STORAGE DEVELOPER CONFERENCE
SDC 21
BY Developers FOR Developers

Virtual Conference
September 28-29, 2021

Quantum Technology and Storage
Where Do They Meet?

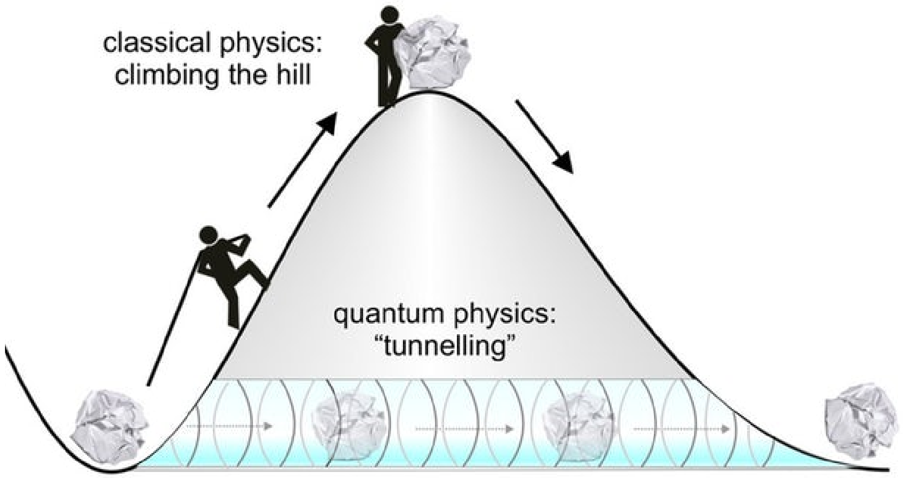
Doug Finke
Managing Editor
Quantum Computing Report

Quantum Computing is Based Upon Quantum Mechanics Principles Discovered Early in the 20th Century

- Early vacuum tube based classical computers were all based upon physics principles discovered in the 18th or 19th Century
  - Ohm's Law
  - Electrons
  - Gauss' Law
  - Maxwell's Equations
  - Boolean Algebra
- Great strides were made in the 1920's to develop quantum mechanics theories
- Semiconductor technology has leveraged only some of the principles of quantum mechanics
- But quantum computing leverages a lot more

Solvay Conference 1927
Attendees included Einstein, Bohr, Heisenberg, Schrödinger, Planck, Curie, Dirac, Born and others

Tunneling



- Used in Flash Memory
  - Tunnel through a floating gate
- Another application is in Quantum Annealing
  - Different type of quantum computer from the gate-based machines most commonly seen
  - Tunnel through an energy barrier to find the ground state and an optimum solution

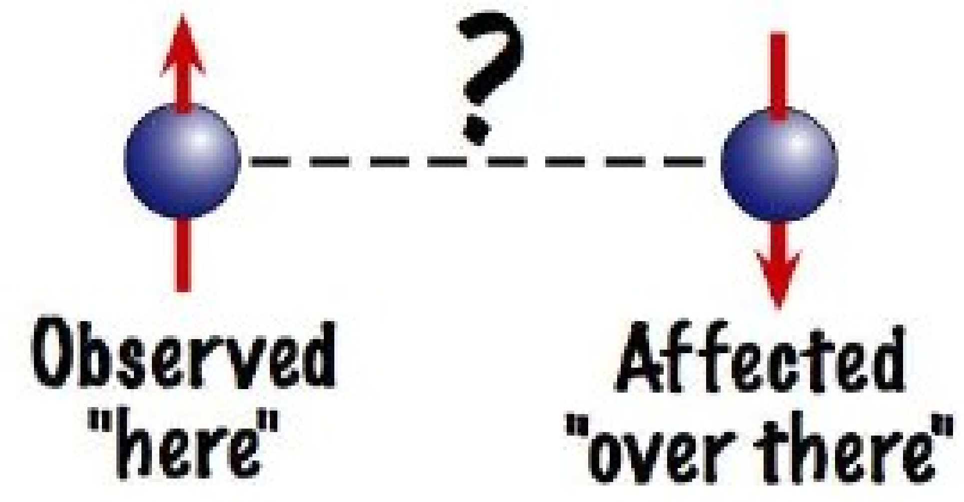
Superposition

0

1

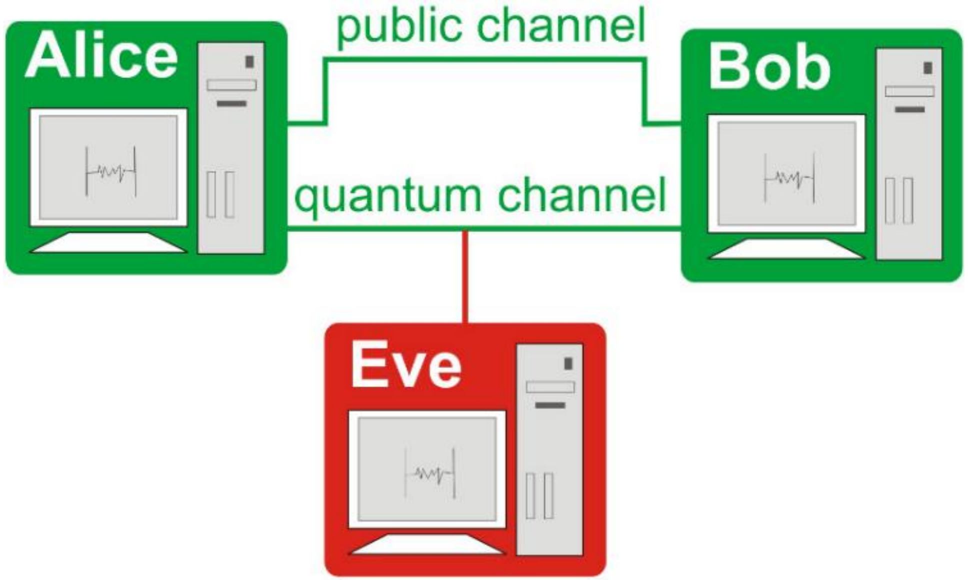
0 1

Entanglement



"Spooky action at a distance" – Albert Einstein

Note: Entanglement does not enable communication faster than the speed of light. Random bits are not equal to useful data.



Entanglement used for unbreakable quantum key distribution

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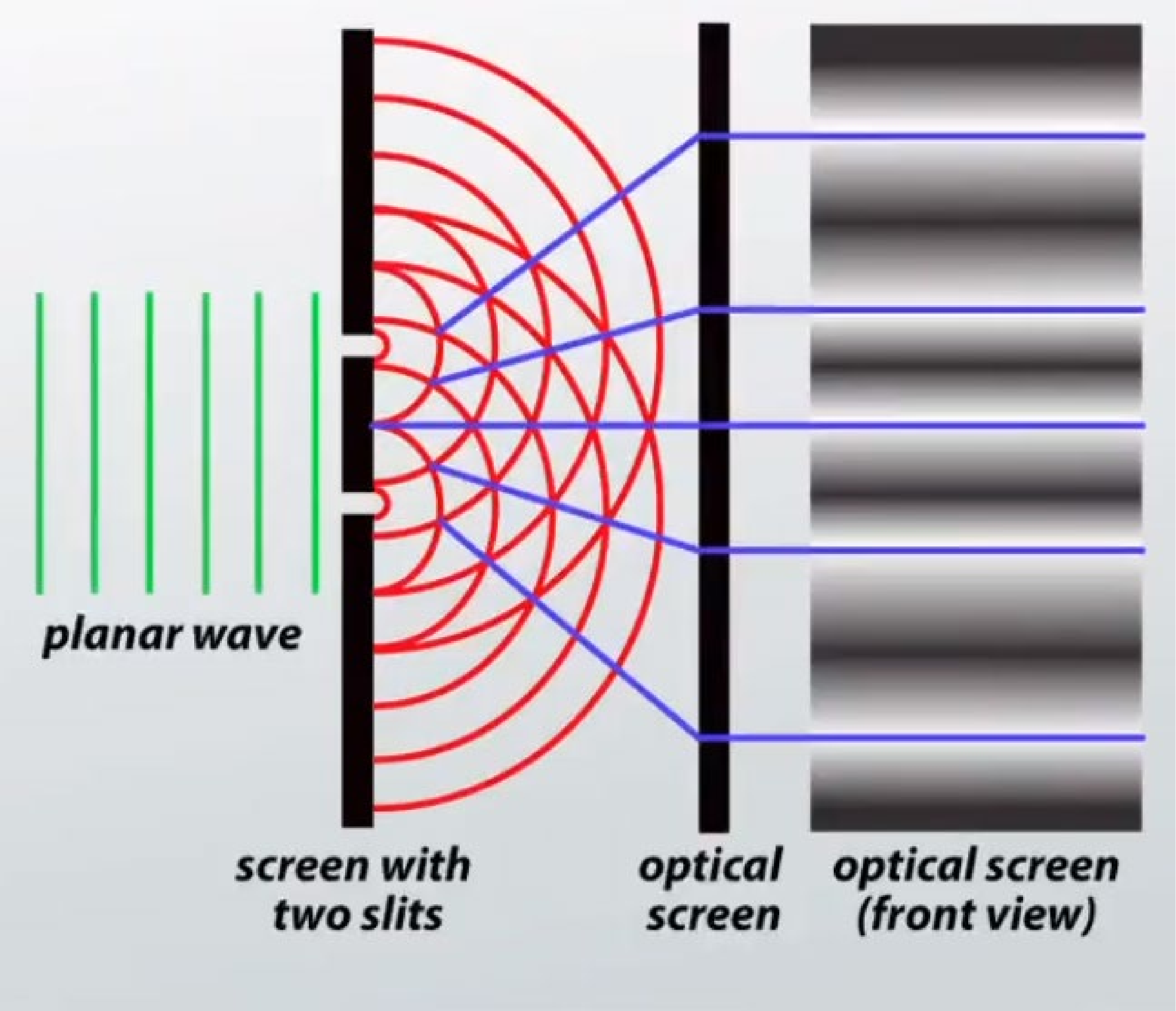
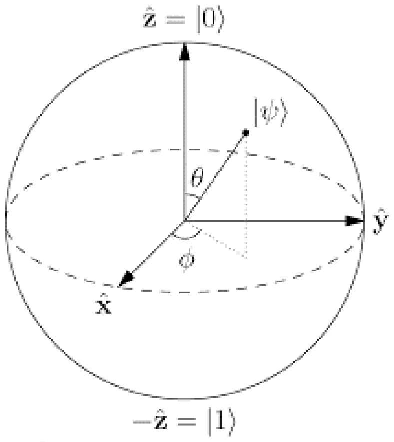
Interference



Qubits – Quantum Bits

- Qubits can be expressed mathematically as $\alpha|0> + \beta|1>$, where:
  - α and β can be negative or even complex numbers
  - $|\alpha|^2 + |\beta|^2 = 1$
- Qubits are very sensitive and will collapse (or decohere) to a “0” or “1” state due to small environment disturbances
  - Coherence times range from 20 μsec superconducting tech to seconds ion trap tech



Bloch sphere representation of a qubit
- The north pole represents “0”
- The south pole represents “1”
- The equator represents an equal probability of “0 and “1”
- The longitude would represent the phase of the qubit.

- Qubits will collapse to a “0” or “1” state when measured on a probabilistic basic
  - A “0” will be measured $|\alpha|^2$ percentage of the time, a “1” will be measured $|\beta|^2$ of the time
  - Measurement is completely non-deterministic
- Qubits cannot be copied (No Cloning Theorem)

Qubits Can Hold an Exponential Number of States

- By taking advantage of superposition and entanglement, qubits can hold an exponential number of states compared to the same number of bits
- n qubits comparable to 2^n bits
- 100 qubits can hold more states than the all the hard drives in the world
- 300 qubits can hold more states than the number of atoms in the universe

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<tr><td>00</td><td>0</td><td>0</td><td>Classical</td><td>1</td><td>|00></td></tr>
<tr><td>01</td><td>0</td><td>1</td><td>Classical</td><td>1</td><td>|01></td></tr>
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<tr><td>00+01</td><td>0</td><td>0+1</td><td>Superposition</td><td>√½</td><td>√½ (|00> + |01>)</td></tr>
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Examples of How Different States Can be Encoded Into Two Qubits

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01+10+11	?	?	Entangled	√⅓	√⅓ (|01> + |10> + |11>)

Examples of How Different States Can be Encoded Into Two Qubits

One Little Problem

- Hoelvo's Bound
  - The amount of data that can be retrieved from n qubits cannot be any larger than the amount of data that could be retrieved from n bits.
- My name: *Hotel California Theorem*
  - *"You can check-out any time you want, but you can never leave!"* (Apologies to the Eagles for using a line from one of their songs!)
- Reasons: No cloning theorem, collapse upon measurement and complexity with entanglement

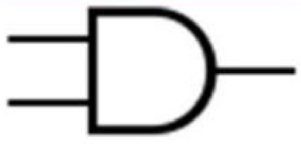
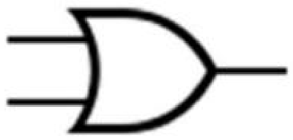
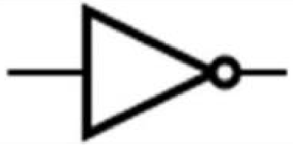
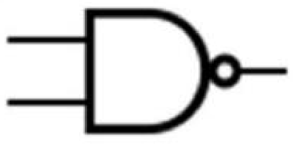
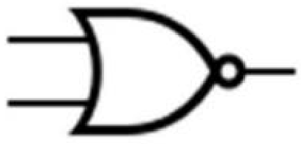
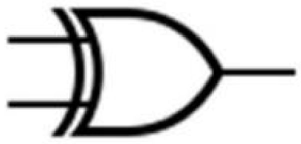
This car can't get out from the middle of this traffic jam. An entangled qubit in the middle of a complicated state has a comparable problem.

Traffic Jam in Beijing

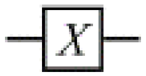
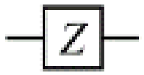
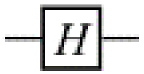
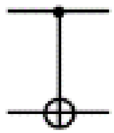
Quantum Gates

Classical Gates

Digital Logic Gate Symbols

Gate	Symbol	Notation	Truth Table
AND		$A \cdot B$	INPUT A B / OUTPUT A AND B 0 0 0 0 1 0 1 0 0 1 1 1
OR		$A + B$	INPUT A B / OUTPUT A OR B 0 0 0 0 1 1 1 0 1 1 1 1
NOT		$\overline{A}$	INPUT A / OUTPUT NOT A 0 1 1 0
NAND		$\overline{A \cdot B}$	INPUT A B / OUTPUT A NAND B 0 0 1 0 1 1 1 0 1 1 1 0
NOR		$\overline{A + B}$	INPUT A B / OUTPUT A NOR B 0 0 1 0 1 0 1 0 0 1 1 0
XOR		$A \oplus B$	INPUT A B / OUTPUT A XOR B 0 0 0 0 1 1 1 0 1 1 1 0

Quantum Gates

Gate	Notation	Matrix
NOT (Pauli-X)		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
CNOT (Controlled NOT)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

Quantum Gates are Very Slow, Very Error Prone and Quickly Lose the Data

- Typical Superconducting Quantum Gate: 20 – 400 nsec.
- Typical Ion Trap Quantum Gate: 200,000 nsec.
- State of the Art Semiconductor Gate: ~0.1 nsec.

- Typical Superconducting Coherence Times: 20 – 150 microseconds
- Typical Ion Trap Coherence Times: A few seconds*
- Typical DRAM Refresh Period: 64 milliseconds

*T2 Phase Coherence Time

- Typical Quantum Gate Fidelity: 99.5%
- Typical Classical Gate Fidelity: 99.9999999999999999999%

Why Does Quantum Have any Potential?

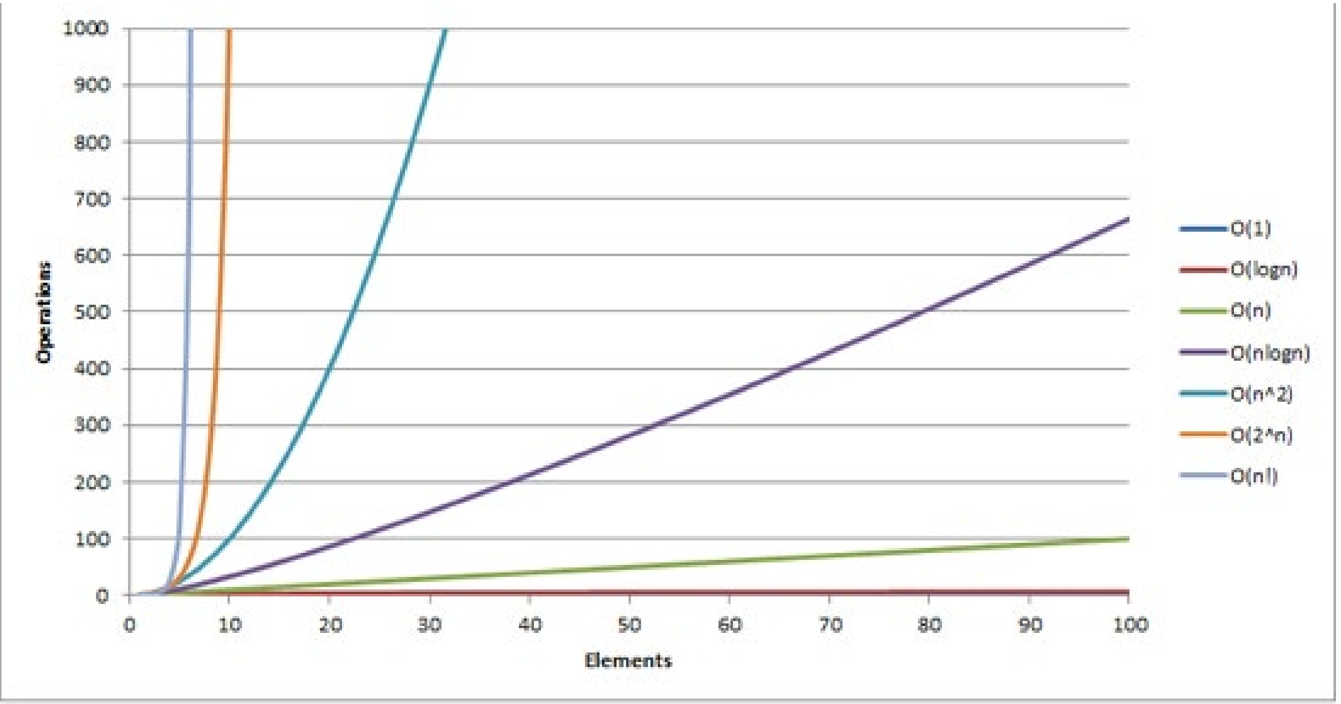
- A weird type of parallelism
  - Quantum computing does <u>not</u> work by trying all possibilities at once to select the one that works.
- Quantum computers are only good for certain types of problems. It won't replace classical computers.
- Quantum computing is good for problems with low amount of data element, but highly complex relationships between the data elements.
  - Travelling salesman and logistics problems
  - Chemical simulations
  - Binary optimizations
- Quantum computing can be used in AI and ML problems with high amounts of data using the equivalent of <u>Computational Storage</u> techniques.

There are N! number of routes a salesman could travel through to reach all of these cities. Even if there are only 100 cities it would take the largest supercomputer millions of years to check each of the possible routes.

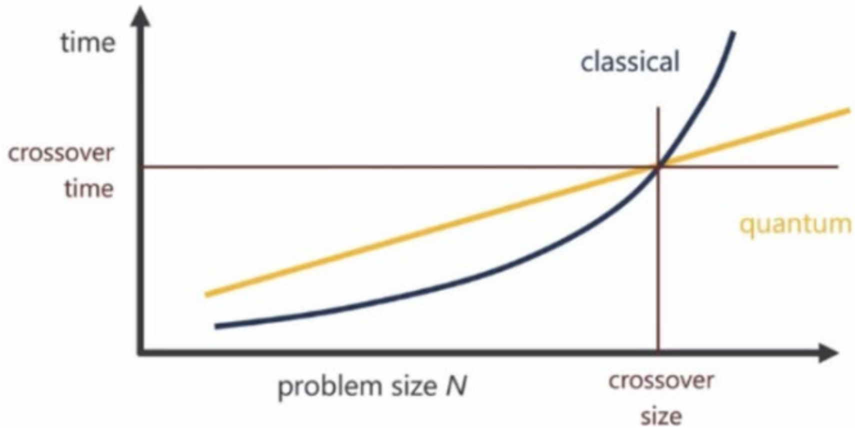
Why Does Quantum Have any Potential?

The secret of quantum computing is that it provides additional tools for an algorithm developer to design a quantum algorithm that scales slower than the corresponding classical algorithm.

Algorithmic Complexity Chart



Algorithm	Classical Time	Quantum Time	Speedup
Simulation (quantum chemistry)	$O(2^n)$ (for n atoms)	$O(n^c)$	Exponential in Space Polynomial in Time
Factoring	$O(2^n)$ (for n digits)	$O(n^3)$	Exponential
Linear Systems (Ax+b)	$O(2^n)$ (for n digits)	O(~n)	Exponential
Optimization	$O(2^n)$	?	?
(unsorted, unstructured list)	O(n)	$O(\sqrt{n})$	Polynomial
Binary Search (sorted list)	*O(log(n))*	*O(log(n))*	none
Bubble Sort	*$O(n^2)$*	*$O(n^2)$*	none
Heap Sort	*O(n log(n))*	*O(n log(n))*	none



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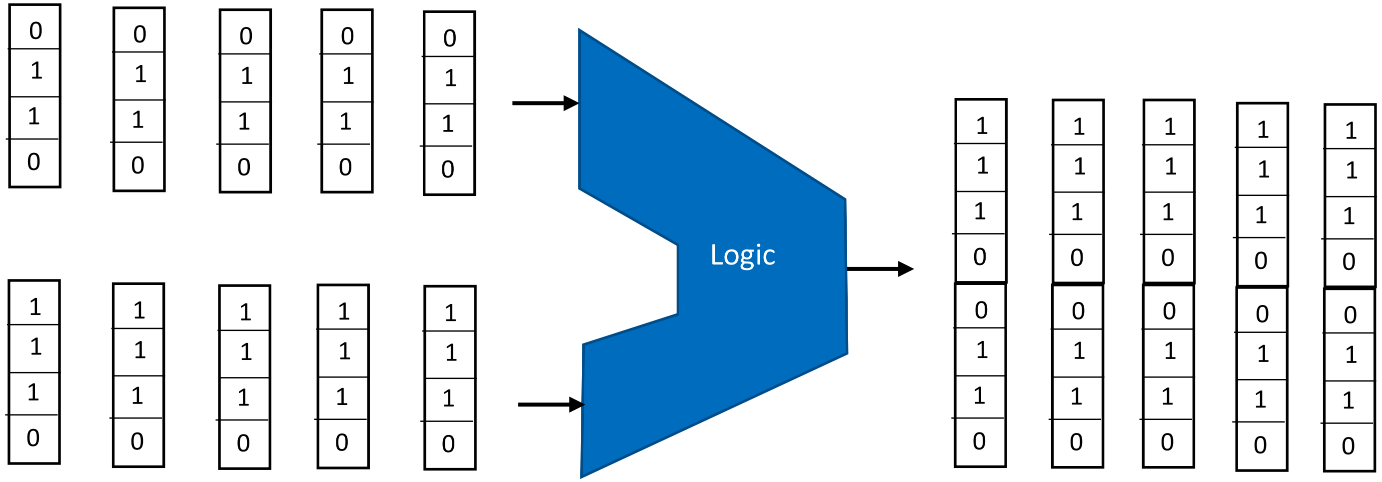
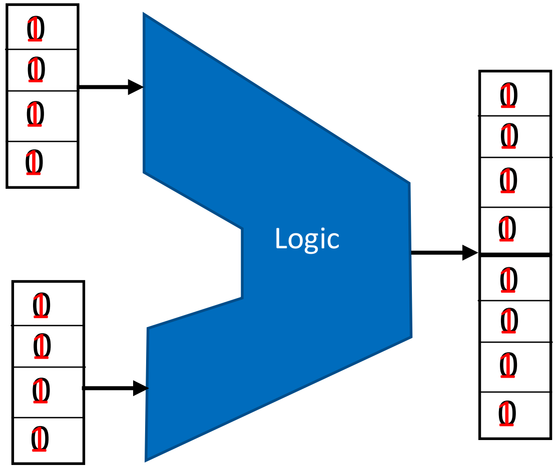
Parallelism in a Gate Level Quantum Computer

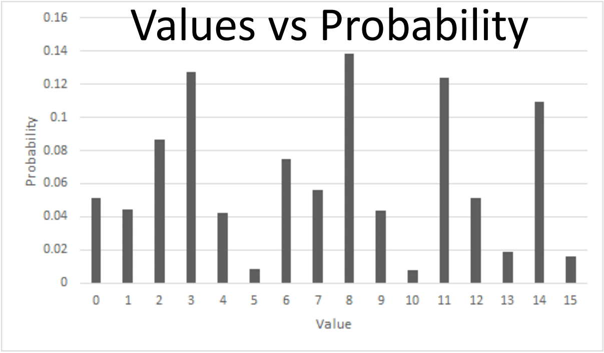
Classical Logic Operation



Must iterate through all possibilities to see all results. Requires 2^N iterations

Quantum Logic Operation

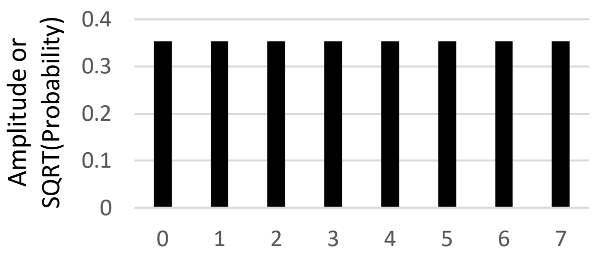




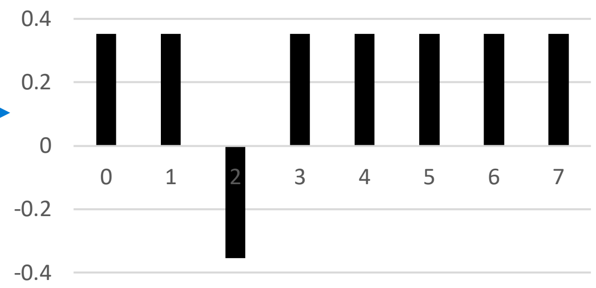
Only one iteration for all possibilities, but results mixed together. Measurement will pick one randomly based upon probabilities

Example: Grover's Algorithm for Quantum Search

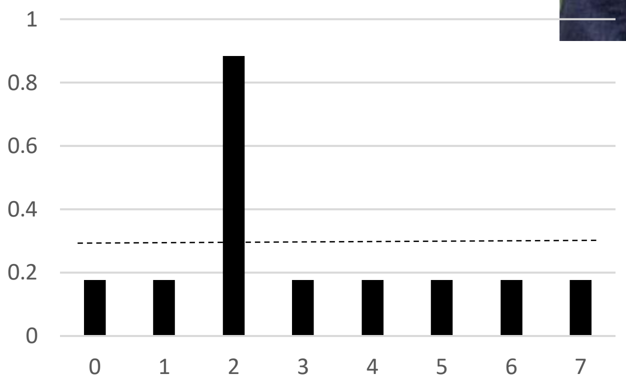
Start in Superposition State



Quantum Compare & Negate



Invert Around the Mean



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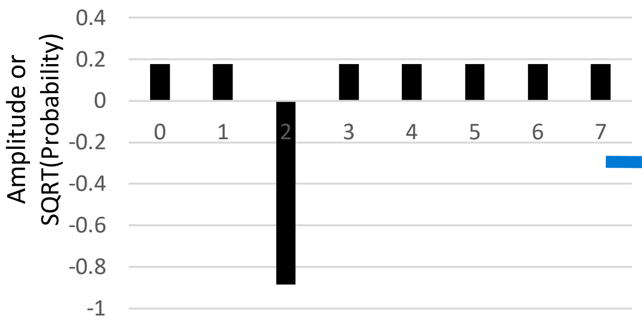

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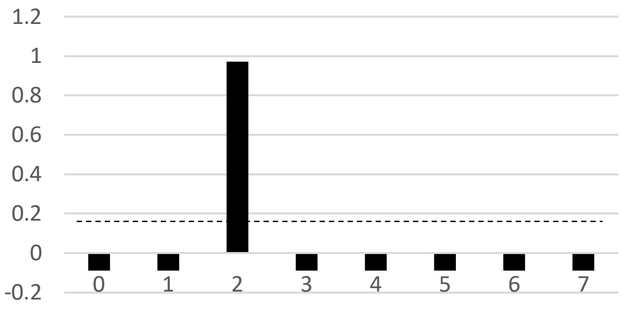

Comparison of Search Time for Length N

Classical: ~N

Grover's Quantum Algorithm: $\sim\sqrt{N}$

Uses constructive interference to increase the probability of the correct answer and destructive interference to decrease the probability of the incorrect answers

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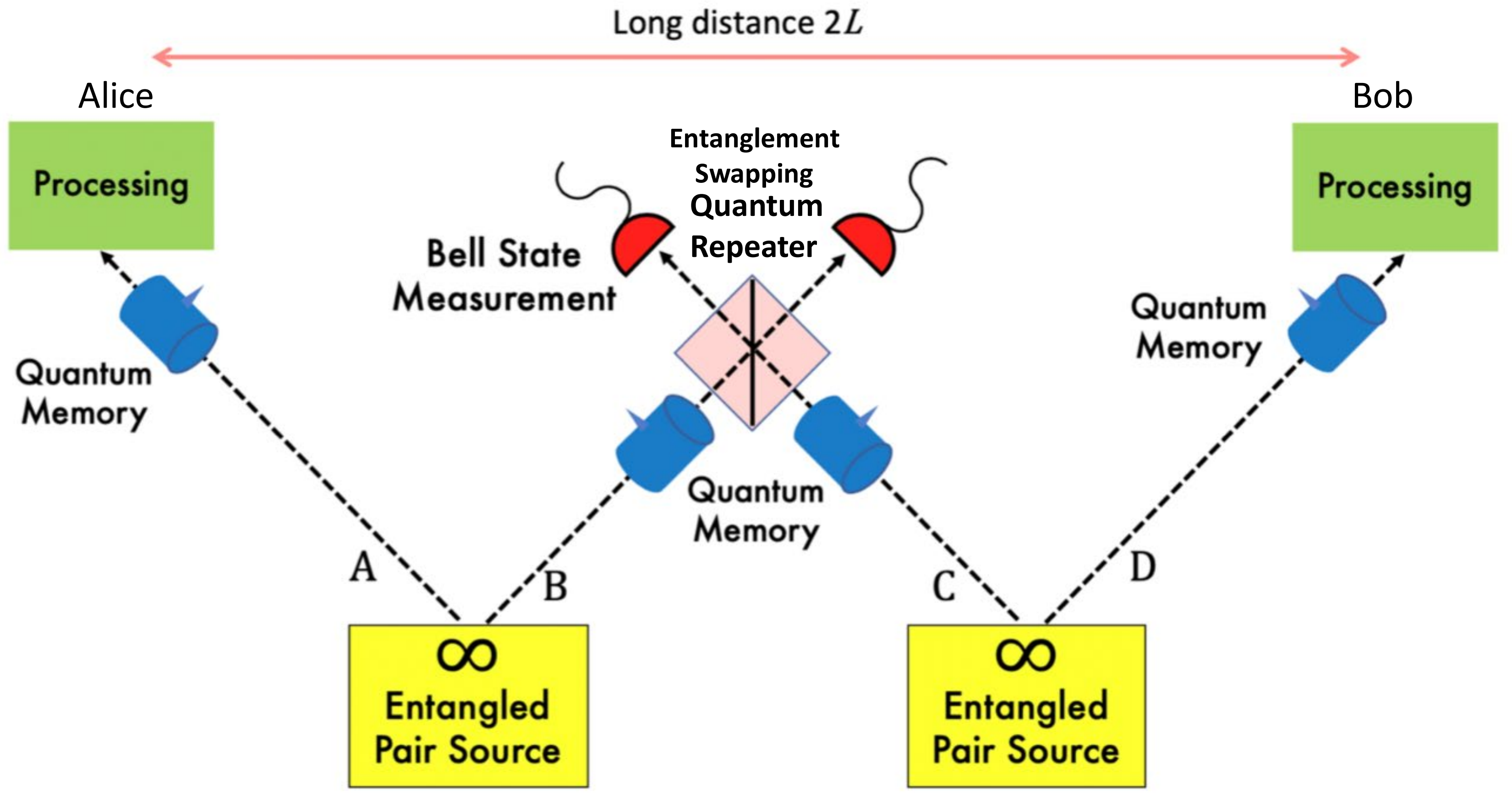
Quantum Memories for the Quantum Internet

- Much research to create a quantum internet to send entangled photons over fiber optic cables
- Use cases:
  - Send unhackable keys for Quantum Key Distribution (QKD)
    - No Cloning Theorem prevents someone in the middle from intercepting and copying a message
    - Removes the threat that powerful quantum computers could one day break RSA based key distribution used in today's internet through the use of Shor's algorithm to factor a large number
  - Build quantum computing clusters by enabling multiple quantum computers to communicate entangled qubits
- Challenge - How to send a quantum signal over long distances
  - No Cloning Theorem prevents use of classical photonic repeaters
- Solution – Either use satellites (expensive) or special quantum repeaters that utilize quantum memories

Quantum Memory Used In a Quantum Communication Channel

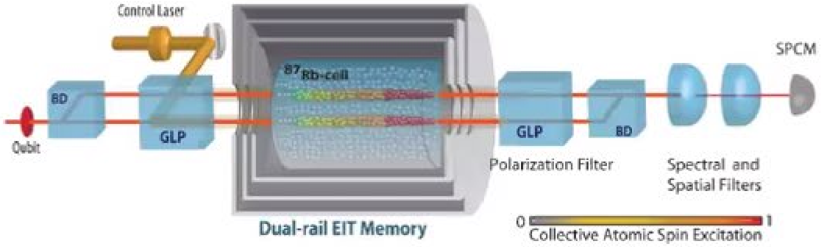


- Entangled photon pairs A-B and C-D are generated
- The Quantum Repeater uses Entanglement Swapping so that photon A ends up entangled with photon D
- Quantum Memories are used to synchronize the signals so that the photons arrive at the same time

One of Industry's First Quantum Memory Starting to Ship

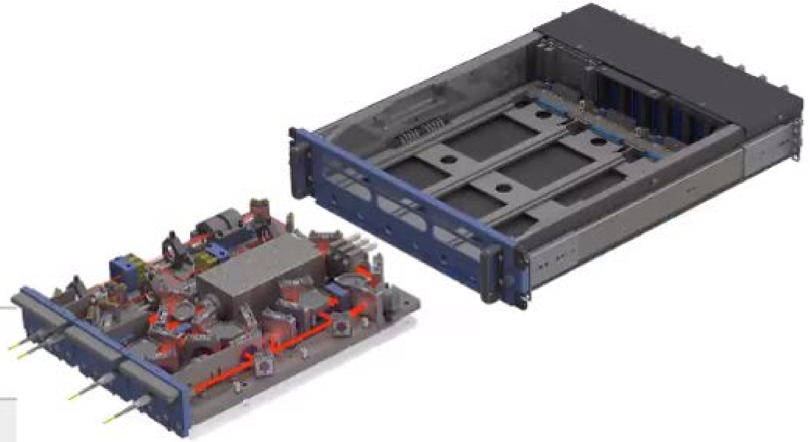
Qunnect's On-Demand EIT Memory

(EIT = Electromagnetically Induced Transparency)



Kupchak, et al. Sci.Rep.(2015) | Namazi, et al. Phys.Rev.Appl.(2017)

Filed in US, CA, EU, AU, SK, JP; PCT WO2019/191442, Priority date 9/11/2018



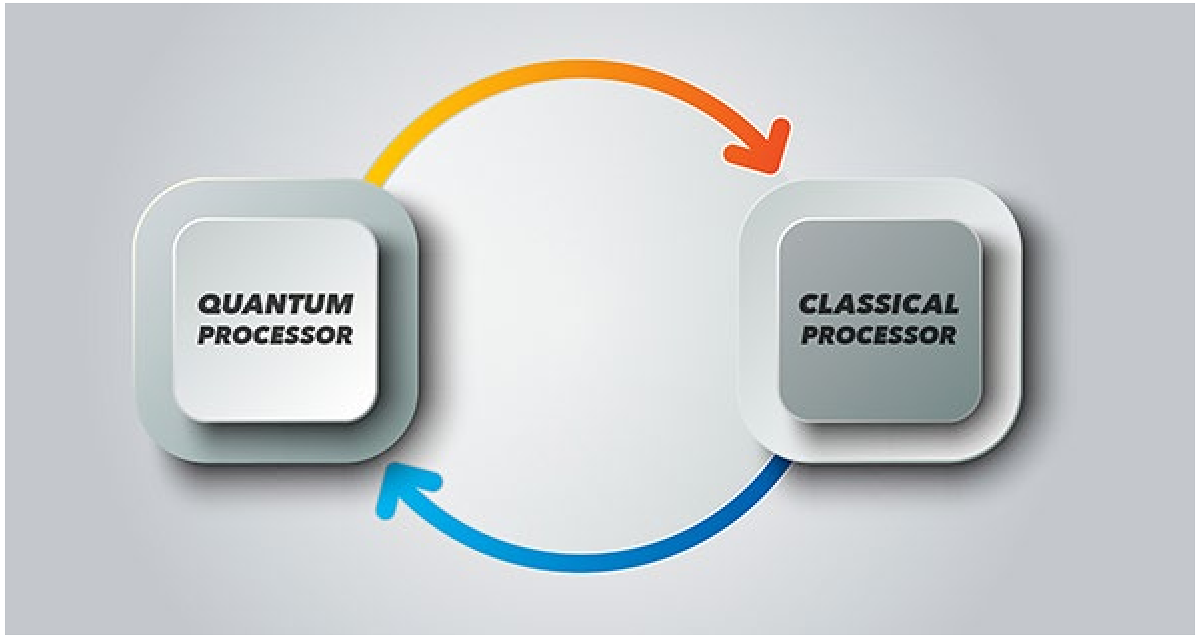
	Mark Alpha	Mark Beta	Mark1 (TRL3)
Fidelity (SNR)	87% (2.9)	>95% (>15)	>98% (>25)
Storage eff	~5%	~5%	>40%
Transmission	~5%	>30%	>40%
Coherence time	40us	>100us	>500us
Stability	>10hrs	>week	>month
Supp. Software	None	Auto temp adj	Auto optimizer

Shipping 1st unit Sept 2021 !!

Source requirements <10MHz linewidth
Wavelength = 795nm

Quantum Processors and Classical Processors are Closely Integrated Together

- Quantum Processing Units (QPU) require heavy support from classical computers
  - Implementing qubit control mechanisms
  - Maintaining calibration data
  - Maintaining a job queue
  - Compiling programs
  - Storing results
  - Executing on hybrid classical/quantum algorithms
- These functions will drive some demand for standard HDD/SSD attached to the classical processor
- Most near and medium term usage will be through the cloud
  - So unit numbers will be relatively low



Hybrid Classical/Quantum Computing Conceptual Diagram. Credit: DARPA

Quantum Computing Bottom Line for the Storage Industry

- Probably more impact as a user of quantum computing technology rather than as a brand new market for you.
  - Unit volumes relatively low, at least for the next 5 years and maybe more
  - Do not see any requirements for any new architectures or special features
- Areas where the storage industry could utilize quantum computing technology
  - New materials discovery for HDD or Flash cells
  - Logistics optimization for manufacturing and distribution
  - AI for use in customer forecasting or detecting customer patterns

Thank You!

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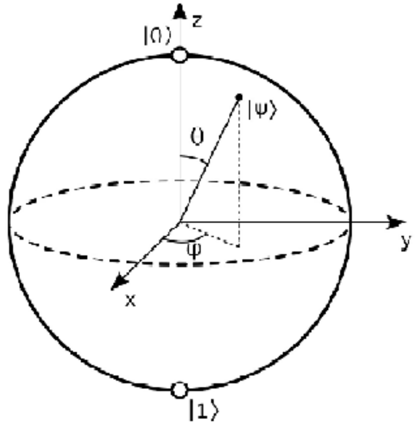
Quantum Computing Report
Where Qubits Entangle with Commerce



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