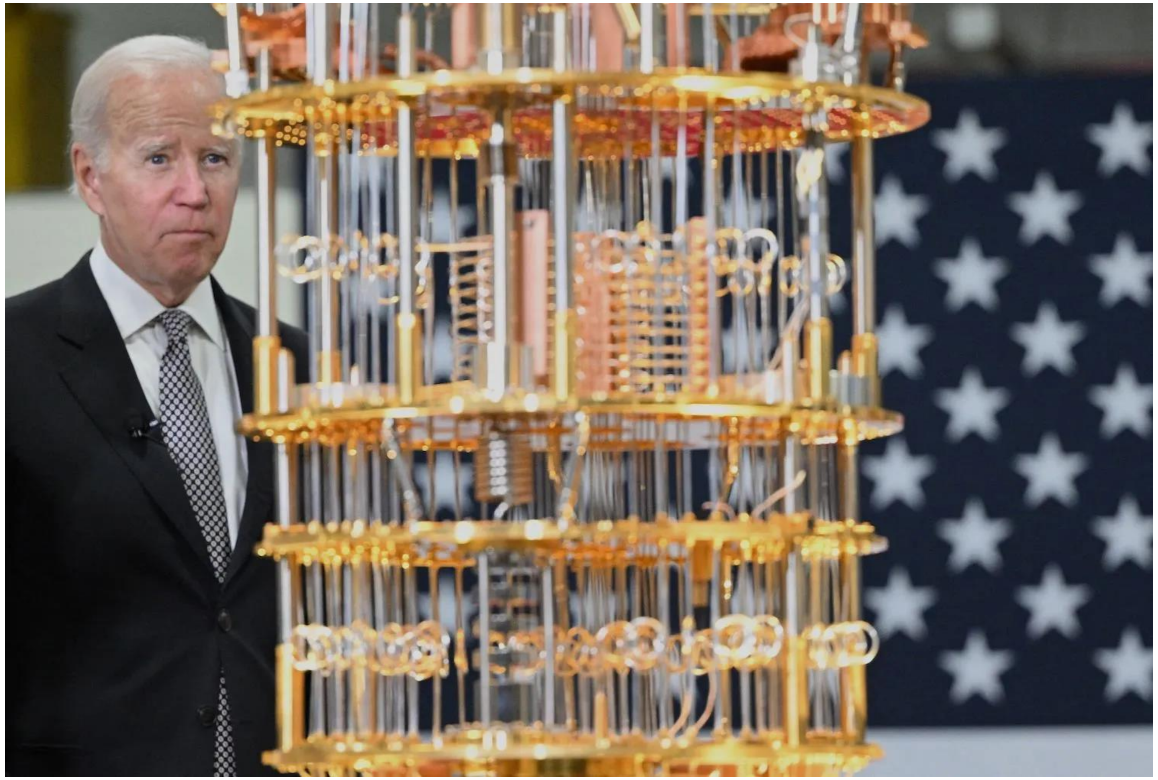
The United States' Quantum Talent Shortage Is a National Security Vulnerability. A critical technology area promises to transform nearly every industry dependent on speed and processing power, from agriculture and financial services to health care and defense: quantum information science and technology, or QIST.

- Center for New American Security, 2023

Quantum is National Security Vulnerability

"The United States' Quantum Talent Shortage Is a National Security Vulnerability"

https://foreignpolicy.com/2023/07/31/us-quantum-technology-china-competition-security/



Chicago Region Designated US Tech Hub for Quantum Technology by Biden-Harris Administration

October 23, 2023

The Bloch Tech Hub (pronounced "block"), a coalition of industry, academic, government, and nonprofit stakeholders led by the Chicago Quantum Exchange, was one of 31 designees from nearly 400 applications across the country.

https://pme.uchicago.edu/news/chicago-region-designated-us-tech-hub-quantum-technologies-biden-harris-administration

"Home to world-class institutions and first-rate research centers, Illinois is transforming technology, biomanufacturing, and innovation at every turn," said Illinois Governor JB Pritzker.

EDA will fund the Bloch Tech hub with up to $75 million. B2Quantum could get some of that funding.

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CHICAGO
QUANTUM EXCHANGE

THE UNIVERSITY OF CHICAGO

Argonne NATIONAL LABORATORY

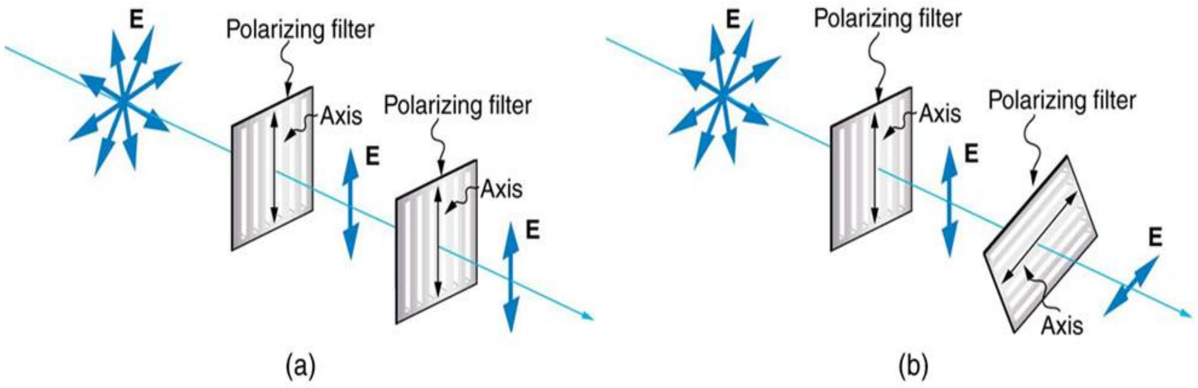
Fermilab

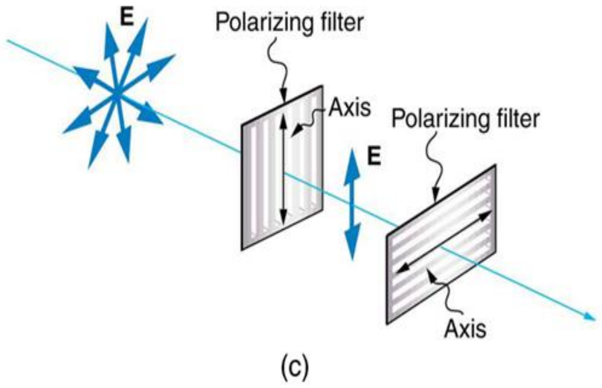
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Northwestern University

Example of Photon Superposition





- When particle is in superposition
  - The configurations of the particle are all positions,
  - So the superpositions make a complex wave in space.

Quantum Computers Based on Qubits

- Qubit mathematical representation more complex than binary
- Zero bit is $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ (top 1 means all zero, bottom 0 means no 1)
- One bit is $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ (top 0 means no zero, bottom 1 means all 1)
- Still more complex
- Qubits are in a quantum state
- Quantum states are best described by wave functions using complex numbers
- $\begin{bmatrix} 1 + 0i \\ 0 + 0i \end{bmatrix} \begin{bmatrix} 0 + 0i \\ 1 + 0i \end{bmatrix}$

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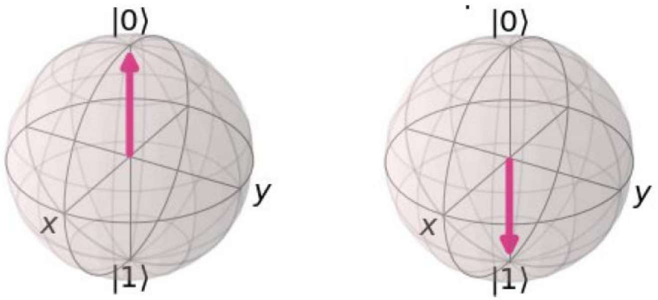
Quantum Computers Based on Qubits

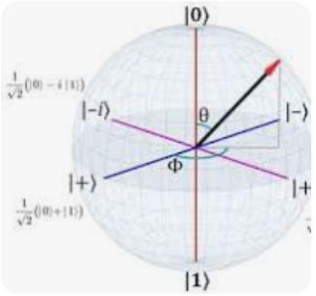
- $\begin{bmatrix} 1 + 0i \\ 0 + 0i \end{bmatrix} \begin{bmatrix} 0 + 0i \\ 1 + 0i \end{bmatrix}$

- These states can each be depicted as a point on a unit sphere.



- Called Bloch Sphere

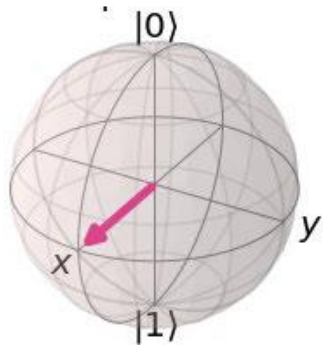
- The complex value *i* maps onto the y axis



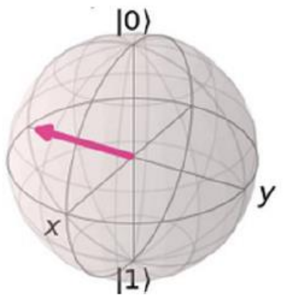
- Everything along the equator is half 0 half 1.
- Between either north or south pole and equator is a combination of 0 and 1

Quantum Computers Based on Qubits

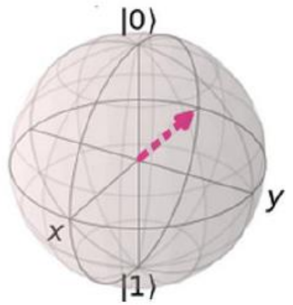
- $\begin{bmatrix} \frac{1}{\sqrt{2}} + 0i \\ \frac{1}{\sqrt{2}} + 0i \end{bmatrix}$



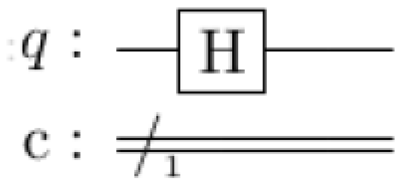
- $\begin{bmatrix} \frac{1}{\sqrt{2}} - i \\ \frac{1}{\sqrt{2}} - i \end{bmatrix}$

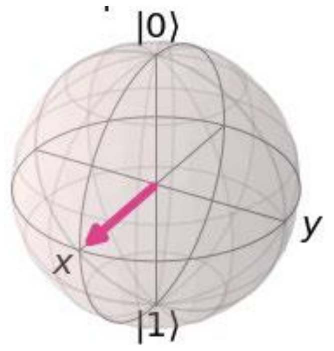


- $\begin{bmatrix} \frac{1}{\sqrt{2}} + 0i \\ \frac{-1}{\sqrt{2}} + 0i \end{bmatrix}$



Gates (Operations)

- Quantum computers don't really have gates
- They have operations, but are called gates
- Putting a qubit into superposition is done with a Hadamard Gate
- 



$$\begin{bmatrix} \frac{1}{\sqrt{2}} + 0i \\ \\ \frac{1}{\sqrt{2}} + 0i \end{bmatrix}$$

- This puts the qubit into 50% 0 and 50% 1
- Note that squaring the matrix representation gives the 50%

Gates (Operations)

- Quantum operations are also mathematically described as matrices
- $\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} + 0i \\ \frac{1}{\sqrt{2}} + 0i \end{bmatrix}$
- Much more complicated than Boolean logic!

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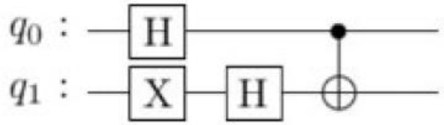
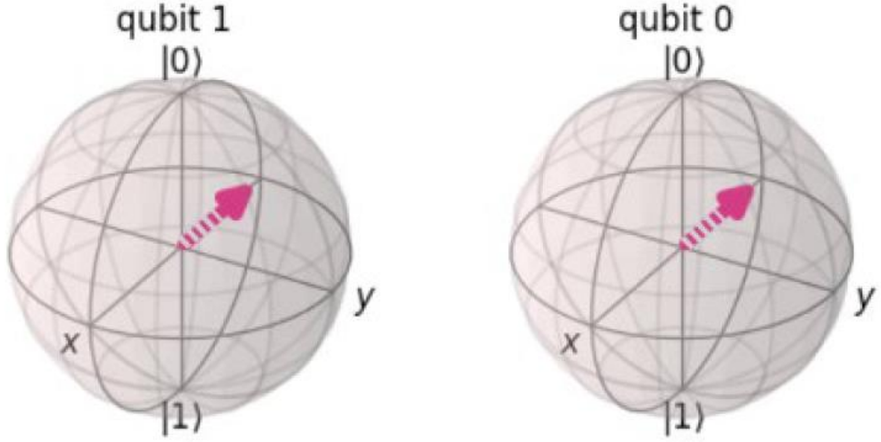
More complex circuits and math representations

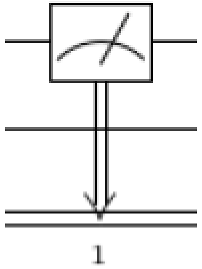


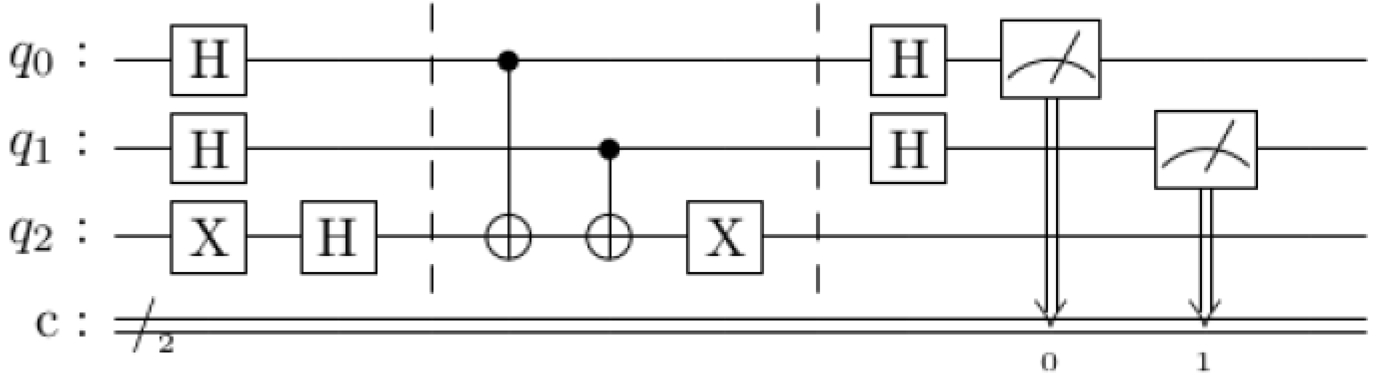


$$\frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 1 \\ -1 \\ -1 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 \\ -1 \\ -1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix} \otimes \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix} = |-\rangle \otimes |-\rangle$$

Measuring

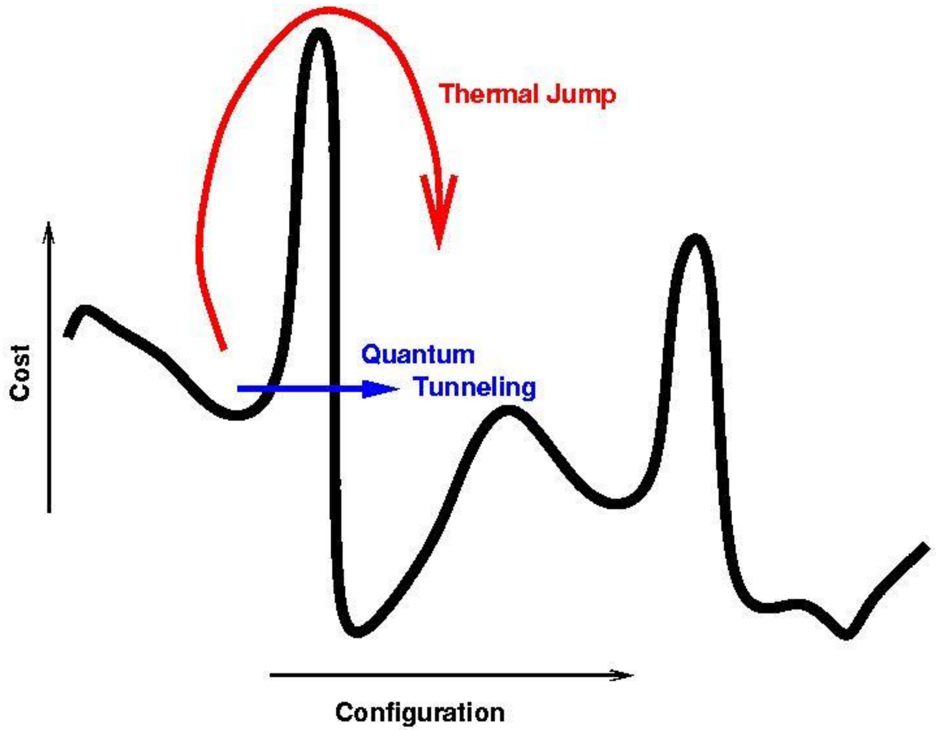
- Measurement always gives a 1 or a 0
- Which one is measured depends statistically on the portion that is 1 or 0 in the quantum state
- Measurement destroys the state of the qubit





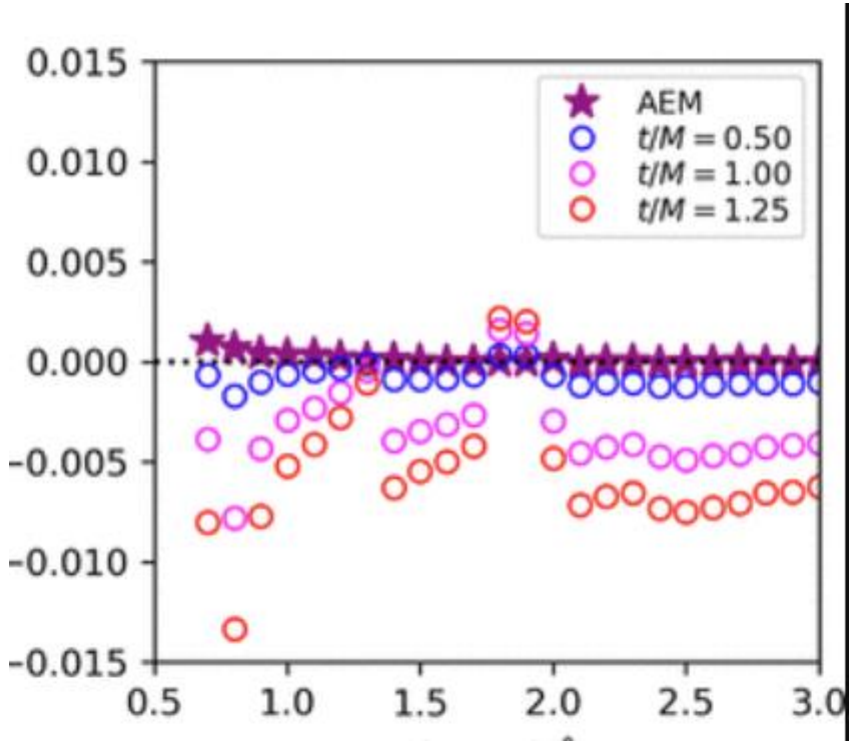
Quantum Annealling

- Quantum Annealing
  - Efficiently traverses energy landscapes
  - By leveraging quantum tunneling
  - To find the global minimum.
- Each qubit has a bias
- When formulating a problem
  - Users choose values for the biases.
  - The biases define an energy landscape
  - The Quantum Annealing quantum computer finds the minimum energy
- So, setting the biases to reflect minima finds the answer



Quantum Phase Kickback

- Another type of problem solver
- An operator is used that
  - only adds a phase to the qubit
  - doesn't change its state
- A value is kicked back to a control qubit
- An oracle is designed that applies
  a negative phase to the state being sought
- When that is done, the answer is found



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Introducing Quantum Programming

- Quantum Mechanics attempts to describe physics of the universe at unimaginably small scales that exist in the “subatomic” realm.
- The behavior of the universe at these tiny scales, whether predicted by Quantum Mechanics theory or observed in sophisticated laboratory experiments, are notorious for defying common sense.
- Simply put, these behaviors do not match with the physics that we observe in our macro universe or our everyday life.
- Quantum Mechanics has given rise to Quantum Computing and Quantum Information processing.
- The main Quantum Mechanical concepts that drive Quantum Computing are Superposition and Entanglement.
- By exploiting these concepts, Quantum Computers running Quantum Computing algorithms can demonstrate an advantage over classical computers.

Summary

- Quantum Computing is in an Early Stage
- Quantum Computing Can Help Solve Some NP Hard problems
- Quantum Computing is a Rich Area for Research