U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND

Quantum Computing – An Introduction to What it is, Why We Want it, and How We're Trying to Get it

Dr. Sara Gamble

Program Manager – Quantum Information Science

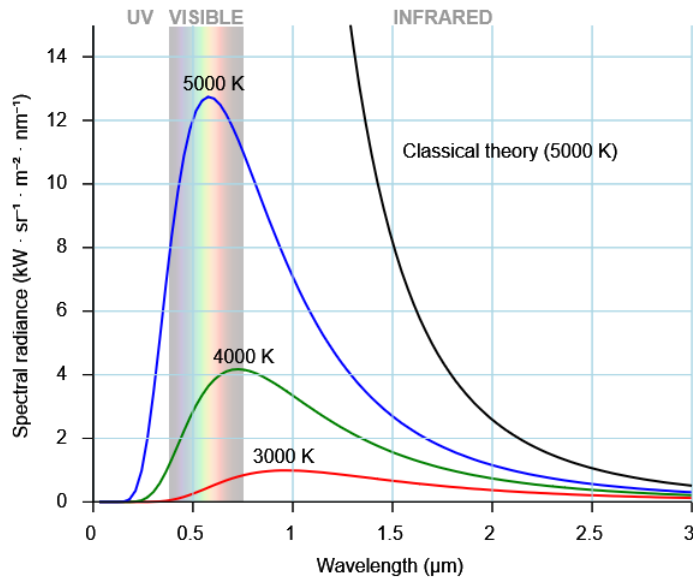U.S. Army Research Laboratory – U.S. Army Research Office

How Did We Get Here?

• What is quantum mechanics?

• What does it have to do with computing?

How Did We Get Here?

Physics Became Very Puzzling in the Early 1900s
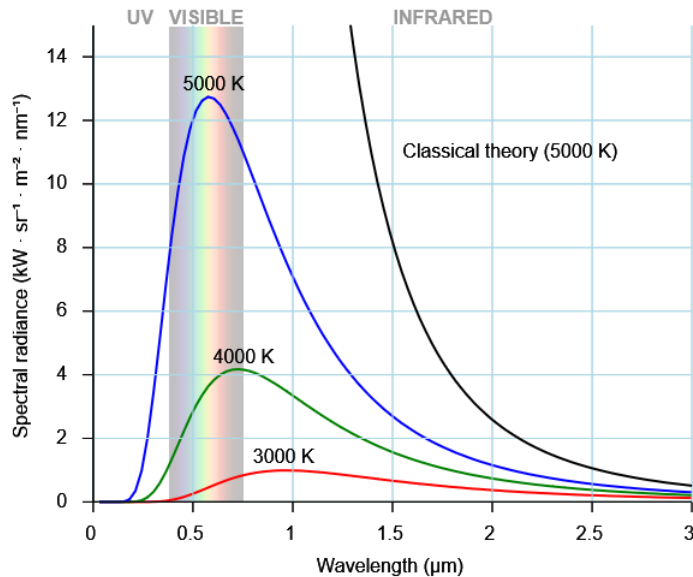

Black Body Radiation & The Ultraviolet Catastrophe

Approved for public release; distribution is unlimited

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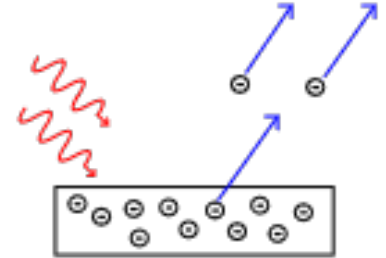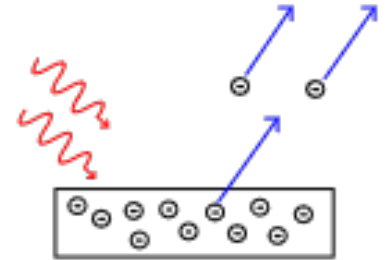Black Body Radiation & The Ultraviolet Catastrophe

Photoelectric Effect

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Black Body Radiation & The Ultraviolet Catastrophe

Photoelectric Effect

Wave Particle Duality

How Did We Get Here?

Physics Became Very Puzzling in the Early 1900s

UV VISIBLE   INFRARED

14

5000 K

Photoelectric

Quantum mechanics is a fundamental theory of physics which describes nature on the small scales of atoms and photons. In this regime, quantities such as energy and momentum can only appear in discrete values; i.e., they are *quantized*

B
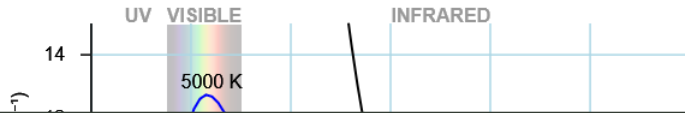
Black Body: By Darth Kule [Public domain], from
Wikimedia Commons

Photoelectric Effect: By Wolfmankurd (en:Inkscape) [GFDL (http://www.gnu.org/copyleft/fdl.html)
or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons

Double Slit: PD-1923
Approved for public release; distribution is unlimited

How Did We Get Here?

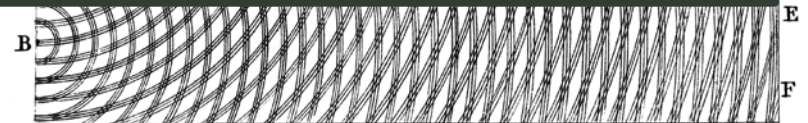Nature isn't classical… and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

- Richard Feynman, 1982

https://en.wikipedia.org/wiki/Richard_Feynman

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This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer.

- Peter Shor, 1994 -1995

http://math.mit.edu/~shor/

How Did We Get Here?

Life of the universe

Classical Computing

Solution Time (log)

Problem Size (log)

How Did We Get Here?

Classical Computing

Life of the universe

Less motivating

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Hope of Quantum Computing

Solution Time (log)

Problem Size (log)
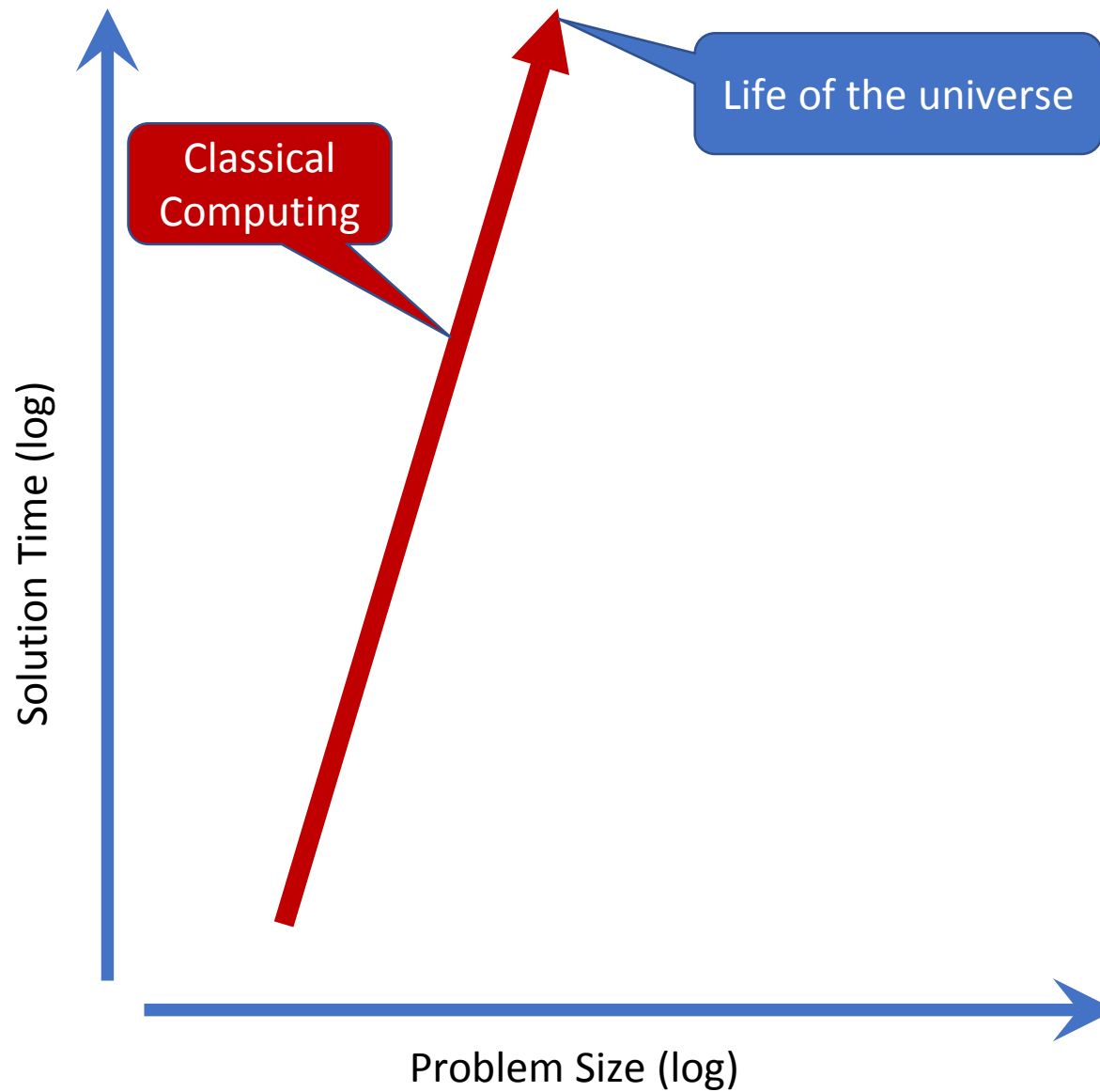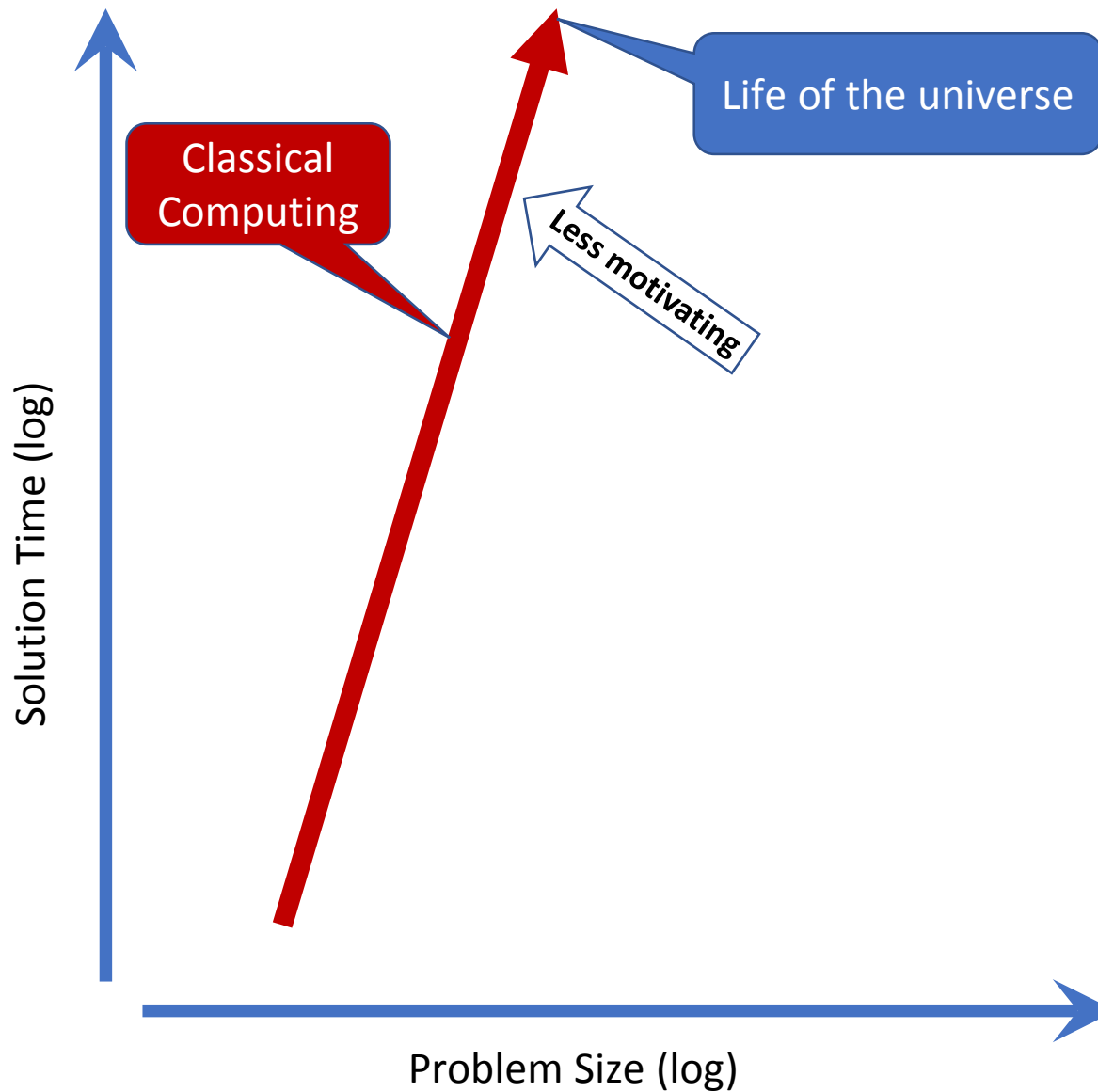
Quantum Computing: What is it?

- Big picture

- Quantum mechanics 101

- Using quantum mechanics to build computers

Quantum Computing – What is it?

Quantum Mechanics

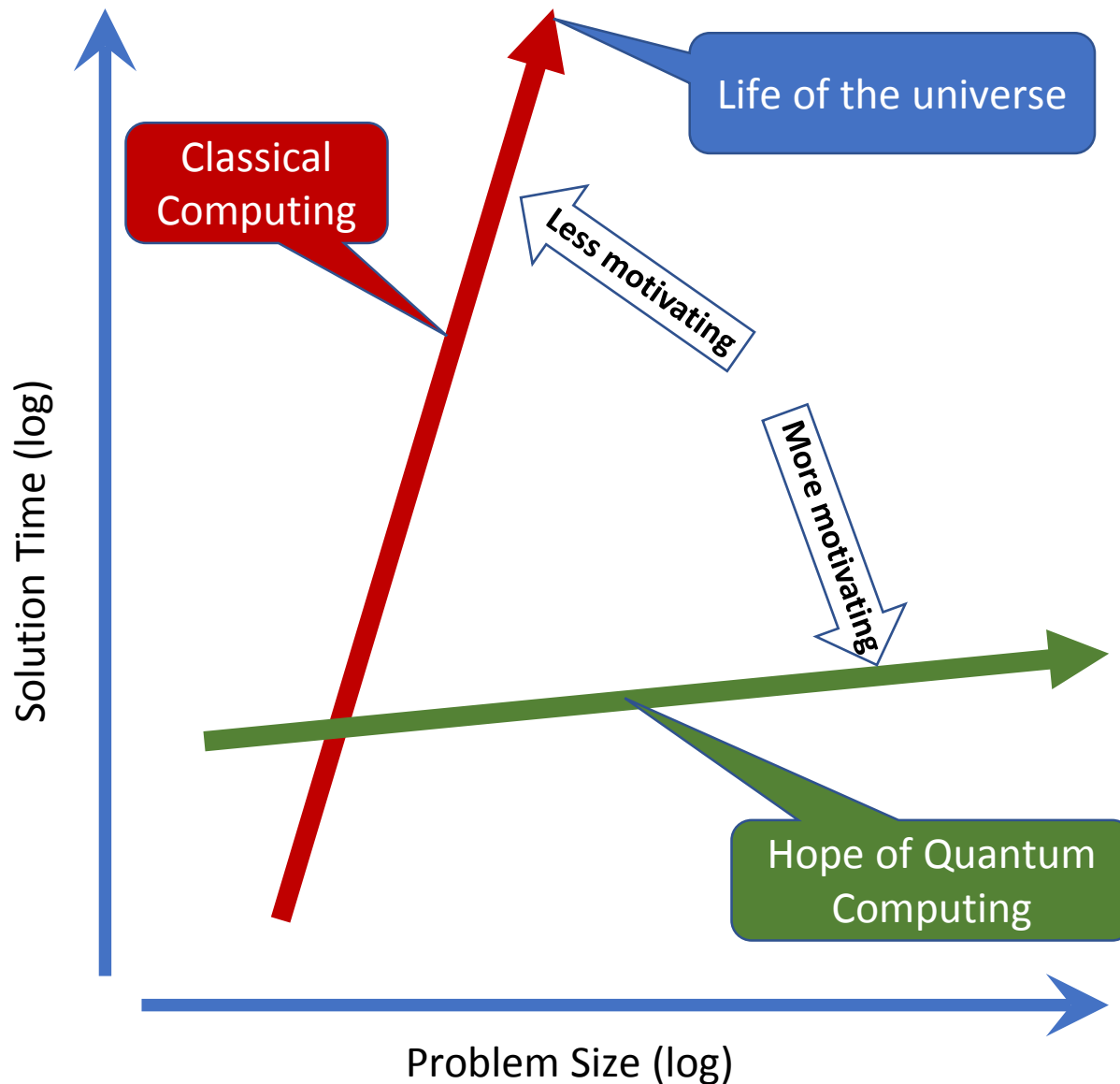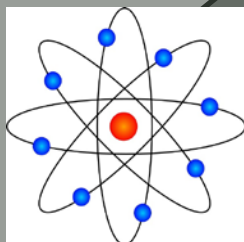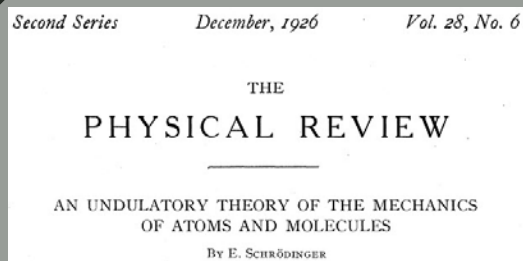**Computer & Information Science**

Quantum Computing!

Engineering

Second Series • December, 1926 • Vol. 28, No. 6

THE

PHYSICAL REVIEW

AN UNDULATORY THEORY OF THE MECHANICS OF ATOMS AND MOLECULES

BY E. SCHRÖDINGER

Cavity Beam path

Axial Path

Camera
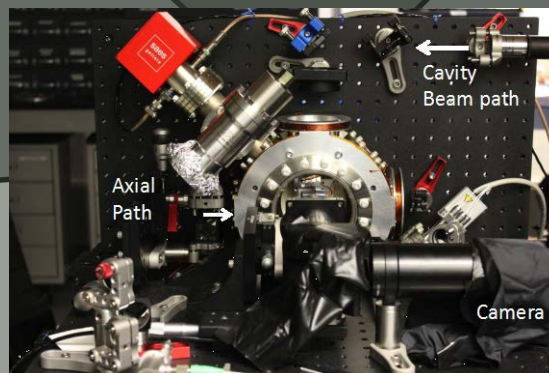
https://all-free-download.com/free-vector/download/atom-symbol-clip-art_16719.html
https://all-free-download.com/free-vector/download/vector-computer-network_155646.html (cropped)

https://all-free-download.com/free-vector/download/binary-file-icon_145149.html
Ion-trap based quantum computing experiment from Univ. of Innsbruck

Quantum Computing – What is it?

Quantum Mechanics 101:

Superposition - the counterintuitive ability of a quantum object, like an atom, to simultaneously exist in multiple states.

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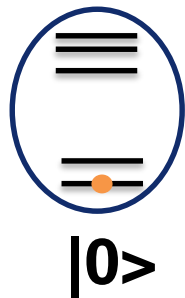
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|0>   or |1>   or   α|0> + β|1>

Quantum Computing – What is it?

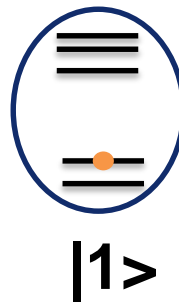**Quantum Mechanics 101:**

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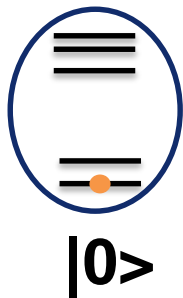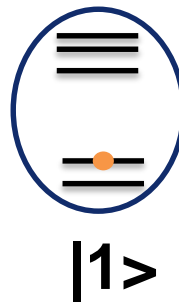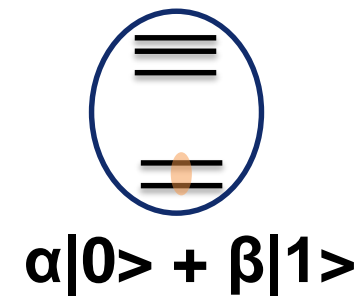
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This is a qubit!

Quantum Computing – What is it?

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Matter-Wave Duality – Quantum entities can behave like both particles and waves. This means they can interfere, just like classical waves.
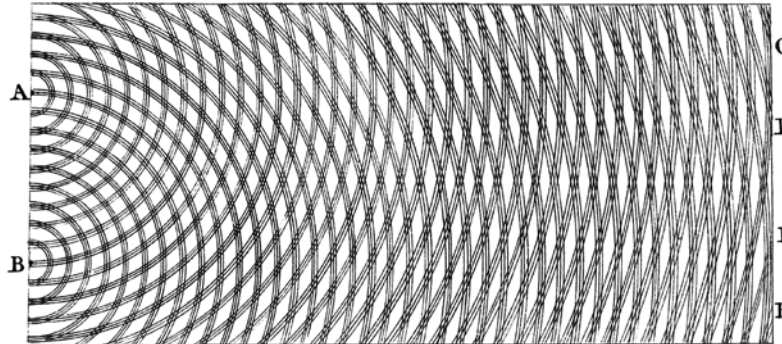
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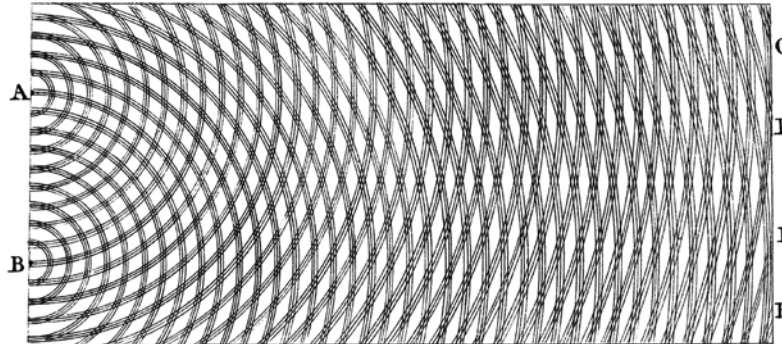

Entanglement – Quantum entities can be created and/or manipulated such that none of them can be described without referencing the others.

Quantum Computing – What is it?

A quantum computer leverages superpositions, matter-wave duality, and entanglement to carry out a series of operations (a quantum algorithm) on qubits such that ***certain probabilities are enhanced*** (those of the right answers) and ***certain probabilities are depressed*** ***even to zero*** (those of the wrong answers)

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Even to zero?

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Even to zero?

$$\alpha|0> + \beta|1>$$

α and β are complex probability amplitudes, whose modulus squared represents a probability density
and
Quantum mechanics allows probability amplitudes to constructively and destructively interfere

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THIS MAKES QUANTUM COMPUTING TRULY UNIQUE!!

Quantum Computing – What is it?
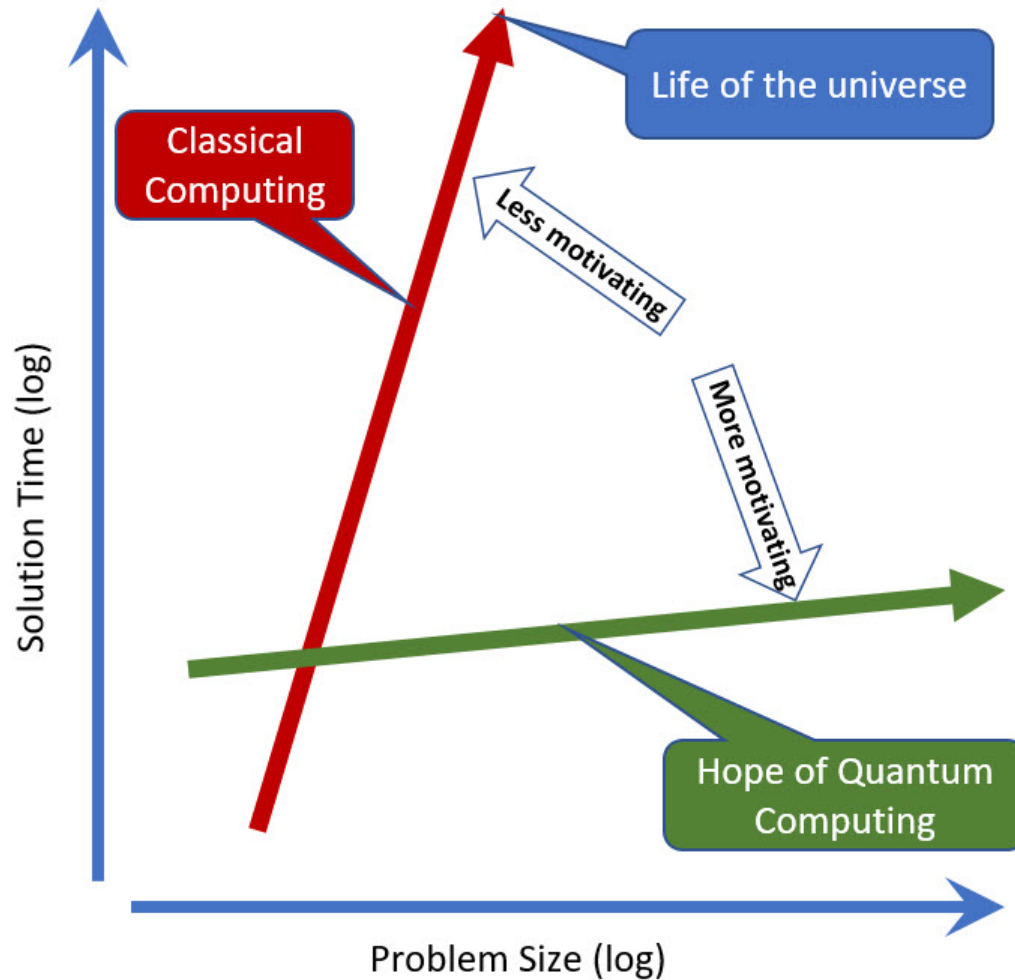
Quantum Computing Take Aways:

- Information is exponential in the number of qubits

- Entanglement provides access to the exponential information space

- Computations are probabilistic

- Computations can be arranged into algorithms such that certain probabilities are enhanced and others are depressed or zeroed
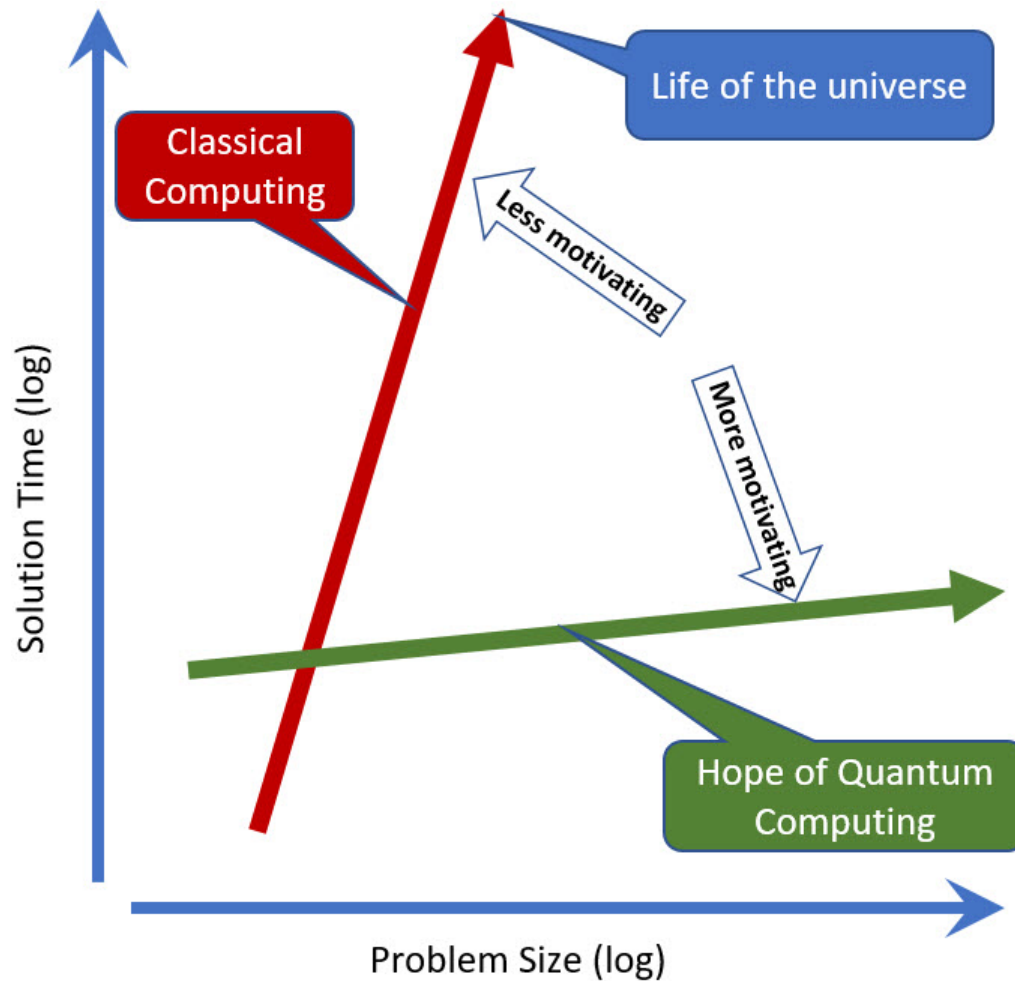
Quantum Computing: Why Do We Want It?

Quantum Computing – Why Do We Want it?

Will **all** problems experience a computational speed up?

Solution Time (log)

Classical Computing
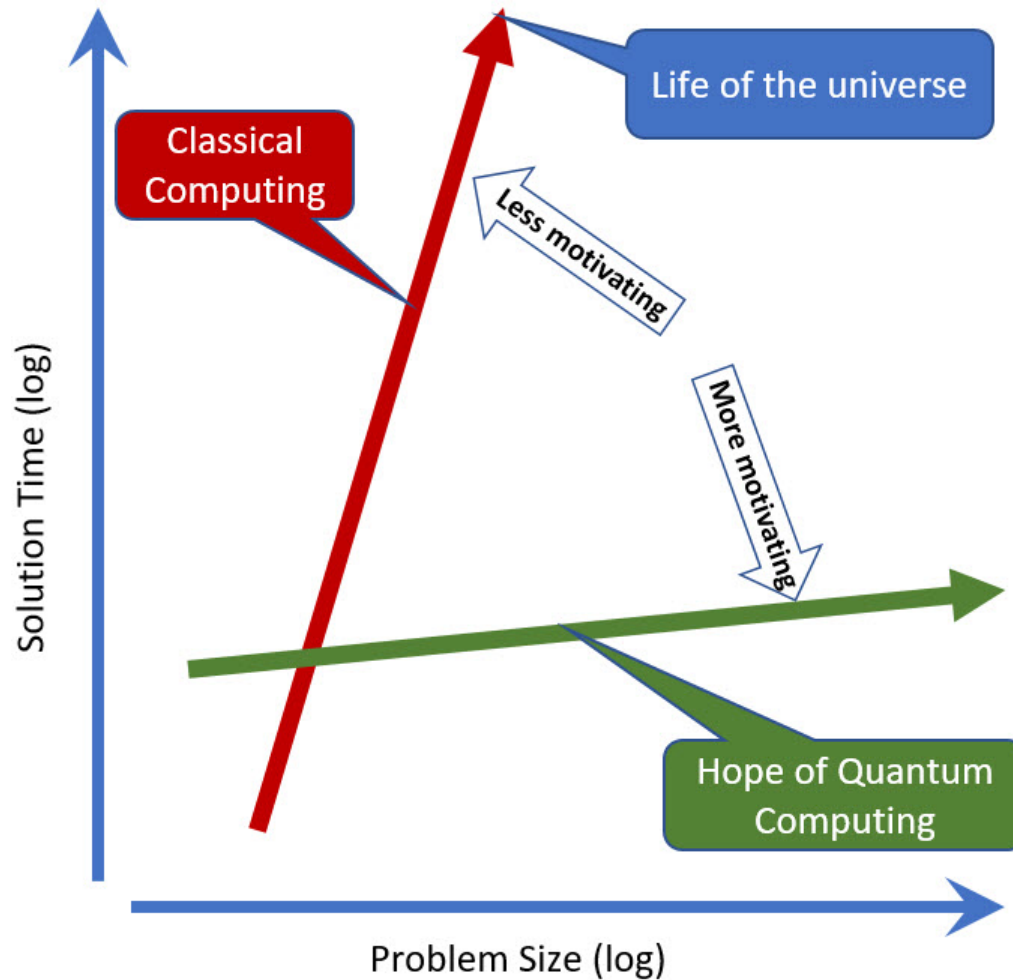
Life of the universe

Less motivating

More motivating

Hope of Quantum Computing

Problem Size (log)

Quantum Computing – Why Do We Want it?

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No, not likely

Quantum Computing – Why Do We Want it?

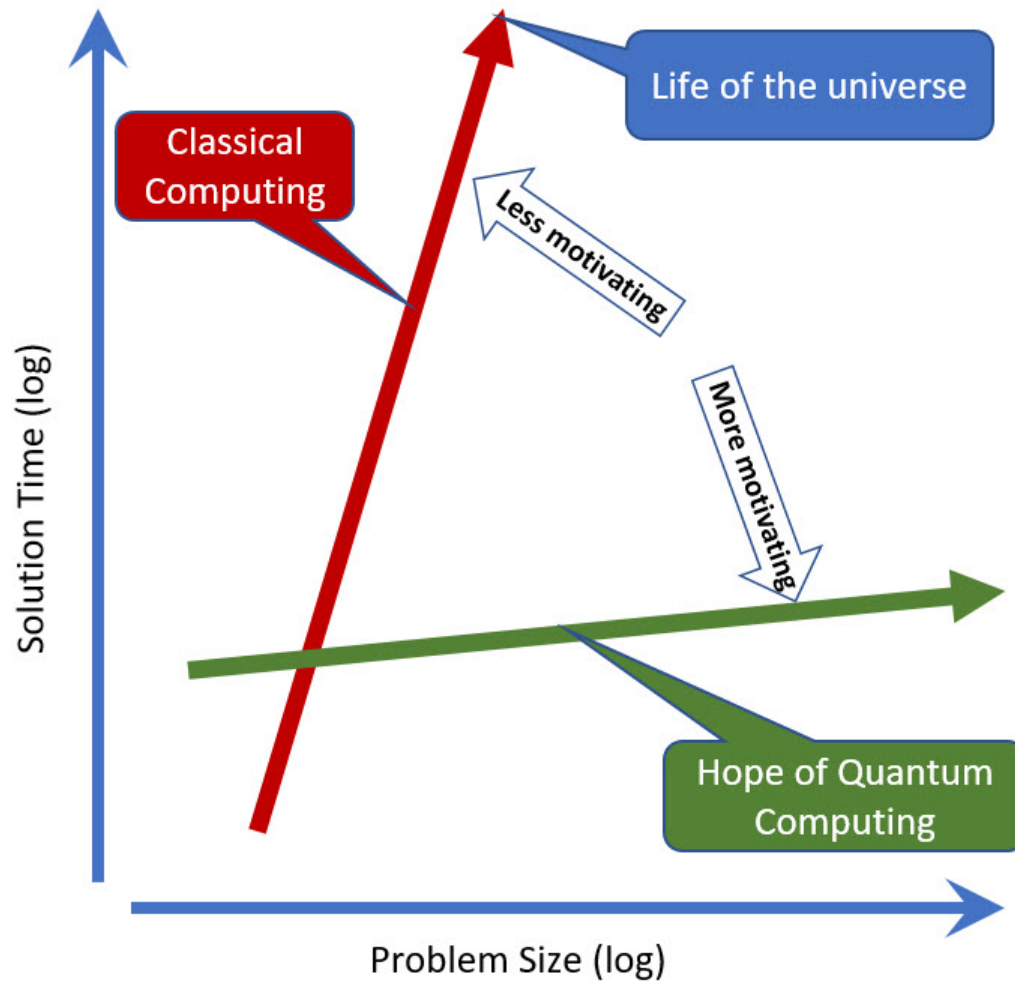Will **all** problems experience a computational speed up?
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Are qubits good for anything beyond computing?

Quantum Computing – Why Do We Want it?

Will **all** problems experience a computational speed up?
No, not likely

Are qubits good for anything beyond computing?
Yes, definitely

Solution Time (log) / **Problem Size (log)**

- Classical Computing
- Life of the universe
- Less motivating
- More motivating
- Hope of Quantum Computing

Quantum Computing: How Are We Trying to Get it?

- Experimental Approaches

- Quantum Computing Models

Quantum Computing – How Can We Get It?

Building Quantum Computers is Hard

Tug of War: Creative Commons License

Quantum Computing – How Can We Get It?

Building Quantum Computers is Hard

Isolation to Preserve Qubits' Fragile States for High "Coherence"

Quantum Computing – How Can We Get It?

Building Quantum Computers is Hard

Isolation to Preserve Qubits' Fragile States for High "Coherence"   Vs.   **Qubits Which Are Readily Manipulated for "High-Fidelity" Operations**

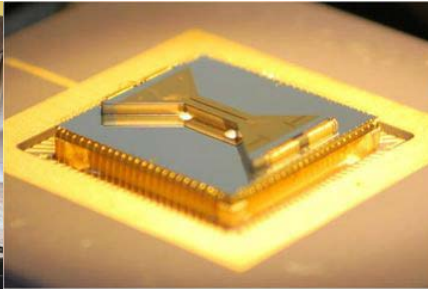# Quantum Computing – How Can We Get It?

Some Leading Hardware Candidates

Quantum Computing – How Can We Get It?
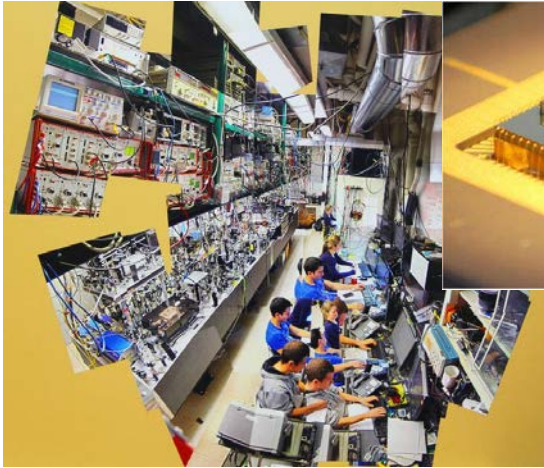
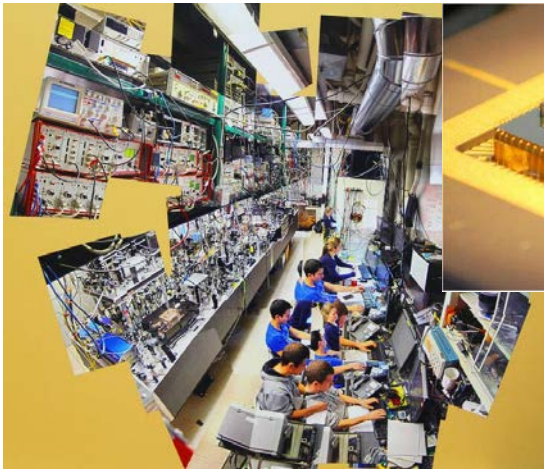## Some Leading Hardware Candidates

Trapped Ions

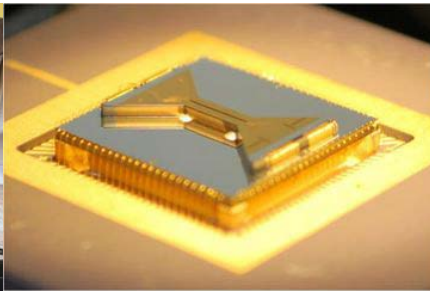High Optical Access Ion Trap
Sandia National Labs

Chris Monroe Lab - UMD

Quantum Computing – How Can We Get It?

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Trapped Ions

High Optical Access Ion Trap
Sandia National Labs

Chris Monroe Lab - UMD

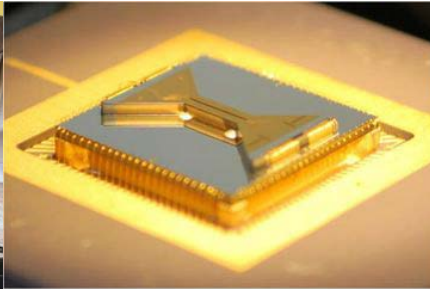## Superconductors

IBM
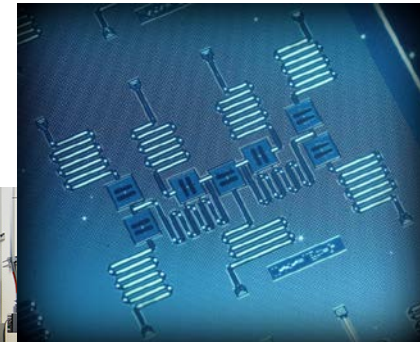
Quantum Computing – How Can We Get It?

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Semiconductors

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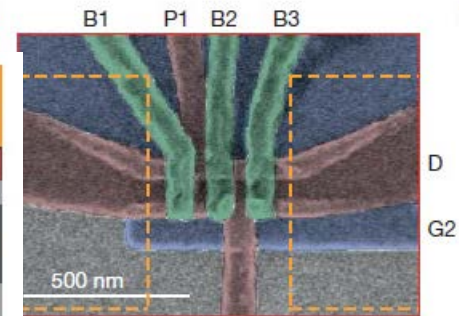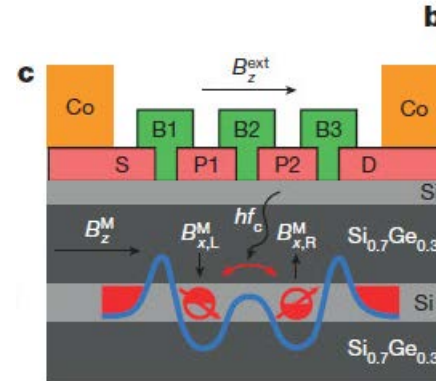
J. R. Petta doi:10.1038/nature25769

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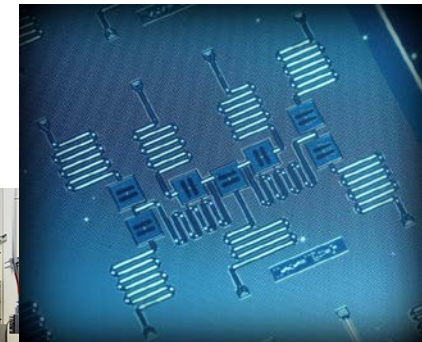
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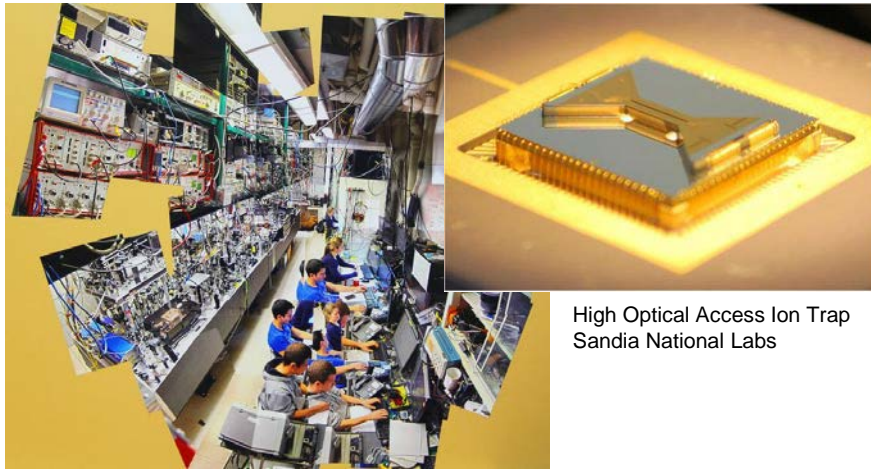
Topological Systems
???

Quasiparticles would be braided to carry out gates…

Quantum Computing – How Can We Get It?

- Gate Based Quantum Computation

By Bender2k14/ CC BY-SA 4.0 via Wikipedia

Quantum Computing – How Can We Get It?
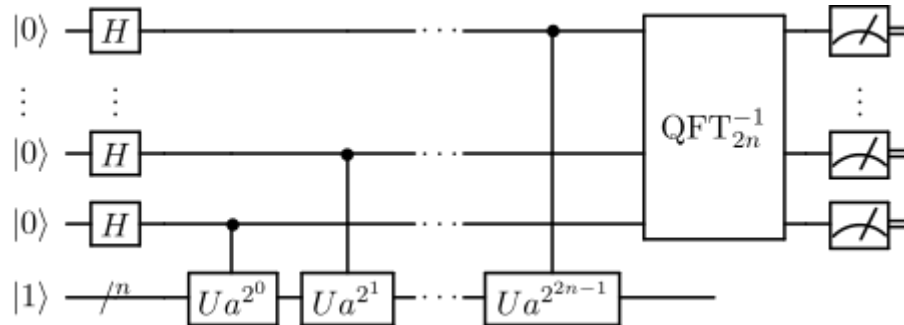
- Gate Based Quantum Computation

By Bender2k14/ CC BY-SA 4.0 via Wikipedia

- Measurement Based Quantum Computation

Quantum Computing – How Can We Get It?

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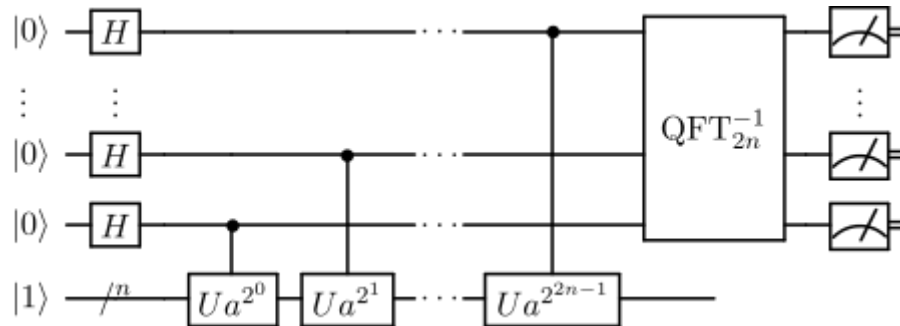

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- Measurement Based Quantum Computation
- Quantum Simulation
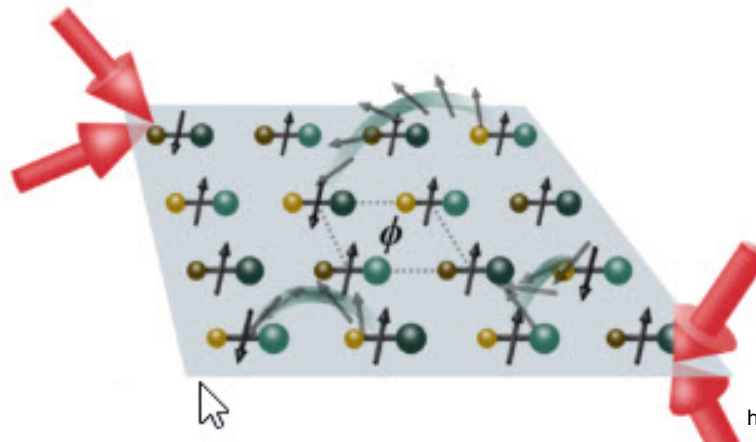
https://quantumoptics.physics.berkeley.edu/quantum-simulation/

<u>Conclusions & Outlook</u>

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THANK YOU!!