Naman Jain

Quantum Computing

A bird’s eye view of the science and tech

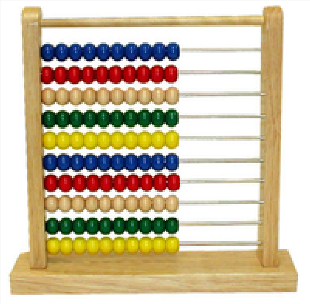
Agenda

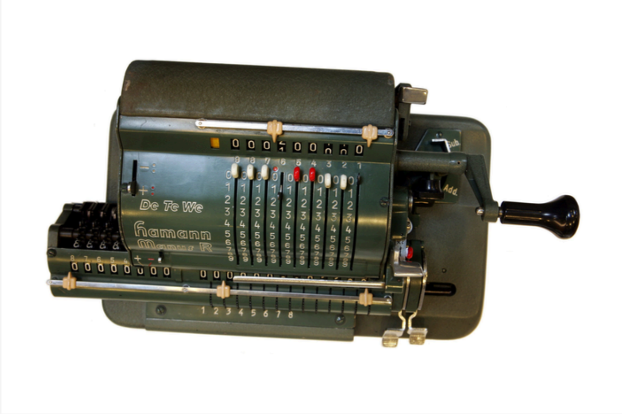
- Introduction to Computing
- History of Quantum Computing
- Classical *Vs* Quantum
- Fundamental idea - no math!
- Why Quantum computers are powerful
- Current state of Research
  - Qubit modalities
  - Quantum Applications
  - Quantum Error Correction
- How to get started?

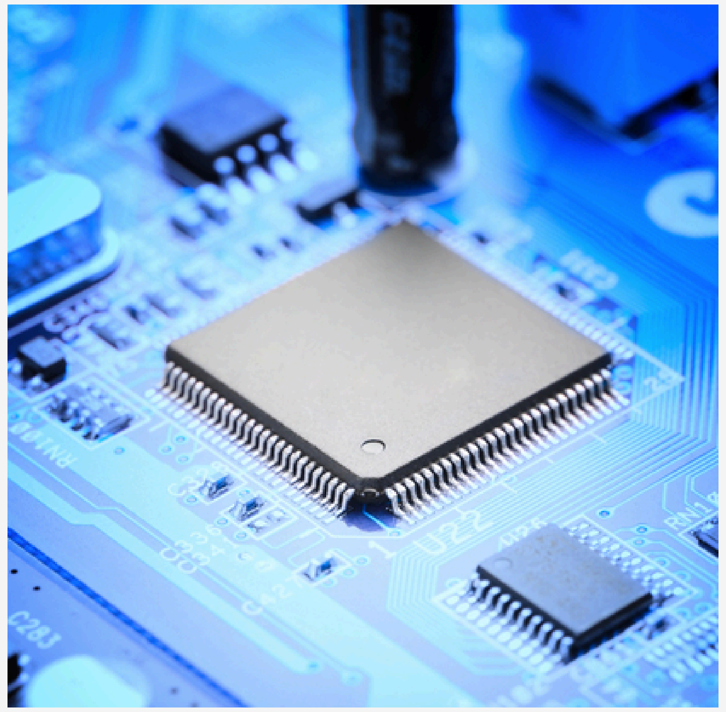
How do we compute?

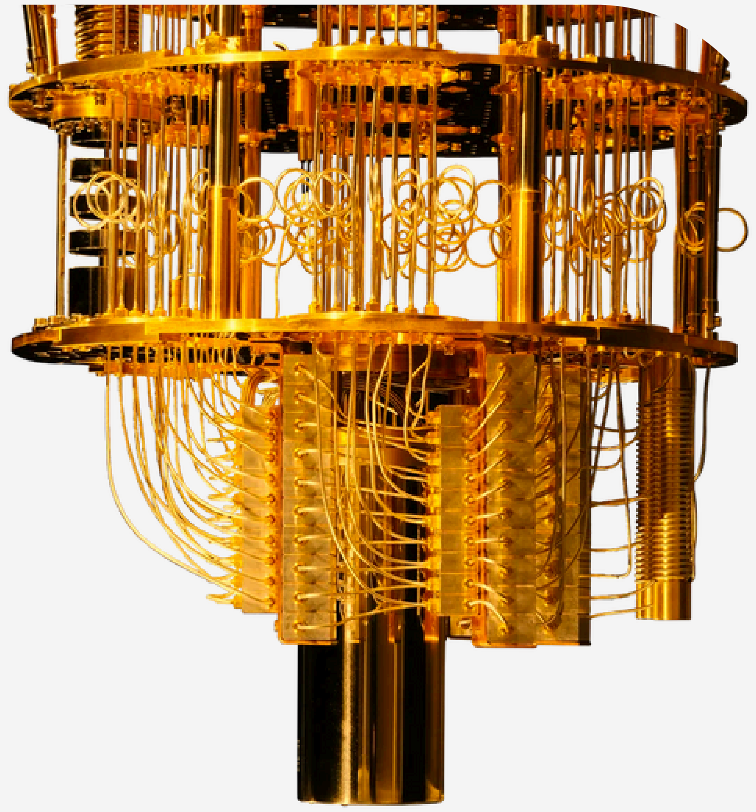
Computers process information using fundamental units.

Information is anything that can be used to reduce uncertainty







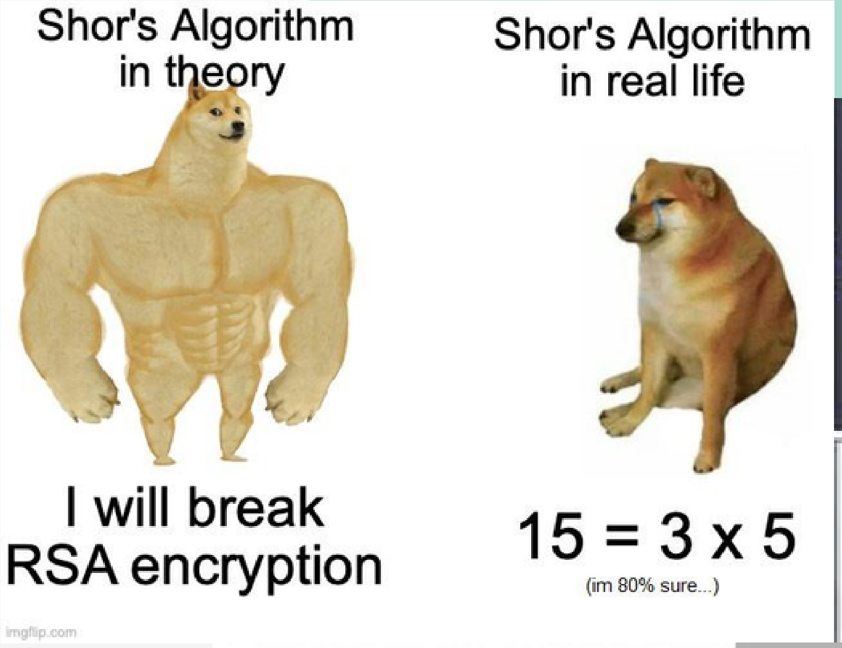


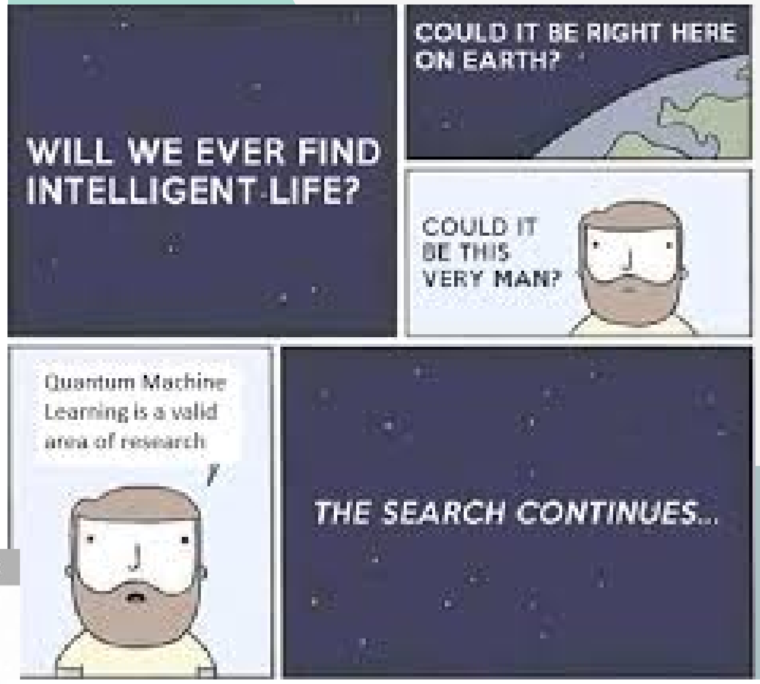
What if we could compute in a way that follows nature's rules more closely?

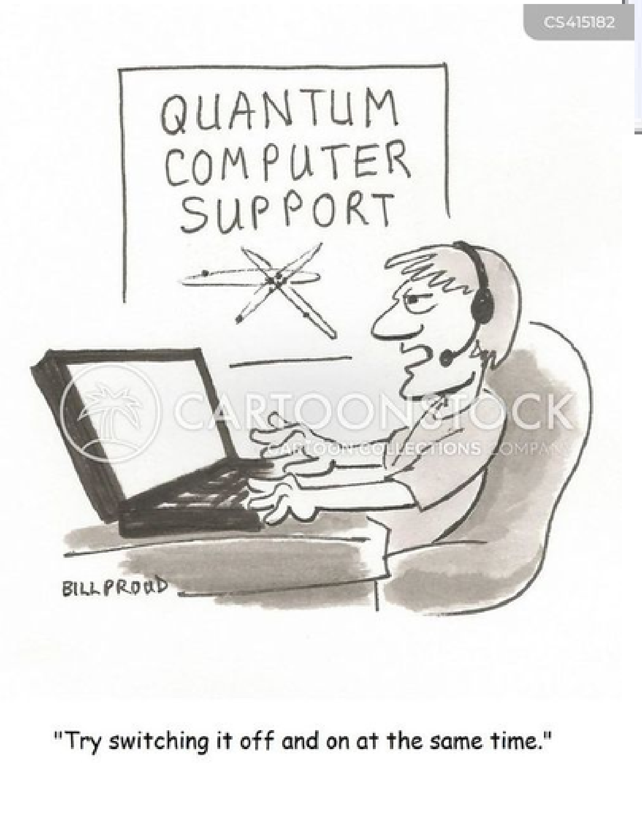
**Information is physical!*

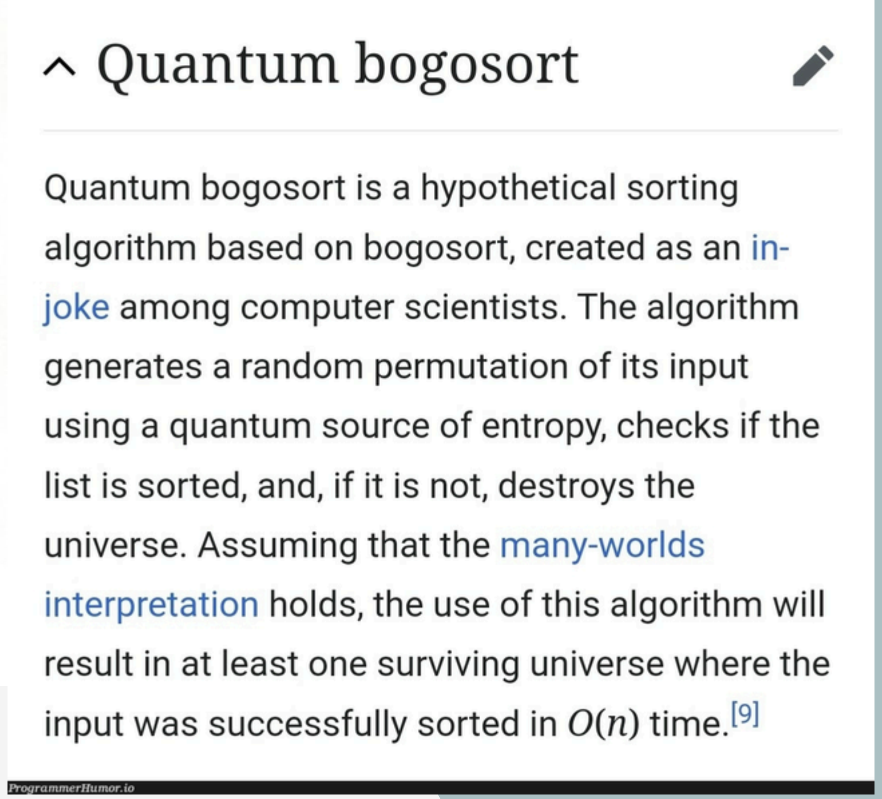
Quantum Computing

Quantum Computing exploits the quantum mechanical properties of superposition, entanglement, and quantum interference to facilitate faster and more efficient computation capability.







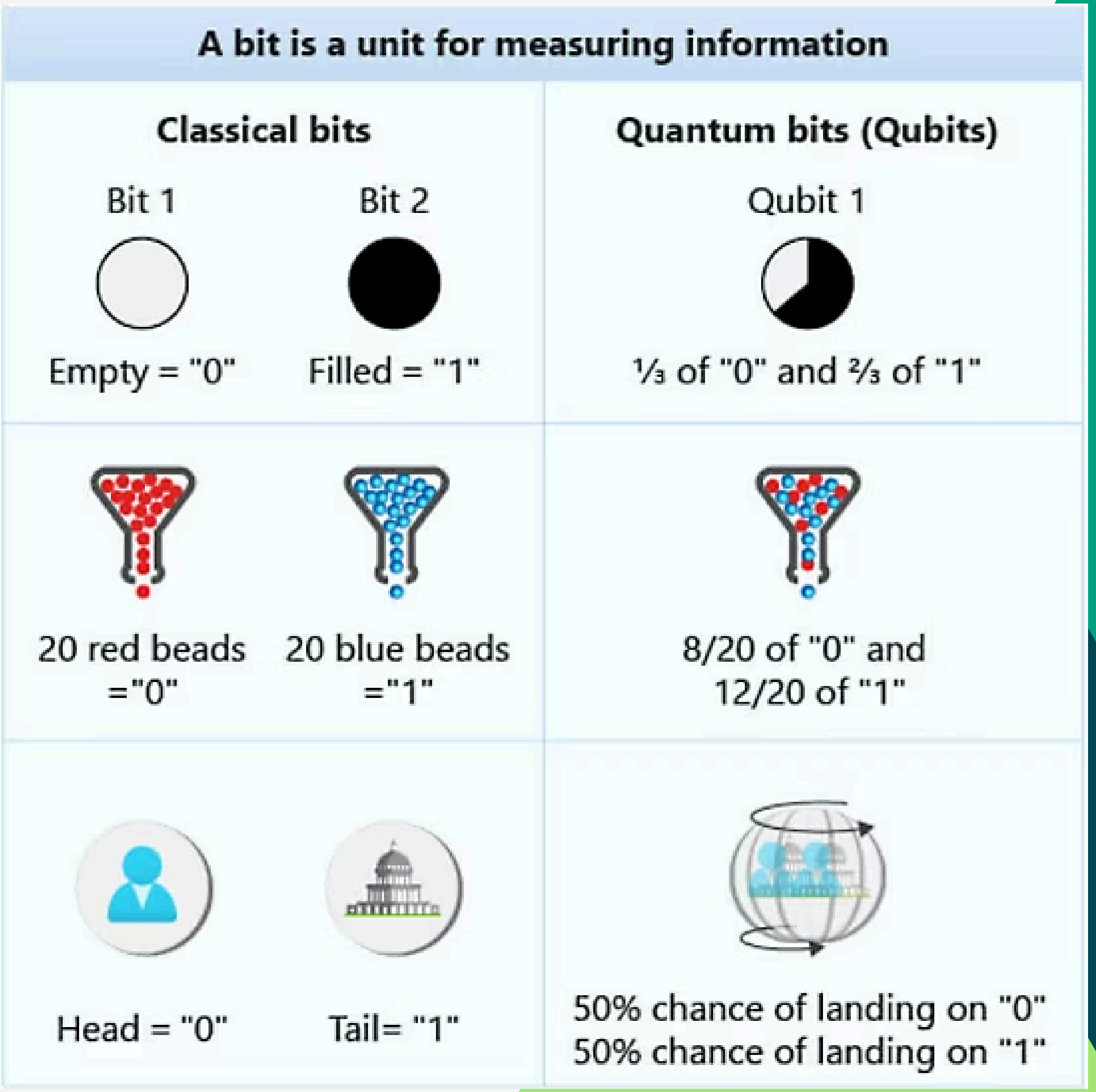

Quantum bogosort

Quantum bogosort is a hypothetical sorting algorithm based on bogosort, created as an in-joke among computer scientists. The algorithm generates a random permutation of its input using a quantum source of entropy, checks if the list is sorted, and, if it is not, destroys the universe. Assuming that the many-worlds interpretation holds, the use of this algorithm will result in at least one surviving universe where the input was successfully sorted in $O(n)$ time.[9]

Classical *Vs* Quantum

Quantum uses a more “general” math

- Real domain -> Complex domain
  - Classical computing is mostly binary (0 or 1)
  - Quantum expands into the complex domain
- Scalars -> Vectors
  - Classical computing doesn’t require “directions”
  - Quantum doesn’t work without “directions”
- Deterministic -> Probabilistic
  - Everything is deterministic in classical computing
  - “Measurement” dictates the outcome in quantum



History of Quantum Computing

1980s

Paul Benioff and Richard Feynman give talks on quantum computing.

1990s

Peter Shor publishes Shor's Algorithm. Lov Grover invents the quantum database search algorithm.

2000s - 2010s

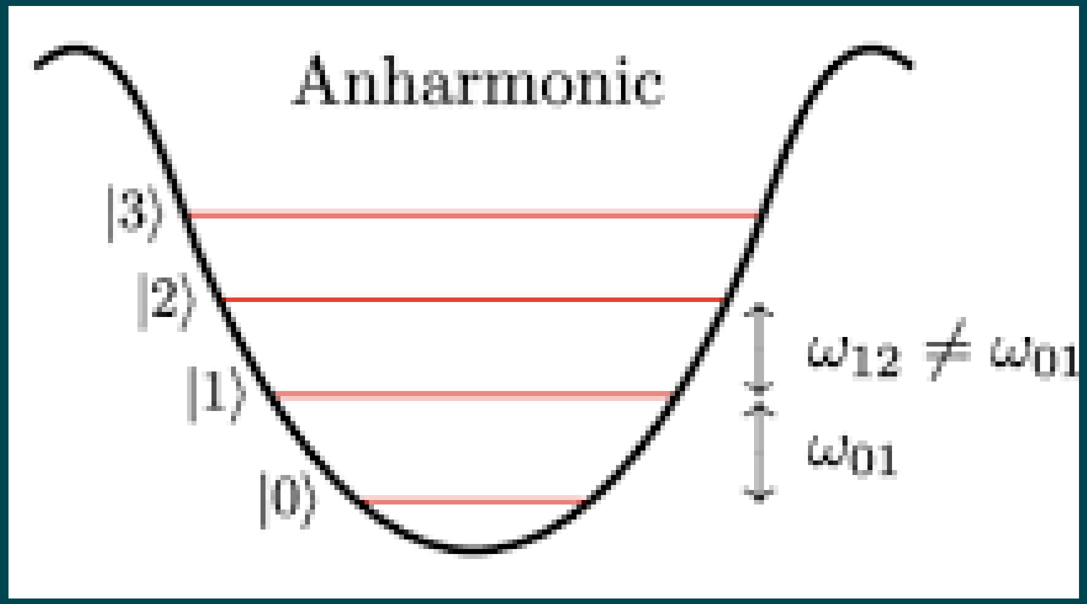
A significant development in hardware capabilities and Quantum Algorithms.

Present

Major developments in hardware capabilities. Advancements in Error Correction.

Qu-dit : Powerhouse of information

*Qubit is a specific case of Qu-dit for two dimensions!



Qubit

Superposition

Linear combinations of solutions to the Schrödinger equation are also solutions of the Schrödinger equation

Entanglement

Maximal knowledge about the whole of a system does not imply maximal knowledge about the individual parts of that system

Interference

Wave nature of quantum particles

Qubits - coupled!

Tensor products

Gives the exponential increase in computational power

Connectivity

Higher connectivity leads to lower depth circuits

Measurement

Coupling breaks

Quantum Computing: Cool, but can it do my homework?

A brief walkthrough of the current state of research in Quantum Computing

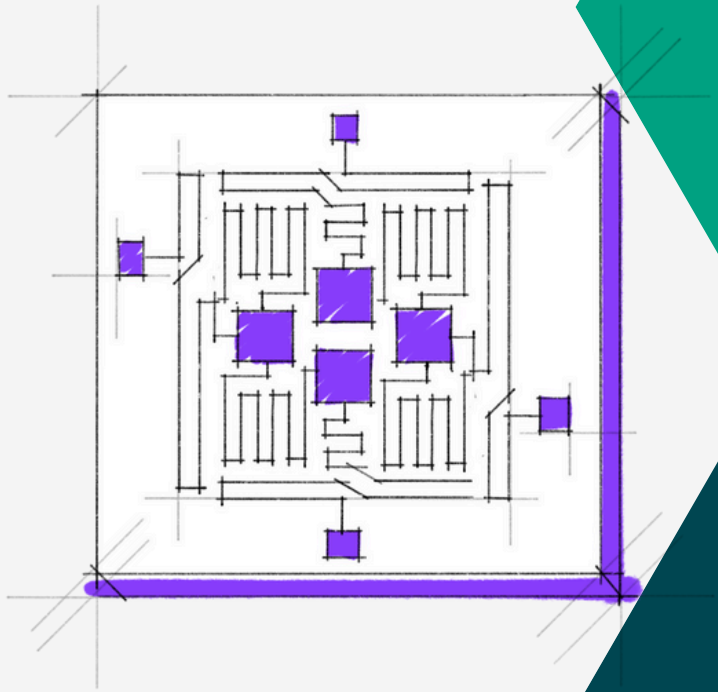
Qubit modalities

Superconducting qubits

Phase qubits: Utilize the phase difference across a Josephson junction to define quantum states.

Charge qubits: Rely on the quantization of electric charge, representing different charge states as qubit states.

Flux qubits: Employ quantized magnetic flux within a superconducting loop to represent qubit states.

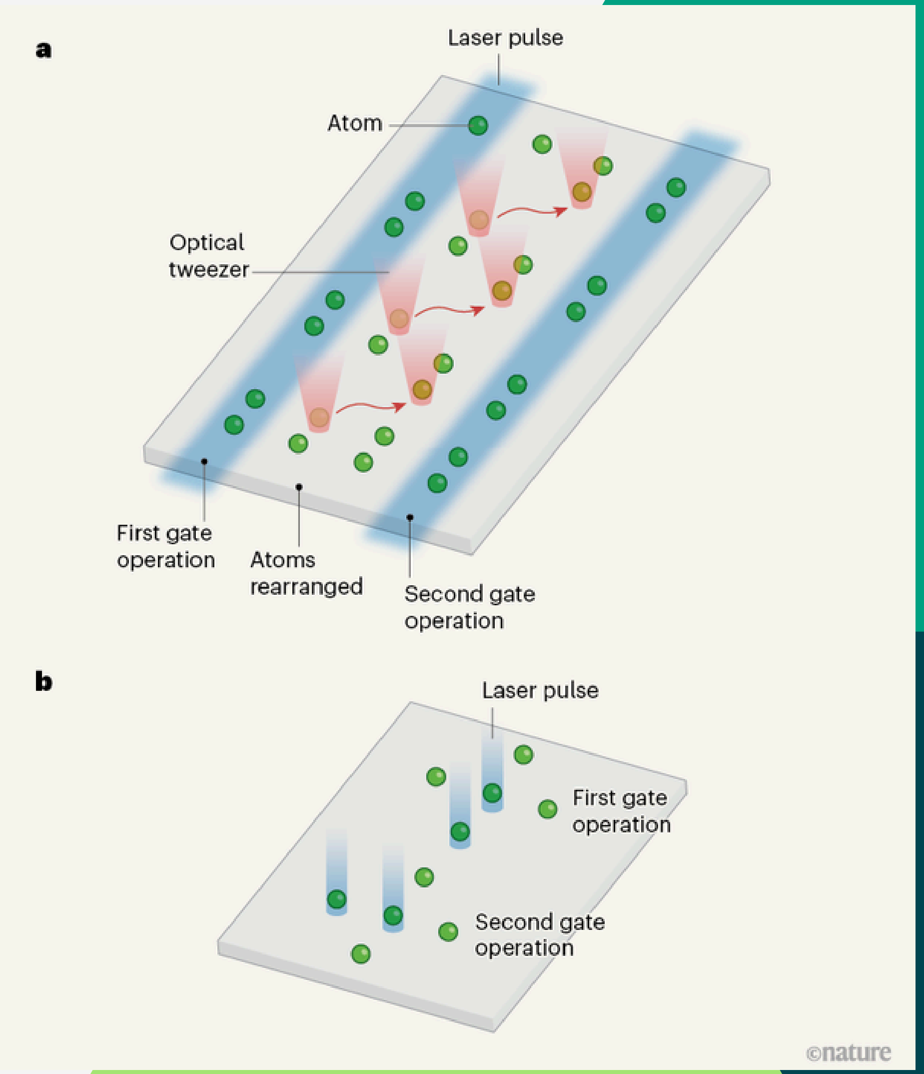


Qubit modalities

Neutral atoms

Scalability: Can be trapped and arranged in scalable arrays using optical tweezers, allowing for the construction of large qubit systems

Long Coherence Times: The intrinsic properties of neutral atoms contribute to longer coherence times



Qubit modalities

Topological qubits

Utilize non-abelian anyons to encode quantum information in a way that is inherently resistant to local errors

Cat qubits

Leverage Schrödinger cat states (superpositions of coherent states) to enhance error correction and extend qubit coherence times.

Silicon based qubits

Use electron or nuclear spins in silicon, benefiting from advanced semiconductor fabrication techniques

Dual rail qubits

Encode quantum information across two optical modes (e.g., two photonic paths), offering robust error resilience and compatibility with optical quantum networks.

Quantum Applications

Condensed Matter Physics

Simulating strongly correlated electron systems, topological phases of matter, and exotic quantum materials, enabling insights into high-temperature superconductors and quantum phase transitions

Quantum Chemistry

Solving the electronic structure problem with higher accuracy, enabling efficient modeling of molecular interactions, reaction mechanisms, and drug discovery by overcoming limitations of classical computational chemistry methods

Quantum Applications

Solving differential equations

Quantum algorithms, such as the Quantum Linear Systems Algorithm (QLSA), can solve PDEs faster than classical methods, benefiting areas like fluid dynamics and electromagnetism.

Finance

Enhancing the computational efficiency for complex problems such as portfolio optimization, risk analysis, fraud detection or cryptography and security

Quantum Applications

Quantum Machine Learning

Quantum-enhanced algorithms for data-driven tasks:
Feature Extraction & Encoding: Quantum circuits can encode high-dimensional data efficiently, potentially finding patterns inaccessible to classical methods

Quantum Neural Networks: Variational quantum circuits serve as quantum analogs of neural networks, offering advantages in expressivity and optimization landscapes

Quantum Kernel Methods: Enable efficient computation of complex similarity measures, improving performance in classification and clustering tasks.

Quantum Error Correction

protecting quantum information from decoherence and noise

Qubits vs. Logical Qubits:

Physical qubits are prone to errors, so multiple physical qubits encode a single, more stable logical qubit.

Error-Correcting Codes:

Popular methods include the Surface Code, Bosonic Codes (e.g., cat qubits) each designed to detect and correct errors without measuring quantum states directly.

Threshold Theorem:

If error rates are below a critical threshold, fault-tolerant quantum computing becomes possible by scaling QEC techniques.

Adiabatic Quantum Computing

Adiabatic quantum computing (AQC) is a model of computation that uses quantum-mechanical processes operating under adiabatic conditions. This model employs continuous-time evolution of a quantum state |ψ(t)› from a well-defined initial value to compute a final observed value.

$$i\hbar \frac{\partial |\psi(t)\rangle}{\partial t} = H(t)|\psi(t)\rangle$$

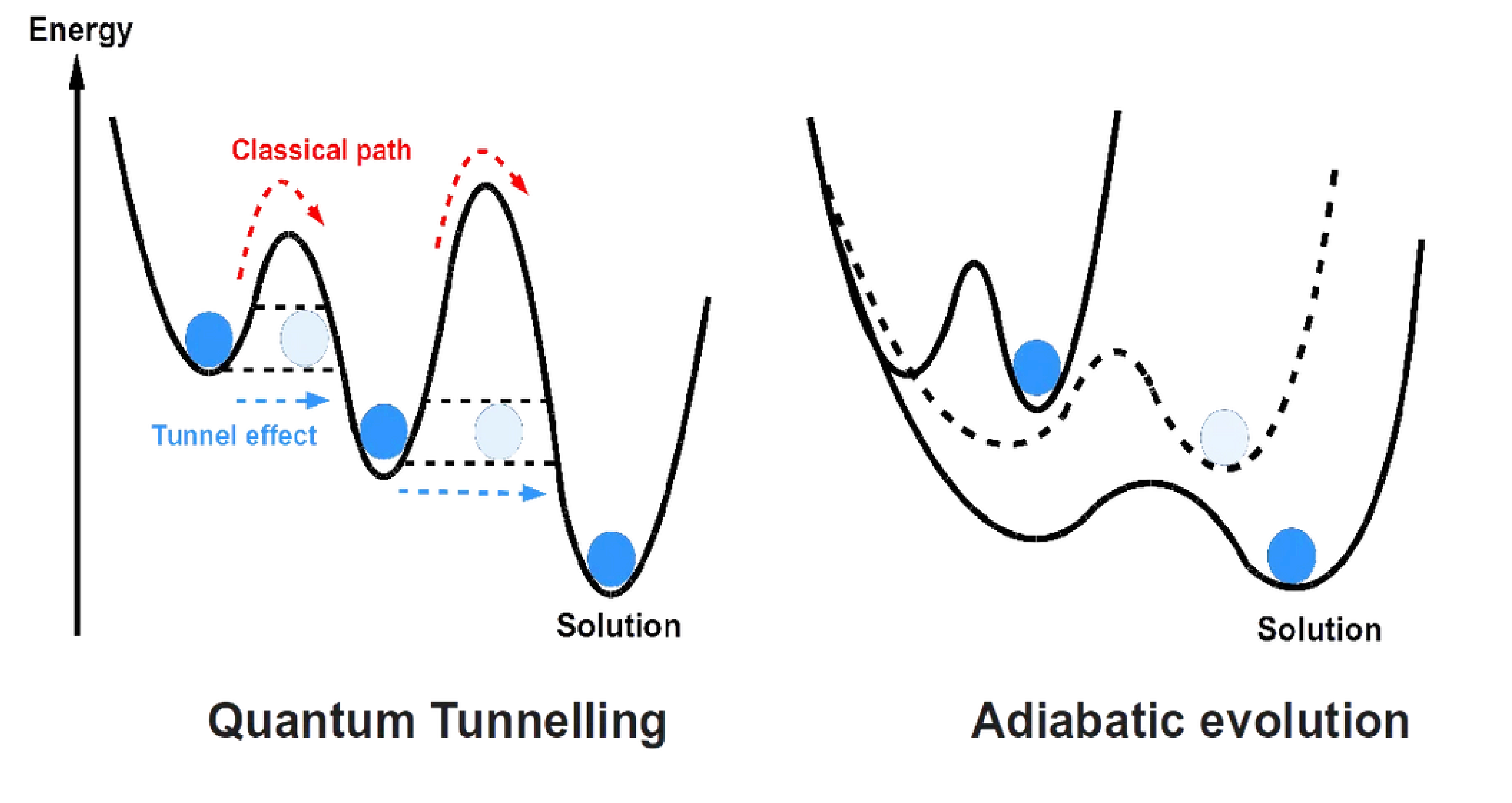


Image credit: medium.com/@quantum_wa/quantum-annealing-cdb129e96601

Quantum Annealing

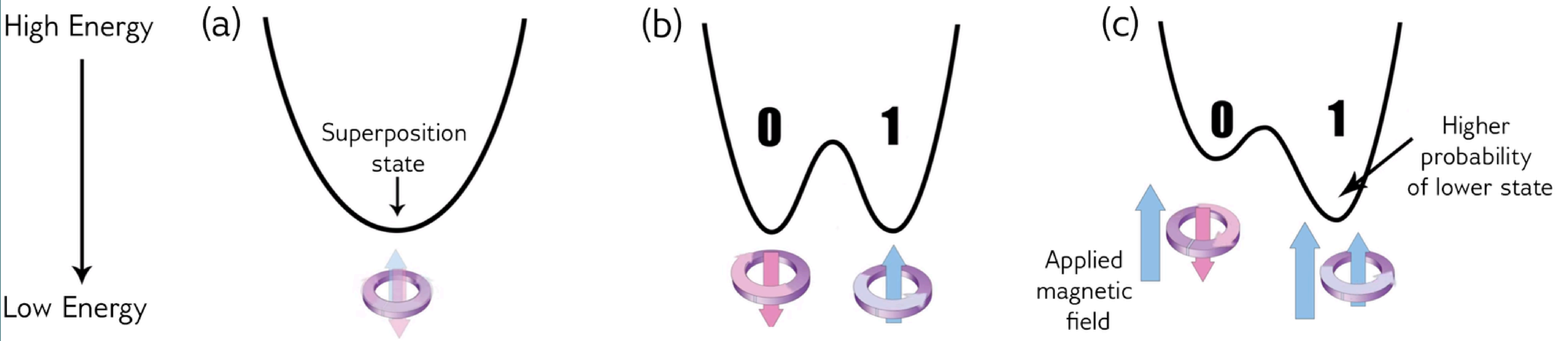


Image credit: D-wave systems

Quantum annealing is a method for identifying the minimum of an objective function based on the principles of operation for AQC derived fundamentally from the adiabatic theorem. It states that a quantum mechanical system will remain in an instantaneous eigenstate of the Hamiltonian provided conditions on the internal energy and time scales are met.

$$H(t) = A(t)H_A + B(t)H_B$$

How to get started?

Math

and Math

.....and a lot of Math

Linear Algebra
Statistics and Probability
Calculus
Complex Analysis
Trigonometry

How to get started?

Physics

Quantum physics

Postulates

Open Quantum systems

Condensed Matter

Many-body dynamics

How to get started?

Code

Scientific computing
Maintaining software

C++
Mathematica
Python

Thank You