Quantum Computing 101

An introduction

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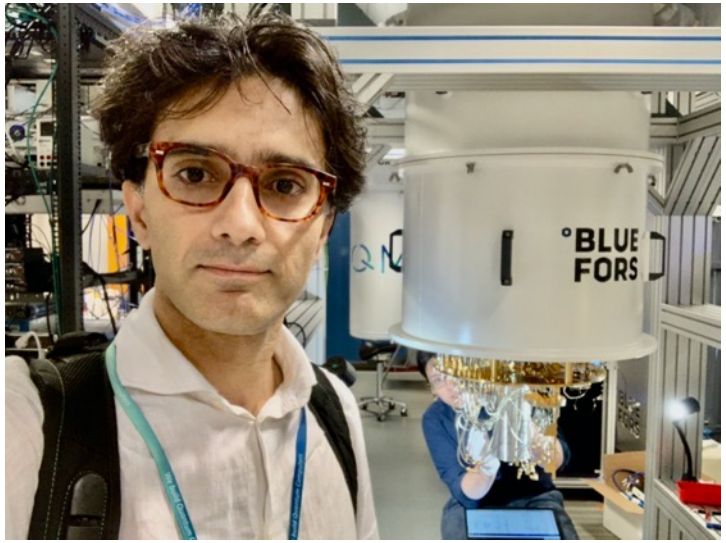
Accenture Technology

Speaker Profile



Hassan Naseri

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- **Ph.D. in Signal Processing Technology in 2018**
- **2004-2010: Telecom Software Engineer**
- **2012-2018: Research in Signal Processing Technology at Aalto Uni. (statistical estimation, machine learning and mathematical optimization).**
- **2018-present: leading R&D activities at Accenture in data science and next generation computing.**
    - **AI Manager at Liquid Studio Helsinki: Computer Vision and Optimization**
    - **Global Tech. Innovation Manager: Quantum Computing, In Silico Science**

Agenda

1

Why and What?

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IT IS ALL ABOUT COMPLEXITY

Computational complexity can make a problem intractable.

There are many intractable problems.

Example:

Delivering 100 packets in a town ~ $O(2^{100})$

Est. AGE OF UNIVERSE < 2^{90} ns

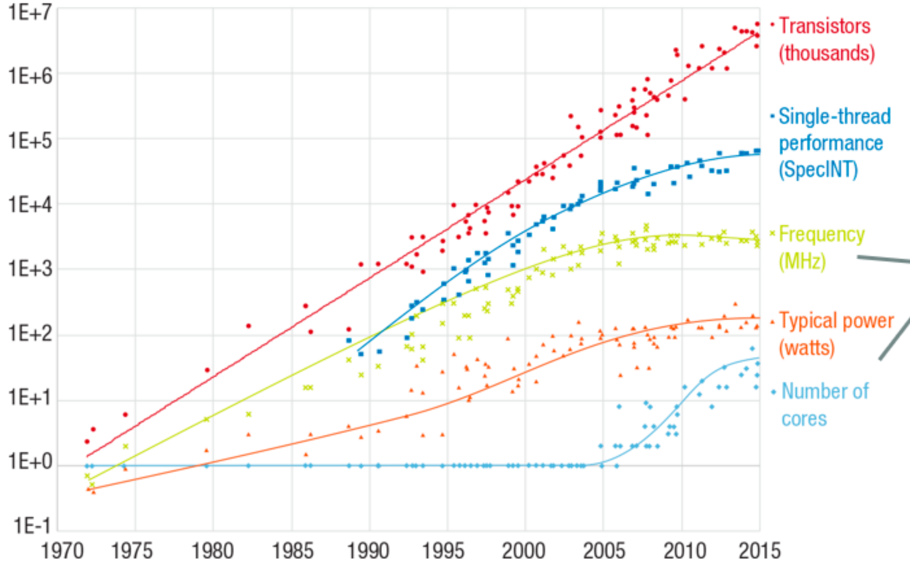
- **Solving problems that are intractable.**
- **Solving problems that are time sensitive.**

An optimal traveling salesperson tour through Germany's 15 largest cities. It is the shortest among 43,589,145,600 possible tours visiting each city once.

Traditional computers are beginning to reach their physical limitations and the fabrication cost of making them faster is economically questionable.

Dennard Scaling

(Lesser known cousin to Moore's Law)

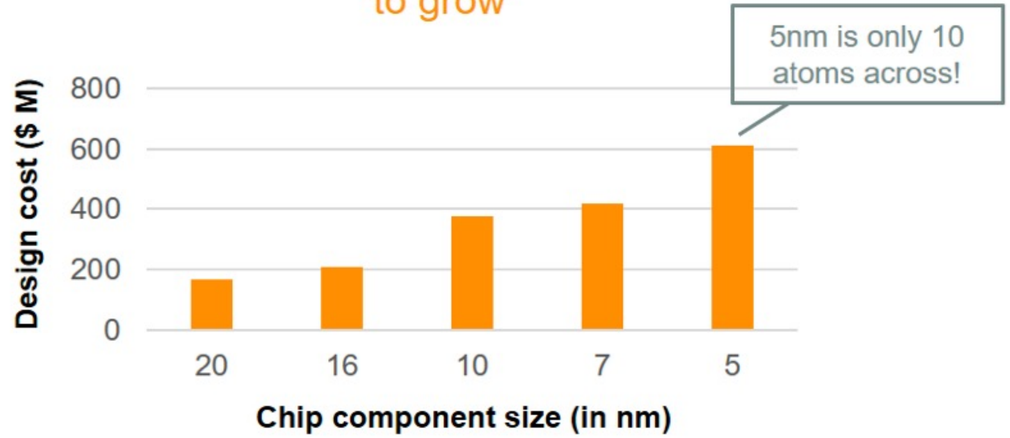


Slowed voltage scaling to match increase in transistor count put's the current method of scaling the number of cores at risk

As transistors get smaller **power density stays constant**, so that power use remains in proportional to area: **both voltage and current scale (down) with length**

Moore's Law Financial Challenge

The cost to design and manufacture smaller chips continues to grow



*Handel Jones, CEO at International Business Strategies, estimates that state of the art chip **fabrication costs** are now around $7Bn and **could reach $16Bn+ with 5nm chip production** – that's **over 1/3 of Intel's annual revenue***

*"from an economic standpoint, **Moore's law is over**" said Linley Gwennap who runs Silicon Valley research firm The Linley Group*

THE PROMISE OF QUANTUM COMPUTING

Outperforming every classical computer to an extraordinary degree for certain tasks.

This may disrupt every sector of the industry.

Moving from theory to a tangible computing technology.

Still few years behind efficient business applications.

Billions of dollar and euros are invested every year.

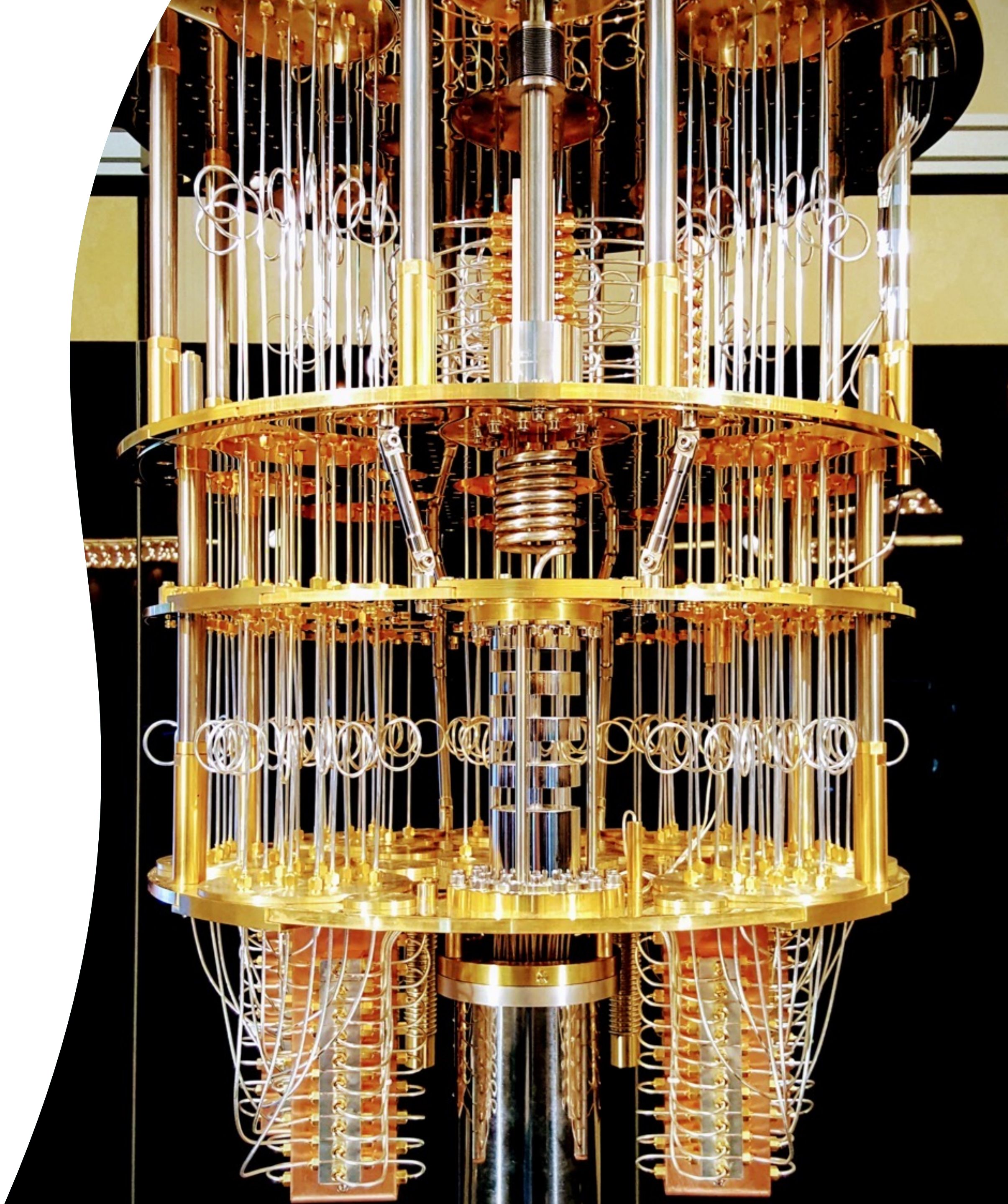
WHAT IS A QUANTUM COMPUTER?

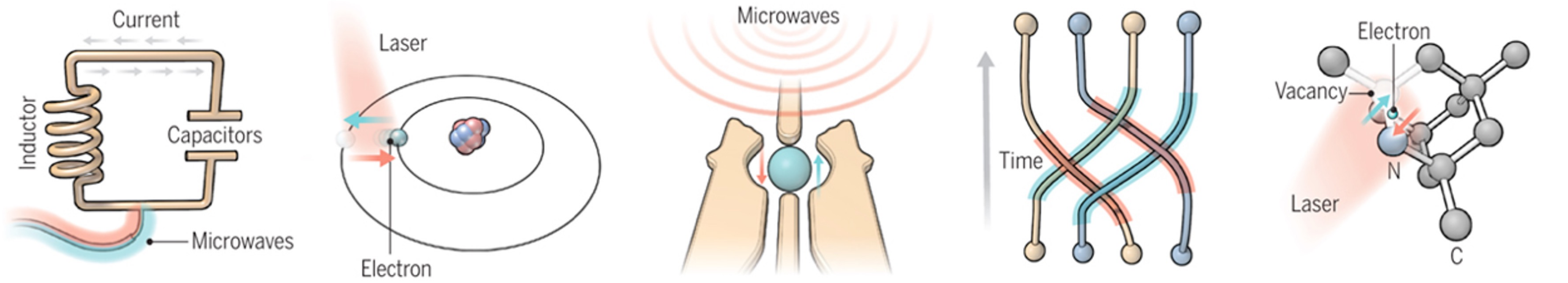
Not a faster super-computer.

Fundamentally different from digital computers:

1. Information in a quantum system.
2. Governed by quantum mechanics.

Runs specific algorithms.





Superconducting loops
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.

Trapped ions
Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

Silicon quantum dots
These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

Topological qubits
Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

Diamond vacancies
A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

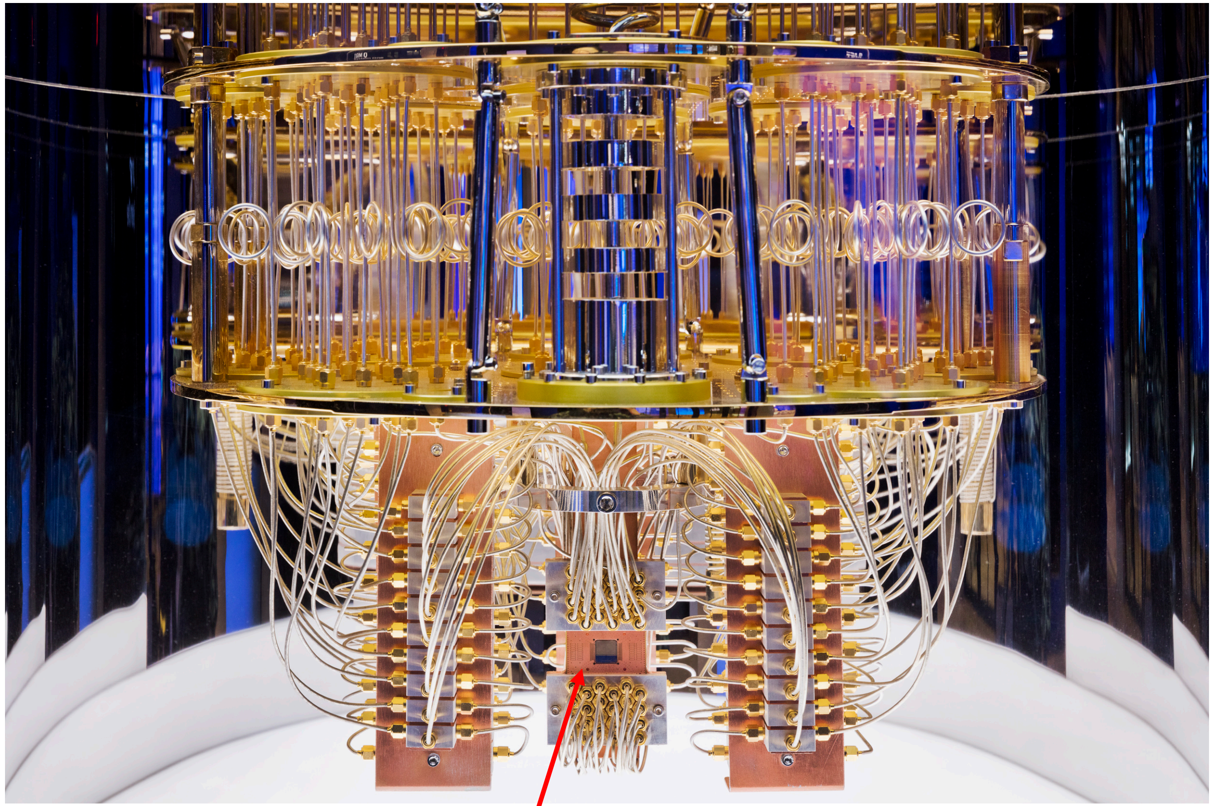
http://www.sciencemag.org/news/2016/12/scientists-are-close-building-quantum-computer-can-beat-conventional-one

THEY OCCUPY AN ENTIRE LAB

MORE IBM PICTURES

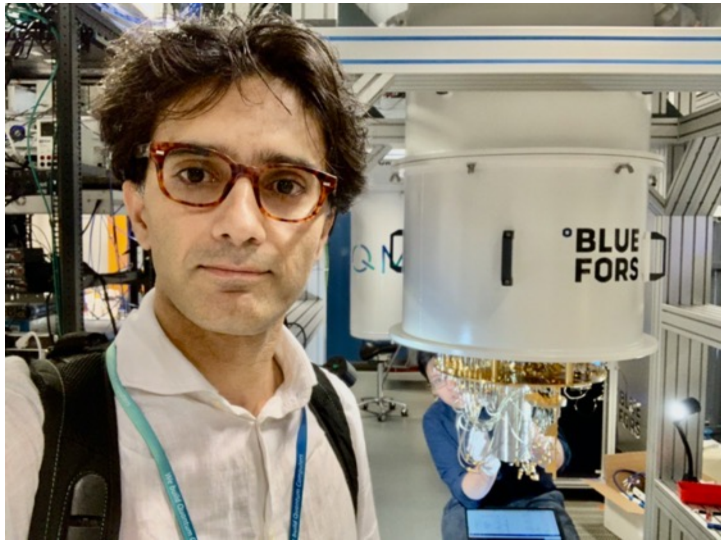
IBM Q System One

20-qubit commercial quantum computer



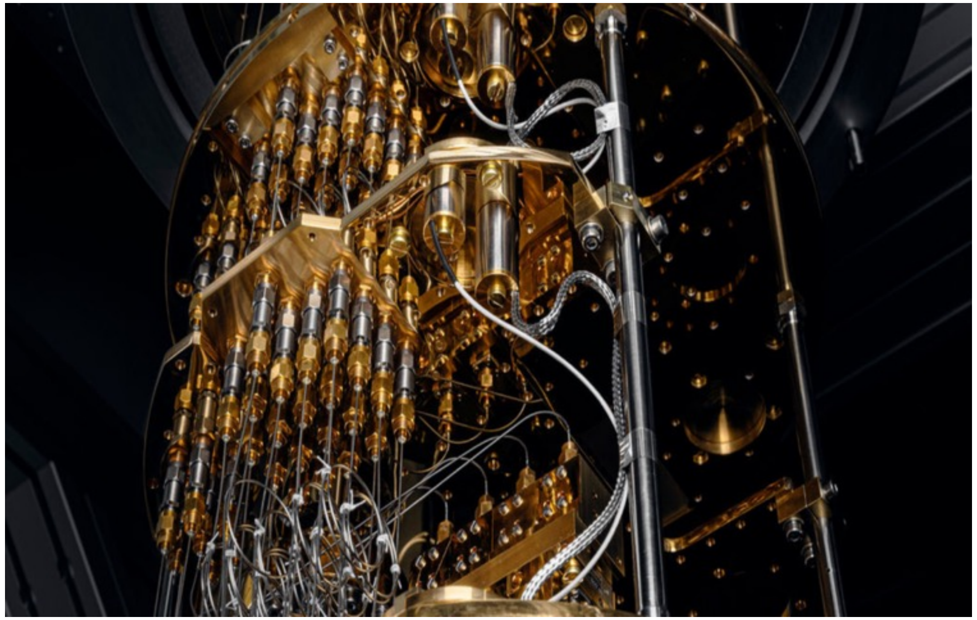
QUANTUM CHIP

IQM - FINLAND

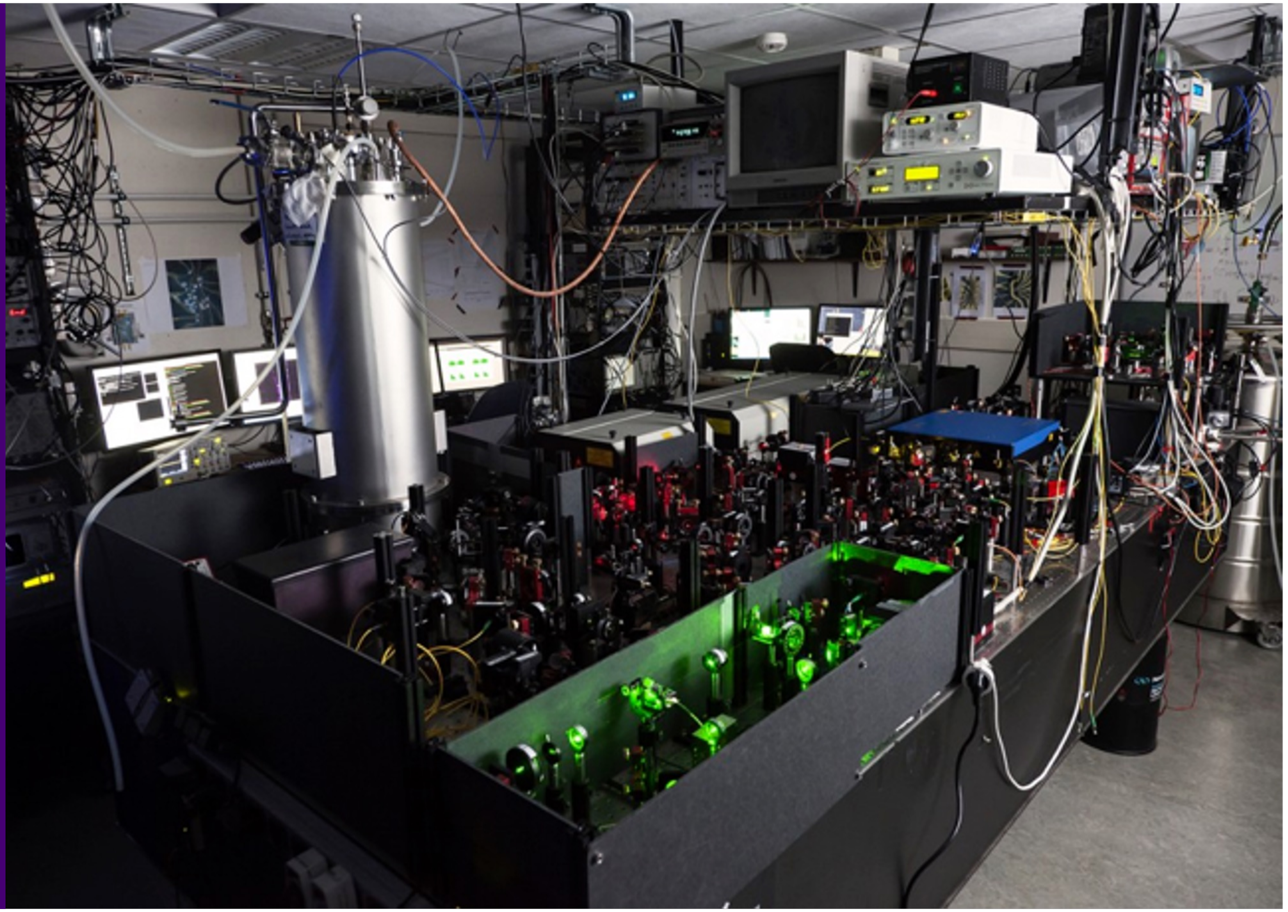


IQM builds on-premise quantum
computers with superconducting qubits

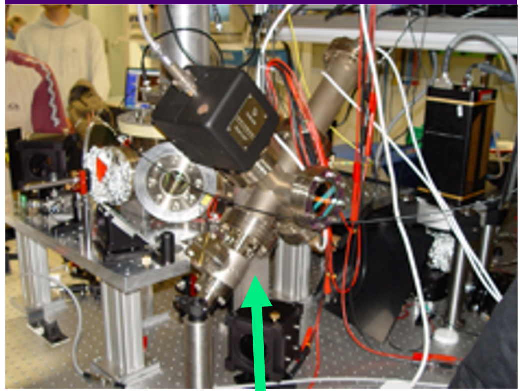
2021	2022	2023
EDUCATION 05-QUBIT QPU	RESEARCH 20-QUBIT QPU	BENCHMARK 50-QUBIT QPU UPDATE: 54-QUBIT for 2024

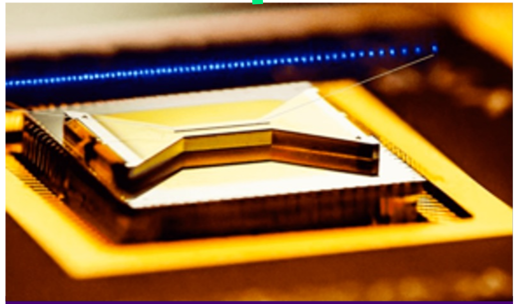


Optics Table



Vacuum Chamber





Ion Trap (QPU)

What's an Ion?
An atom or molecule with a net electric charge due to the loss or gain of one or more electrons.

Which Ions do they use?
Ytterbium-171
Carbon-40
Beryllium-9

Can operate at room temperature, uses electromagnetic fields to trap and move ions. Lasers to manipulate ions for computations

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Quantum Information Theory

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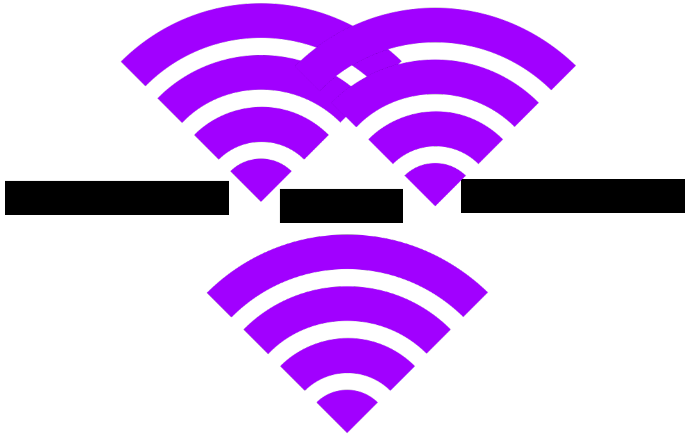
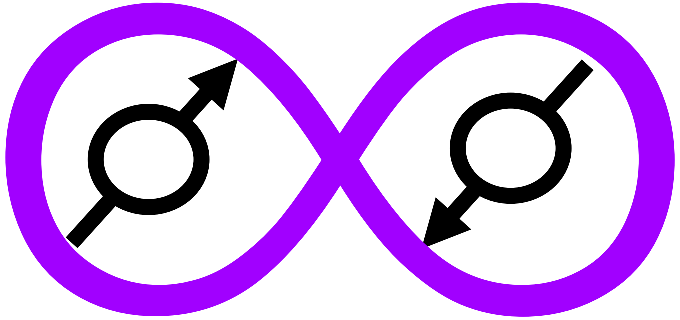
QUANTUM EFFECTS
EXPOLOITED FOR QUNATUM COMPUTING

Superposition



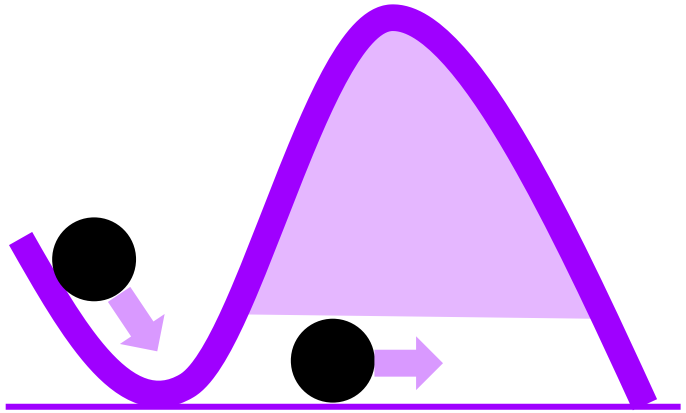
When a particle is in a quantum state, it is in a probabilistic combination of multiple states until it is measured.

Entanglement



Measurements of physical properties such as position, momentum, spin, and polarization for entangled particles are correlated.

Tunneling



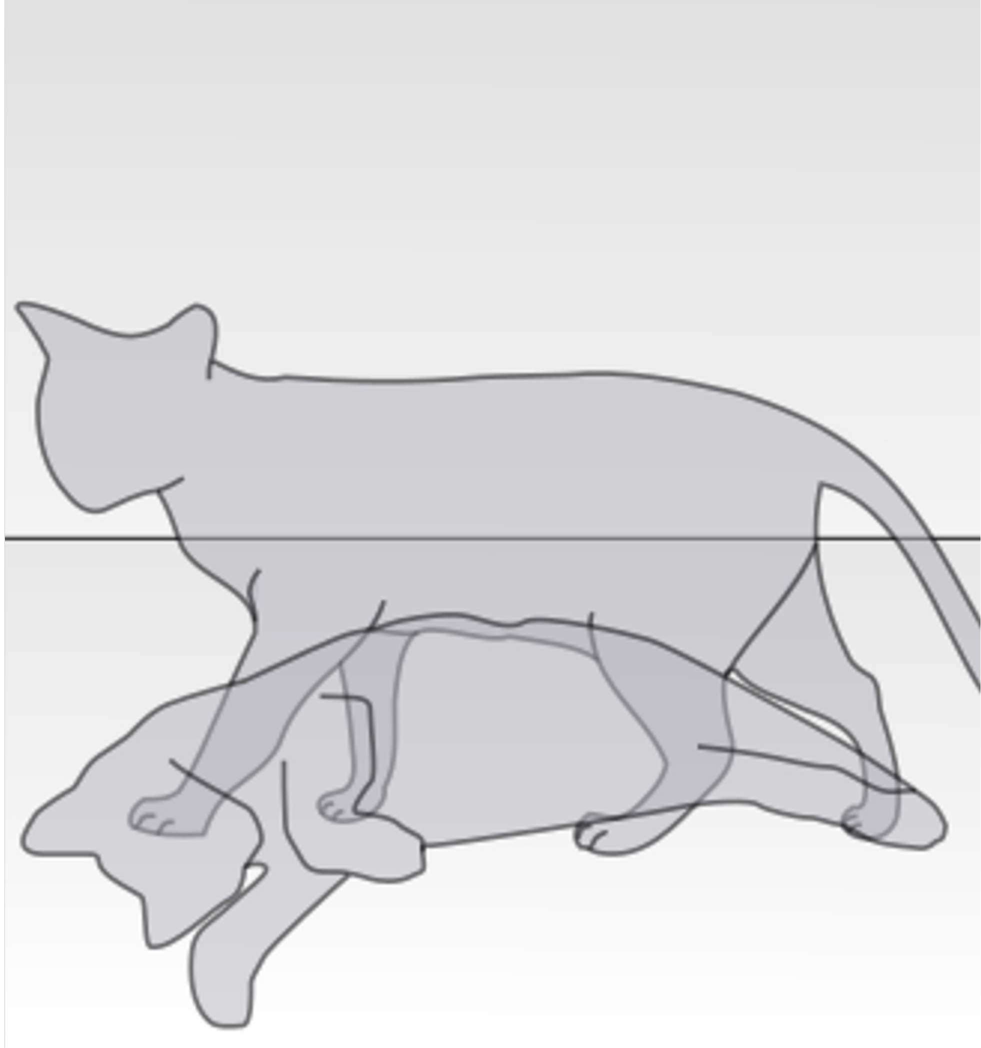
In certain conditions, quantum particles can move in space without passing over the potential energy barrier.

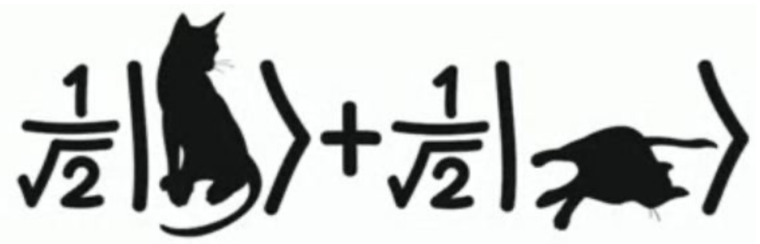
DO NOT WORRY ABOUT QUANTUM PHYSICS

The physics can be difficult and subject to different interpretations.

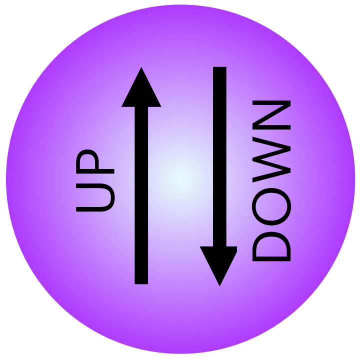
Mathematics are simple and do not require interpretation.

High level libraries for software development do not directly deal with quantum effects.

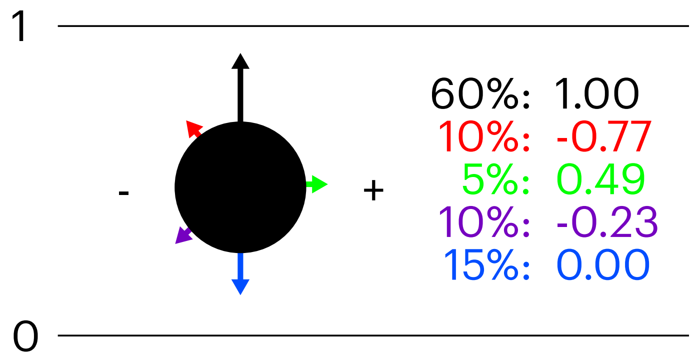




What is a qubit?



A qunatum system with two basis states.



Infinite: A qubit has infinite (continous) number of possible states (superposition).

Probabilistic: Measurement of superposed states yeilds probabilistic answers.

Measurement: The state of a qubit is not accessible from outside. Measurement is done in a basis. The state of a qubit collapses to one of the basis states. Measurement is irreversible, hence not a quantum gate.

$$\mathrm{a}|0\rangle + b|1\rangle \rightarrow \begin{bmatrix} a \\ b \end{bmatrix}$$

- **Linear combination of two states**
- $|\mathbf{0}\rangle$ and $|\mathbf{1}\rangle$ are labels for two quantum states, e.g., the spin of electron.

$$\mathrm{q}_0 = \mathrm{a}|0\rangle + b|1\rangle$$

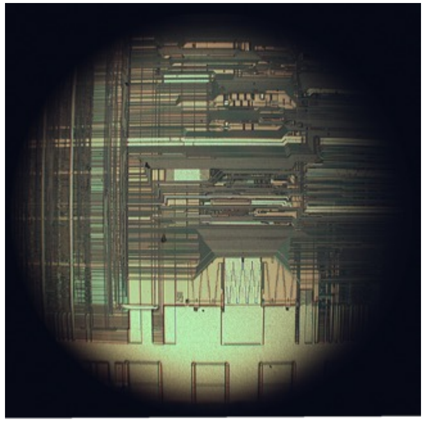
$$\mathrm{Prob}\ (\mathrm{q}_0 = |0\rangle) = a^2$$

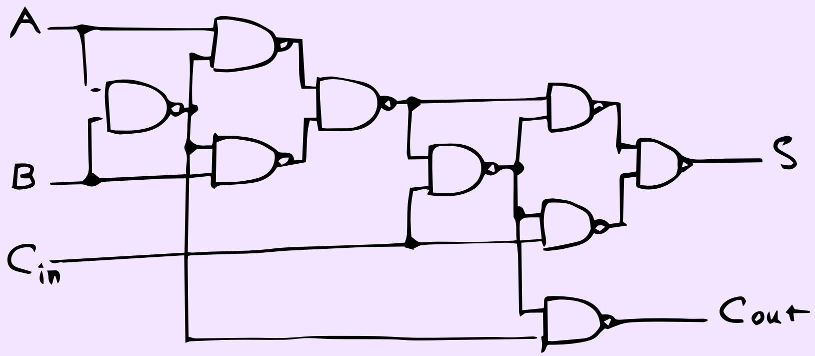
$$\mathrm{Prob}\ (\mathrm{q}_0 = |1\rangle) = b^2$$

$$a^2 + b^2 = 1$$

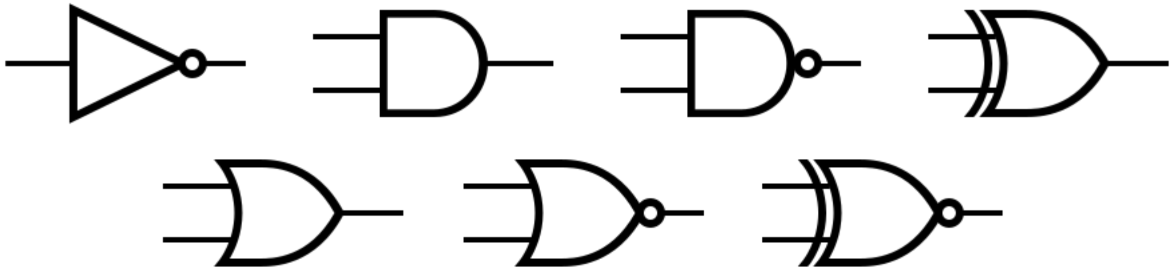
Classical Computing: Modern Digital Computers

- **Electronic**: using electrons to process information
- **Digital**: information units are bits (0/1)
- Silicon-based transistor logic (MOSFET)
- Basic gates: AND, OR, NAND, ...
- **Universal gates**: NAND, NOR
- Most system use a single universal





Full adder made of NAND gates



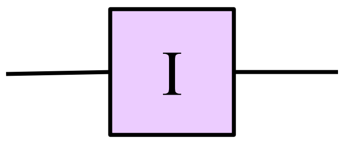
Quantum Gate Model
UNIVERSAL QUANTUM COMPUTER

1. **A universal quantum computer made from simple gates.**
2. Most common gates: **1-qubit and 2-qubit gates**
3. Quantum logic gates are reversible.
4. **Quantum logic gates are represented by unitary matrices.**
5. Due to this inherent randomness (and noise), the process is repeated and measured many times to find the probabilities of each state.

IDENTITY AND HADAMARD GATES

- **Identity**
  - **Does not change the state**

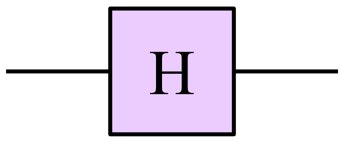
$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$



$$I \times \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} a \\ b \end{bmatrix}$$

- **Hadamard Gate**

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$



$$H \times \begin{bmatrix} a \\ b \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} a + b \\ a - b \end{bmatrix}$$

OTHER ONE QBIT GATES

Pauli gates

- X-gate: $X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

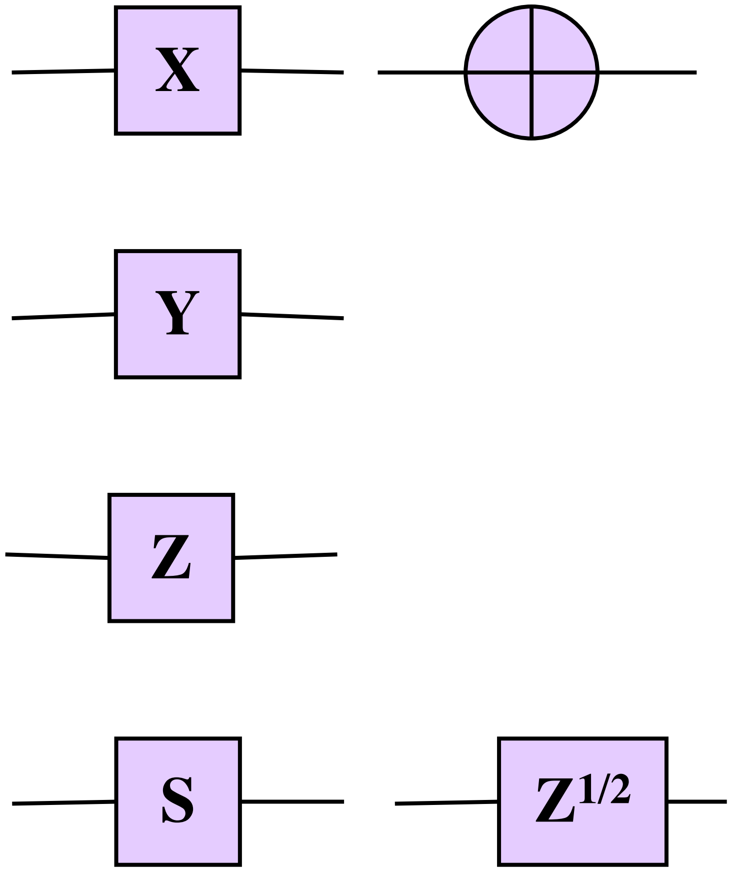
- Y-gate: $Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$

- Z-gate: $Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$

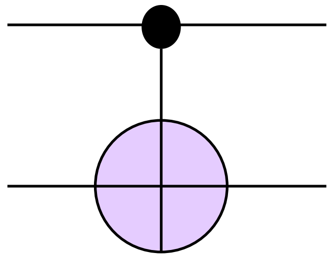
$$\mathbf{I^2 = H^2 = X^2 = Y^2 = Z^2 = I}$$

S-gate

- $S = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/2} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$



TWO-QUBIT GATES



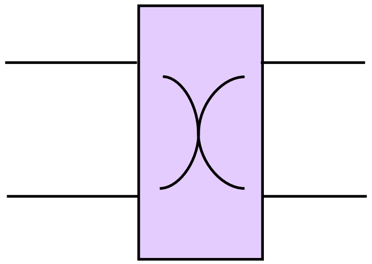
With respect to the basis:

$$|00\rangle, |01\rangle, |10\rangle, |11\rangle$$

$$\text{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

CNOT GATE (A UNIVERSAL GATE)

- It can be used to entangle and disentangle EPR states.
- **Any quantum circuit can be simulated to an arbitrary degree of accuracy using a combination of CNOT gates and single qubit rotations.**



SWAP GATE

$$\text{SWAP} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

VECTOR SPACE AND ENTAGLEMENT

- **When multiple qubits interact, the resulting state is in a vector space that contains all combinations of individual states.**

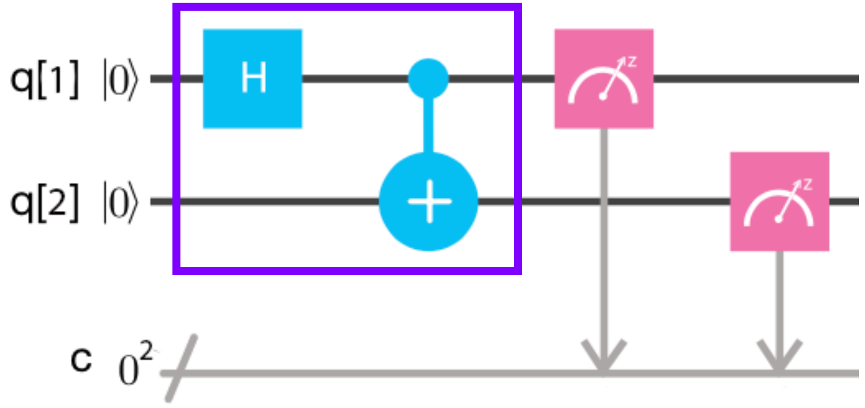
- **N qubits -> 2^N basis states**

- **Vector representation of two qubits in their joint vector space**

$$v_{00}|00\rangle + v_{01}|01\rangle + v_{10}|10\rangle + v_{11}|11\rangle \rightarrow \begin{bmatrix} v_{00} \\ v_{01} \\ v_{10} \\ v_{11} \end{bmatrix}$$

- $|ab\rangle$ **is the basis vector representing a state**

QUANTUM CIRCUIT



Quantum Circuit is composed of

- Quantum and classic registers
- Quantum gates
- Measurement gates

$$|\Phi^+\rangle = \mathrm{CX} \cdot H_1 |00\rangle$$

$$|00\rangle \to \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|0\rangle \to \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Example: Bell states

- The first Bell state can be created using a Hadamard gate and a CNOT gate.
- It creates and entanglement.
- Measurement of one qubit will assign one of two possible values to the other qubit instantly.

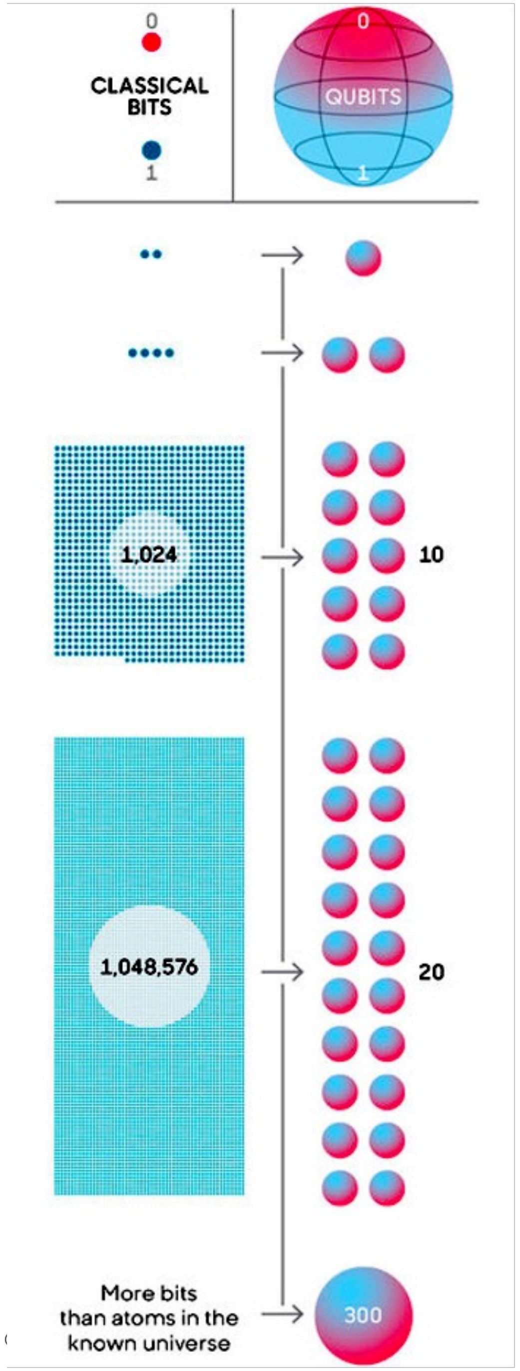
QUANTUM ADVANTAGE COMES FROM TWO MAIN QUANTUM EFFECTS

Quantum Parallelism (superposition)

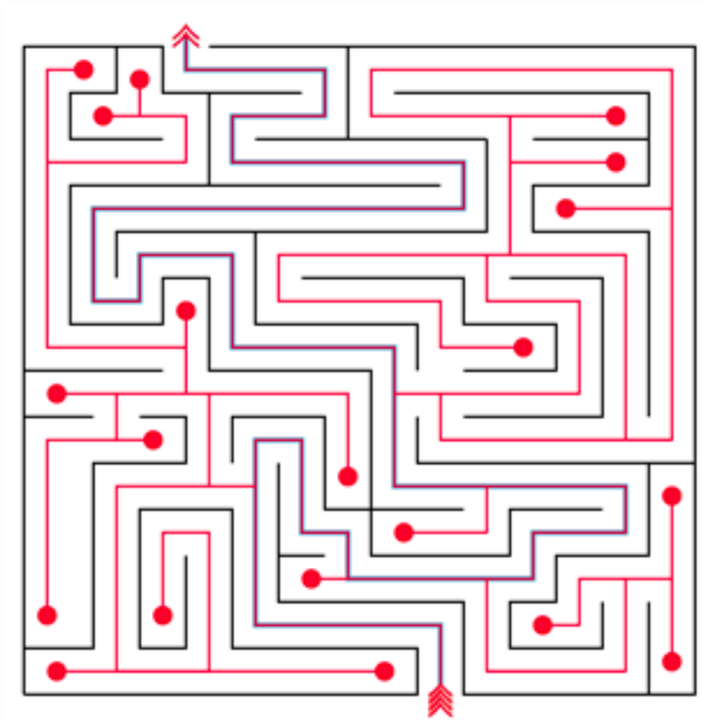
- The space characterizing a quantum computer grows exponentially with the number of qubits.
- N qubits → aspects of 2^N components at the same time (a superposition state)
- A single operation on a single qubit can effectively shuffles the individual probability amplitudes amongst all of qubit configurations making up a quantum superposition state. This is an example of quantum parallelism.

Quantum Interference (entanglement)

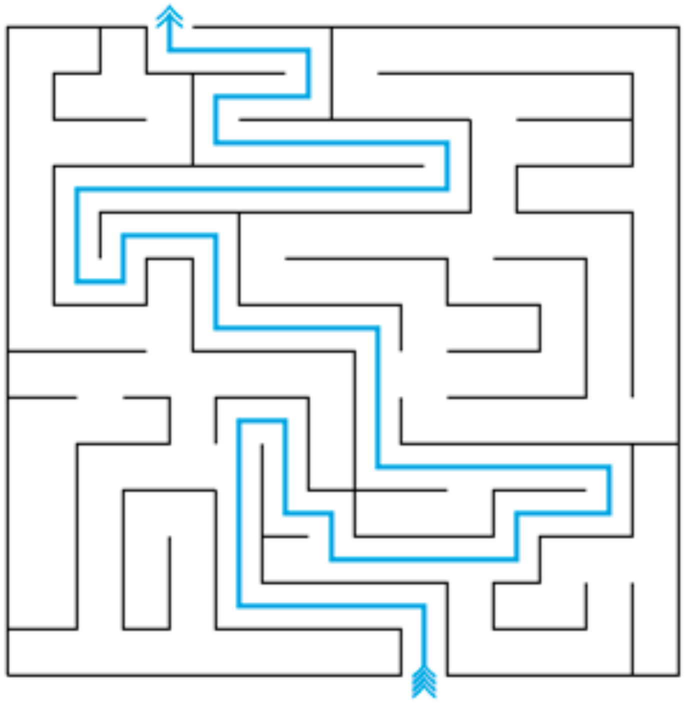
- The state of one or multiple qubits can be related to and affect each other.
- The probability amplitudes add and subtract one another (complex numbers).
- This is a purely quantum mechanical phenomenon.



EXPLOITING QUANTUM PARALLELISM AND INTERFERENCE



A classical computer has to look at each path through the maze

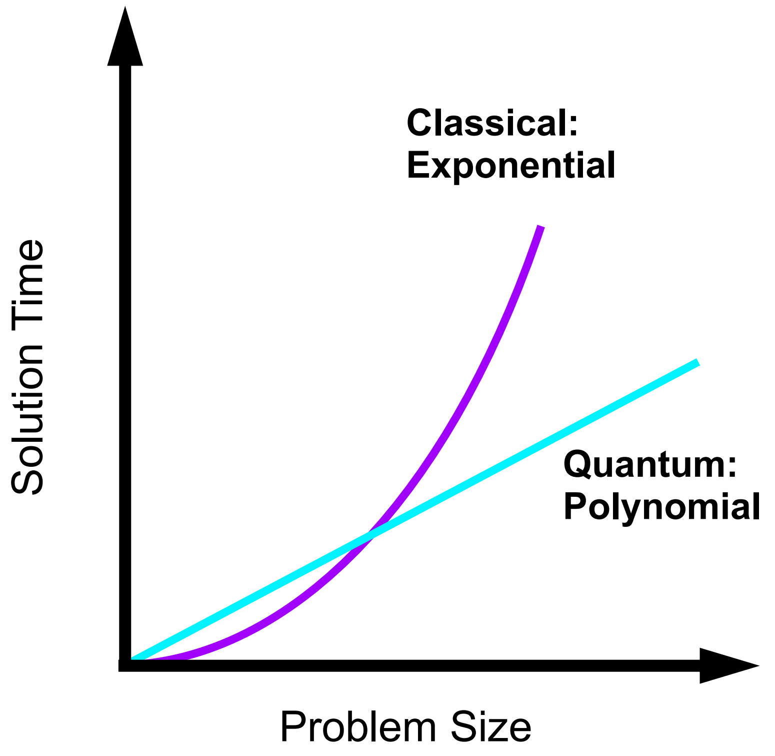


A quantum computer looks at the maze holistically and the shortest path emerges

QUANTUM ADVANTAGE

- Exponential or quadratic speedup.
- It requires quantum algorithms.

- Different categories of algorithms and different speedups.
  - Exact algorithms
  - Approximate techniques
  - Hybrid algorithms

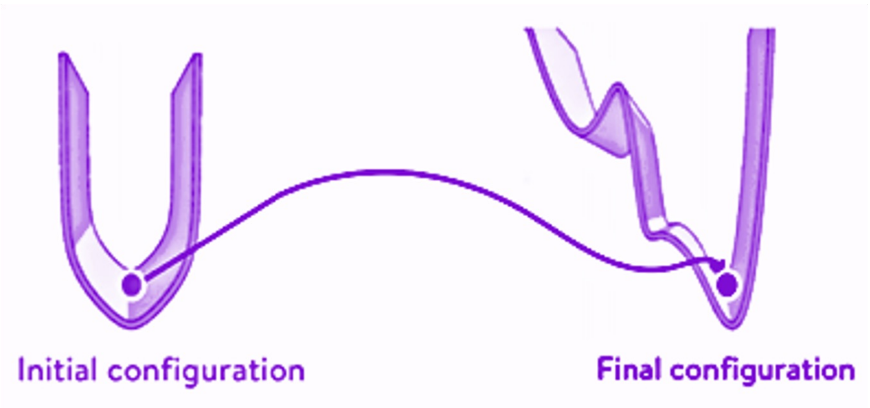


The promise of exponential speedup.

TWO MAIN TECHNOLOGIES

Adiabatic Quantum Computer

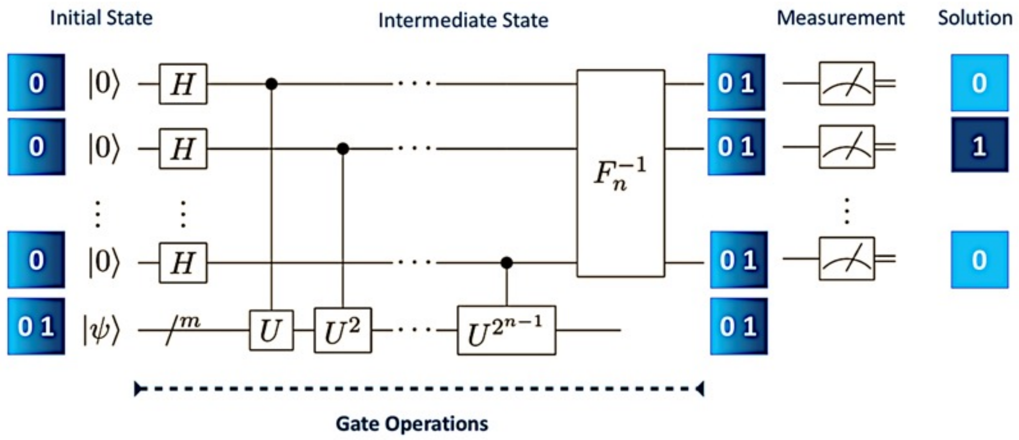
AKA. Quantum Annealing



D:WAVE
The Quantum Computing Company™
1QBit
Microsoft

Universal Quantum Computer

AKA. Quantum Gate Model



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intel
Google
Microsoft
IONQ
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3

Algorithms & Application Areas

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QUANTUM COMPUTING TECHNOLOGY STACK

LEVEL / STEP		EXAMPLE	TOOLS / METHOD		HINT
5	**BUSINESS PROBLEM SPECIFICATION**	FS Asset Portfolio Optimization			Requirements specification
4	**BUSINESS PROBLEM TRANSLATION** Mathematical Modeling	Risk Minimization Graph Coloring	**Problem-Specific Libraries:** Open Fermion, Qiskit Aqua		High-level libraries
3	**QUANTUM-FRIENDLY FORMULATION** Qubit Mapping, Algorithm Mapping	Amplitude Amplification, VQE, QFT, etc.	**Generic Languages:** pyQuil, Qiskit, Q#		Low-level libraries
2	**QUANTUM GATE MODEL CODE** Quantum Assembly, Hardware Description	Qiskit Implementation	**Circuit Schematic:** IBM Q, QASM, etc.		Assembly code or circuit schematic
1	**QUANTUM MACHINE CODE** Hardware Mapping		**Hardware Mapping:** QISKit, Rigetti Quilc, ARTIQ	**Hardware Execution:** QISKit, Labber	Executable
0	**QUANTUM COMPUTER** Hardware				Mainframe

MAJOR QC ALGORITHMS

1. Quantum phase estimation

- **Exponential speedup**
- **Shor's algorithm:** factorization of prime numbers
- **Quantum Fourier transform (QFT)**
- **Quantum algorithm for linear systems of equation**

2. Amplitude amplification

- **Quadratic speedup**
- **Grover's algorithm** searches an unstructured database

3. Quantum walk

- **Exponential speedup**
- Graph optimization algorithms.
- **Quantum Signal Processing**: linearize the operator of a quantum walk using eigenvalue transformation.

4. Quantum annealing (adiabatic/diabatic)

- Solving quadratic binary optimization, sampling from Ising model
- Available on near-term devices for larger problems than others
- Difficult to assess the speedup/advantage

5. Variational algorithms

- Based on variational principle
- Approximation algorithms such as VQE and QAOA
- They are hybrid quantum classical methods

It is difficult to invent a new quantum computing algorithm.

USE CASES IDENTIFIED BY ACCENTURE

Enterprise use cases exist across nearly every industry vertical.

We've identified 150+ use cases that could be disrupted or unlocked by quantum enhancement.

We've identified quantum algorithms for these use cases that have theoretical advantage.

Potential use-cases in products

Life science	Genome sequencing	Protein folding	Molecular modeling for drug discovery	MRT imaging	Radiation therapy	Healthcare data security	Pattern recognition in clinical studies
Retail & consumer goods & services	Autonomous vehicular delivery	Fertilizer modelling and design	Consumer recommendations	Business planning optimization	Transaction security	Forecasting weather and consumer behavior	Optimization in resource wastage
Automotive, Industrial & travel	Car-riding and airfare Planning and scheduling	Autonomous vehicles—security and computer vision	Fleet management/ inventory management	Aerodynamics and fluid mechanics simulation and design	Production process optimization—Job shop scheduling and robot arm movement	Truck dispatch and route optimization	Molecular modeling and material simulation in battery design

Potential use-cases in communication, media & technology

Communications & network practice	GSM networks	Mobile network design	Satellite operations	Quantum internet	authentication	6G wireless systems	Intelligent billing policy
Media, advertising & content	Advertisement recommendation in online services	Advertisement pricing	Content suggestions in streaming services	Business planning optimization	Complex behavioral analysis	Content management	Dynamic portfolio optimization
Software & platforms	Security in enterprise software platforms	Optimization in user task scheduling	Billing policy	User management	Business operations management	Advanced service offering	User behavioral analysis
High tech	VLSI design optimization	High-temperature superconductivity materials	Material design for aerospace carrier	Unmanned transportation	Robotic operations in manufacturing plants	Business operations management	Seismic imaging

Potential use-cases in health & public services

Health payers, providers, public health	Disease outbreak prediction	Patient procedure scheduling	Organ transplant pairing	Inventory management	Facility staff management	Healthcare data security	Fraud detection
Public services Safety, defense, boarder services	Fraud detection	Crime prediction	Material discovery for armed forces equipment	Task force allocation & dispatch	Intelligence information security	Automatic screening homeland security	Patrol assignments
Public services Global cities, post & parcel	Staff scheduling	Service quality improvements chat bots	Infrastructure planning and optimization	Last mile route optimization	Robot management in delivery facilities	Intercity quantum internet	Residential information security
Public service Pensions, revenue	Investment allocation	Risk management	Fraud detection	Dynamic portfolio management	Market forecasting	Capital budgeting	Correlation & causality analysis

Potential use-cases in resources

Chemicals & natural resources	Molecular interaction simulation	Nitrogen fixation	Molecular energy	New material design	Spectroscopy	High-temperature superconductors	Quantum emulation
Energy	Electricity trading	Field development	Extraction of petroleum	Electrical grid optimization	Solar cell design	Generator commitment	Gasoline blending
Utilities	Service grid optimization	Service vehicle scheduling	Waste recycling and cleansing	Staff management	Quantum internet services	Fraud detection	Data protection

Potential use-cases in financial services

Banking	Credit scoring classification	Portfolio optimization	Mobile banking transactions	Business operations management	Risk assessment	Fraud detection	Mortgage Behavior Analysis
Capital markets	Secure information transfer	Capital budgeting	Market data analysis	Convertible bond valuation	Correlation & causality analysis	Risk assessment	Share distribution
Insurance	Insurance behavior classification	Business operations management	Predictive analytics & forecasting	Big data analysis	Risk management	Liability management	Product recommendation

Potential use-cases in Accenture Federal

Defense				Inventory management	Facility staff management		
Civilian	Fraud detection	Crime prediction	Material discovery for armed forces equipment	Task force allocation & dispatch	Intelligence information security	Automatic screening in homeland security	Patrol assignments
Safety and citizen services	Staff scheduling	Service quality improvements chat bots	Infrastructure planning and optimization	Last mile route optimization	Robot management in delivery facilities	Intercity quantum internet	Residential information security

Optimization Machine learning Simulation/sampling Cryptography

Quantum computing as a path to solve intractable problems

Many problems in business and science are too complex for classical computing systems

Today the problems that QC has the potential to solve, group together in three broad are

MACHINE LEARNING

(e.g., regression, clustering, classification)

OPTIMIZATION

(e.g., traveling salesman, bin packing, integer programming)

SIMULATION

(e.g., chemistry, material science, physics simulation)

CRYPTOGRAPHY

While QC will **solve many business problems**, there is an **associated threat** with the technology that will make conventional encryption more **vulnerable to attack**. Post-quantum cryptography will offer **stronger encryption**, protecting businesses and consumers.

OPTIMIZATION

There are many intractable optimization problems due to complexity or time sensitivity.

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What is matheatical optimization?

There are many intractable optimization problems due to complexity or time sensitivity.

Finding a global solution to a non-convex optimization problem can become intractable.

Mathematical optimization is the building block of many other algorithms.

Continuous (Real) Optimization

- Linear programming, Quadratic, Semidefinite programming, Non-convex, etc.

Discrete (Combinatorial) Optimization

- Graph algorithms and heuristics, Mixed integer programming, QUBO, etc.

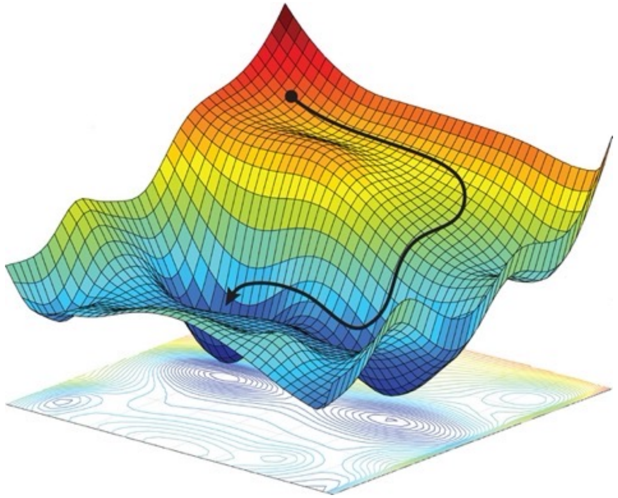


Image source: Amini, Alexander, et al. "Spatial uncertainty sampling for end-to-end control." *arXiv preprint arXiv:1805.04829* (2018).

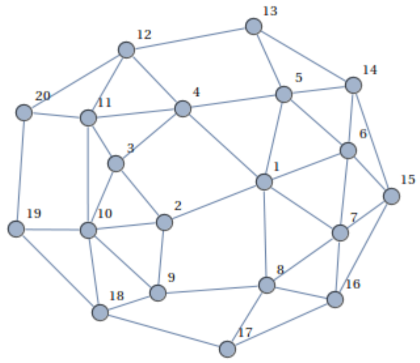
Quantum Optimization Methods

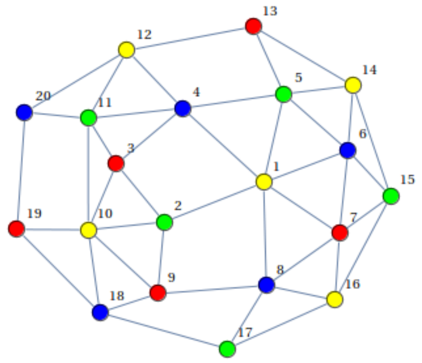
Quantum Optimization Methods

- **Quantum Annealing**
- **Quantum Semidefinite Programming**
- **Quantum Least Squares Fitting (HHL)**
- **Quantum Approximate Optimization Algorithm (QAOA)**
- **Variational Quantum Eigensolver (VQE)**
- **Amplitude Amplification: Grover's algorithm**
- **Quantum Walks: Graph optimization algorithms.**
- **Quantum Phase Algorithm and Quantum Fourier transform**

Example: Portfolio Optimization

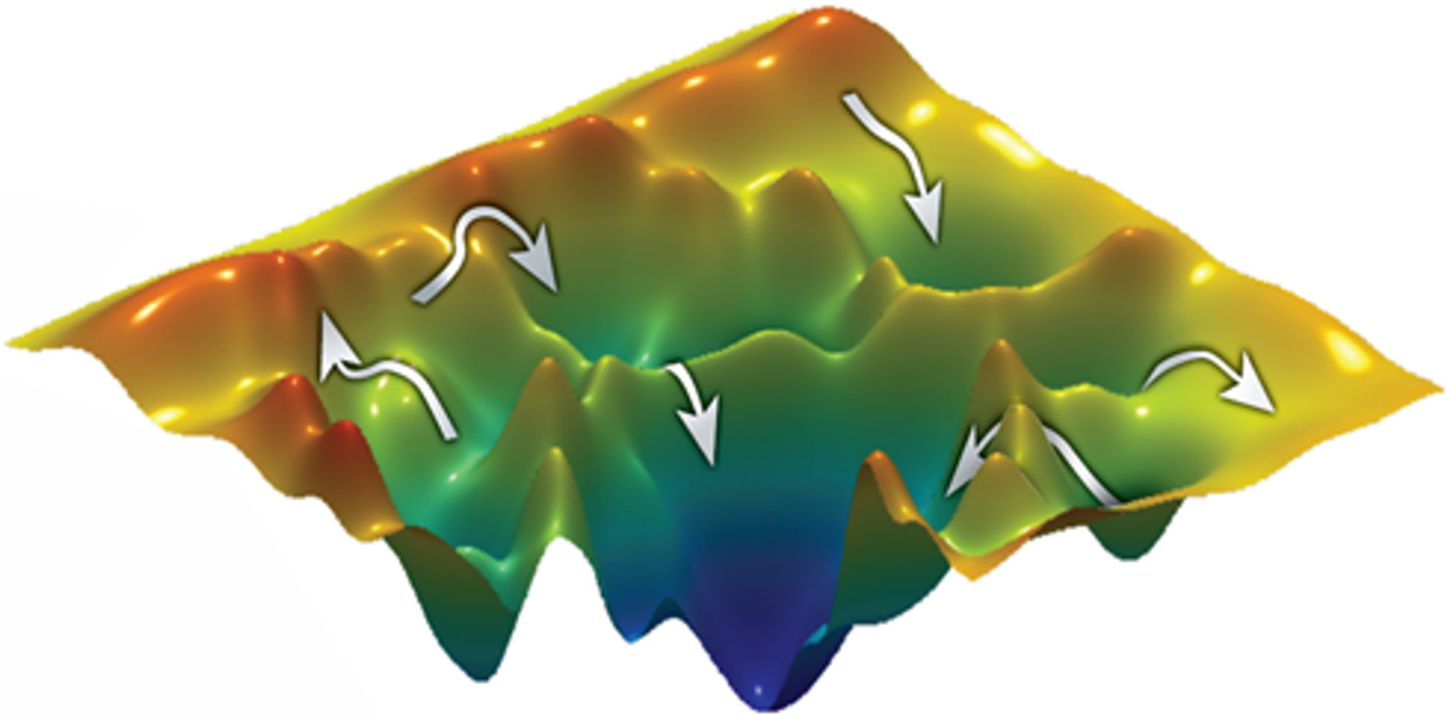
- In order to minimize investment risk, find sets of assets that are minimally correlated.
- Formulated as a graph coloring problem.
- Converted to QUBO and solved using a quantum annealer.





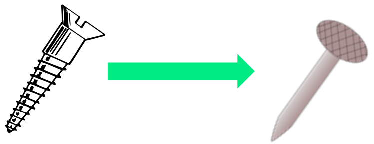
Qunatum Annealing

Annealers: solve very narrow problem type really well



Where's the lowest point?

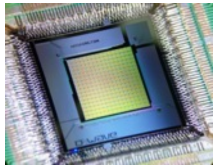
$$\text{minimize} \sum_{ij} q_{ij} x_i x_j$$

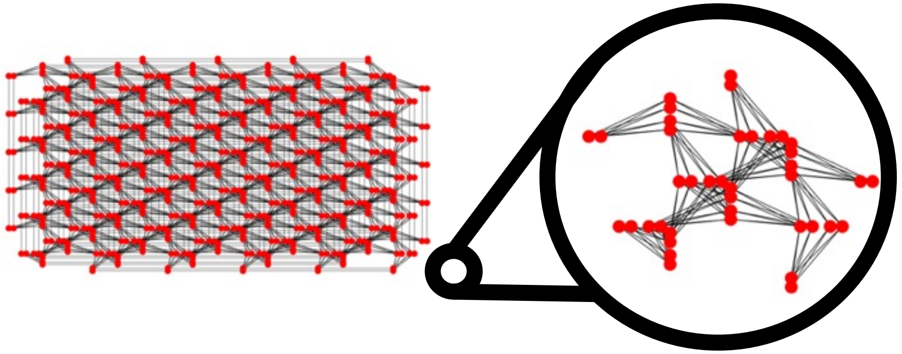


https://physics.aps.org/

Quantum Annealing Example

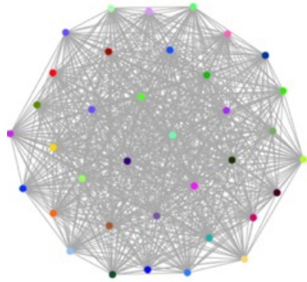
https://link.springer.com/chapter/10.1007/978-3-030-50743-5_10



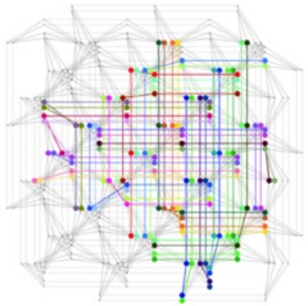


D-Wave Quantum Chip
(Red dots are qubits)

Navigation,
lots of possible
paths

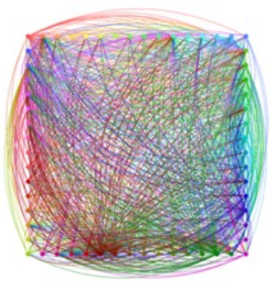


Information
(ex. possible
transit routes)

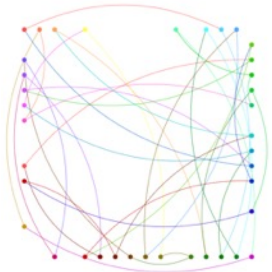


Information
on the chip,
Run to find best route!

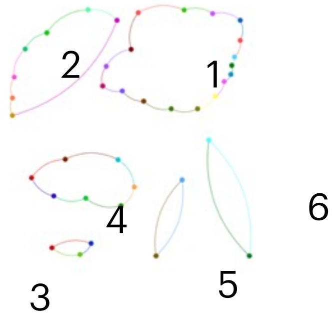
Kidney Exchange Network Optimization



Sample Kidney Exchange Model
- 60 nodes and 1032 directed edges
- 1092 binary variables in the QUBO formulation



Runtime
- Solved using D-Wave Hybrid
- LeapHybridSampler solver runtime of 4.036 second



Solution
- 6 clusters (17, 7, 7, 3, 2, 2)
- 38 donor/recipient pairs matched (63% of participants)

MACHINE LEARNING

Simulating nature at its finest level to enable innovations in chemistry, physics, biology, drug design, and material science

accenture

QUNATUM MACHINE LEARNING

Different categories of QML:

CC Classical Data ➔ Classical Algo.	**CQ** Classical Data ➔ Quantum Algo.
QC Quantum Data ➔ Clasical Algo.	**QQ** Quantum Data ➔ Quantum Algo.

Optimization methods are the building blocks of machine learning.

Challenges:

- **Data Input: cost of loading data, no QRAM yet.**
- **Data Output: probabilistic measurement, cost of sampling**
- **Algorithm Speedup: how to perform better than best classical methods**

QUNATUM MACHINE LEARNING METHODS

Quantum Computing Methods

1. Amplitude Amplification
2. Adiabatic Optimization
3. Block Encodings
   - HHL algorithm for a linear system of equations
4. Variational Methods (Hybrid)

Machine Learning Models

Quantum Support Vector Machine

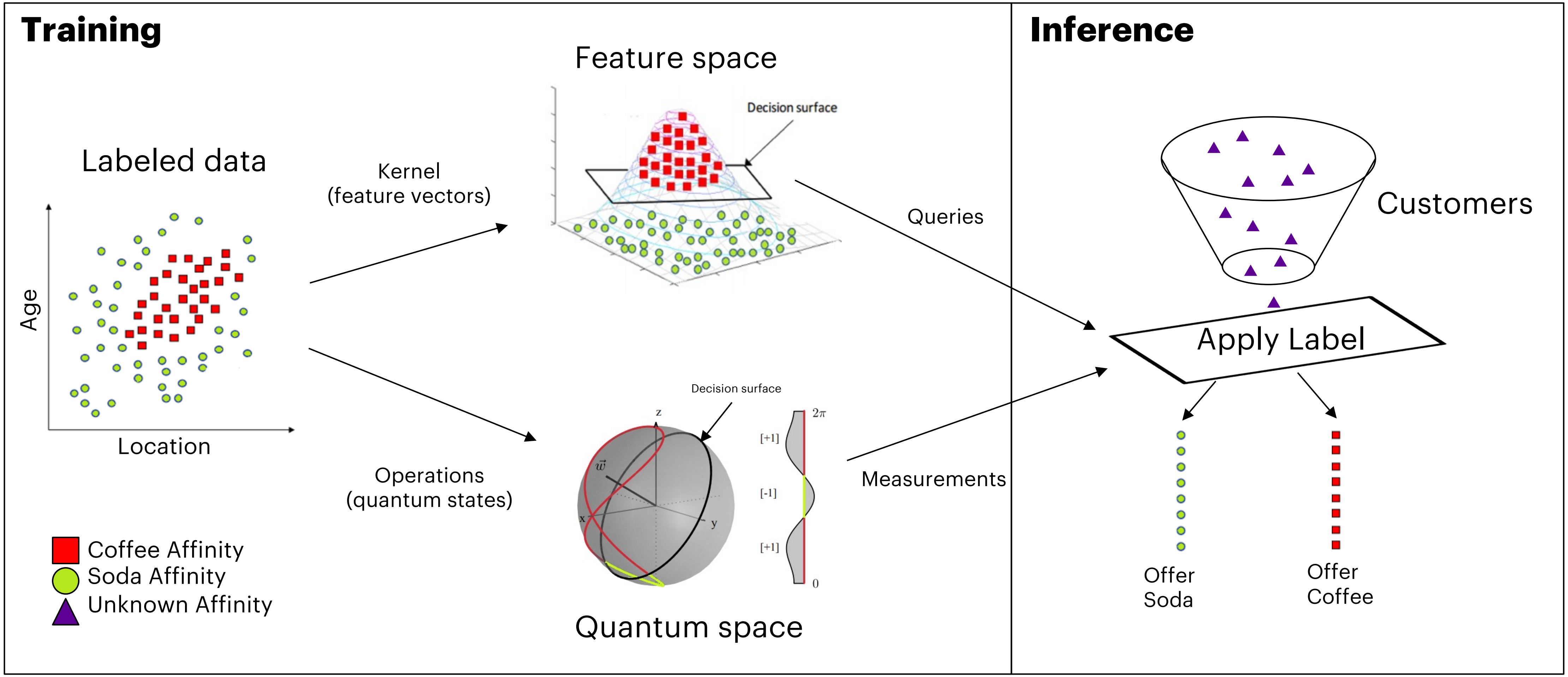
Quantum Neural Network (QNN)

Quantum Regression Methods

Quantum Probabilistic Models

- Factor Graphs / Bayesian Networks
- Quantum Boltzmann Machine
- Quantum Born Machine

MACHINE LEARNING EXAMPLE: QUANTUM SVM

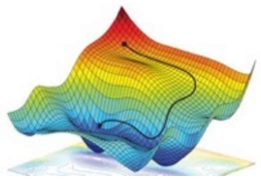


MACHINE LEARNING EXAMPLE: QUANTUM NEURAL NET (RBM)

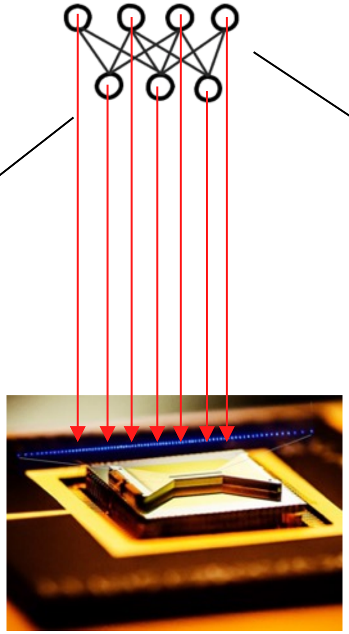
Training

Images
(Handwritten digits,
pre-processed)

Compute gradient and apply
gradient descent



Model (DNN)

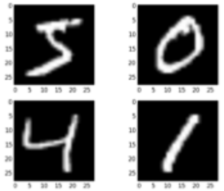


Use samples from the model to re-compute
and improve the model

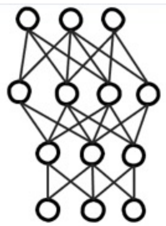
Classical: contrastive divergence (not efficient)

Quantum: embed model to quantum processor then measure (the nodes on the neural network map to logical qubits)

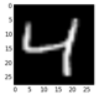
Inferencing



Handwritten
Digits

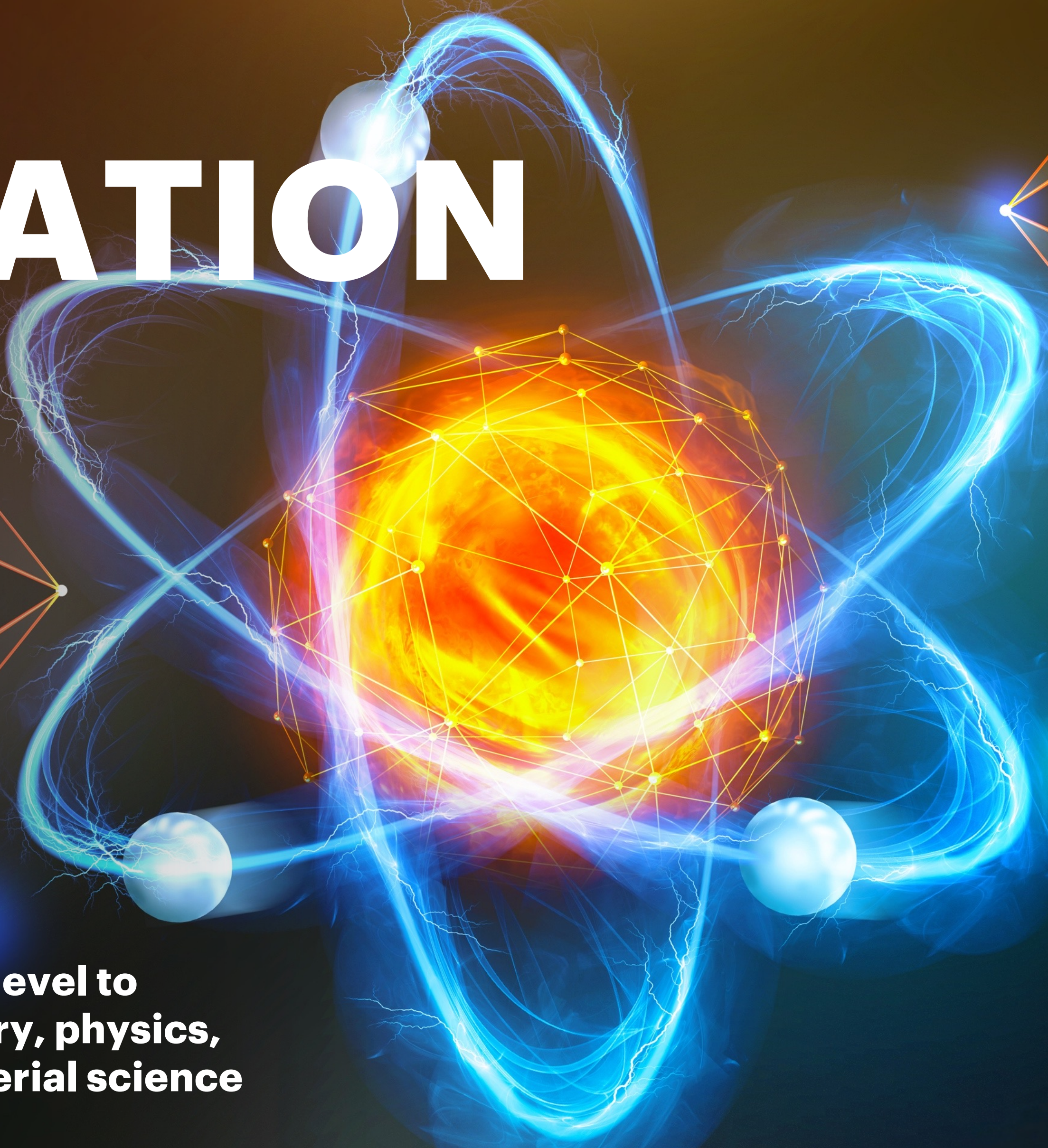


Classification
with Deep
Neural Network



It's a four!

SIMULATION



Simulating nature at its finest level to enable innovations in chemistry, physics, biology, drug design, and material science

accenture

WHAT IS QUANTUM CHEMISTRY?

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical"

RICHARD FEYNMAN

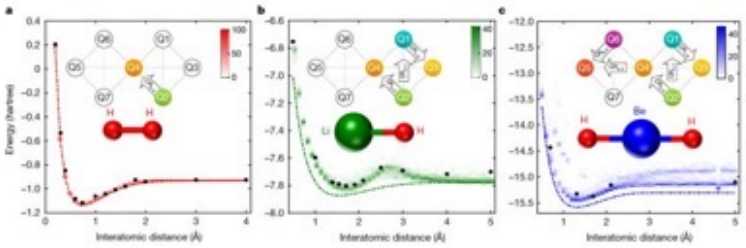
Quantum chemistry involves studying the electronic structure and dynamics of molecules using quantum mechanics.

This is a natural problem for quantum computers.

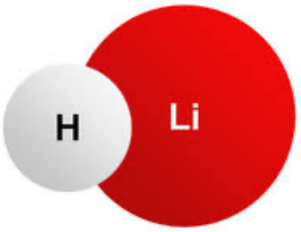
"A typical goal is to **solve the molecular electronic structure problem** for the ground-state energy of a molecular system.

Chemistry Simulation Example

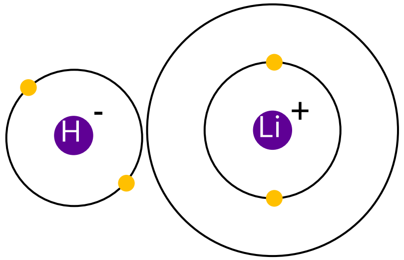
Certain chemistry problems map directly to quantum systems because they are also quantum systems!



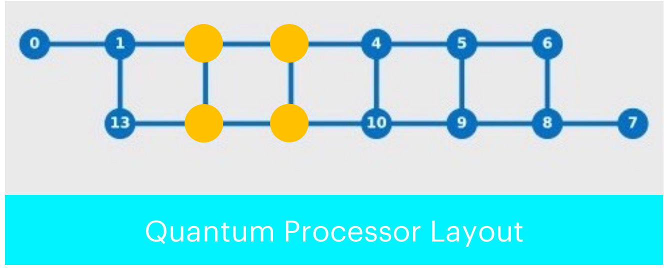
https://www.ibm.com/blogs/research/2017/09/quantum-molecule/



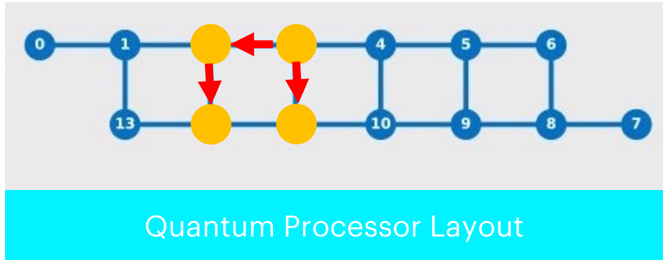
Lithium Hydrate Atoms



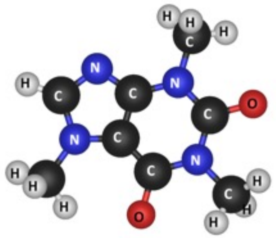
4 Electrons



Map Electrons to Qubits



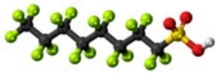
Run Simulation



Caffeine

31 Electrons

Currently impossible

PFAS 

Benefits:

- New materials
- New drugs
- More efficient reactions
- Lower costs to production

VARIATIONAL QUANTUM EIGENSOLVER

Time-independent Schrödinger Equation:

$$\hat{H}|\Phi\rangle = E|\Phi\rangle$$

$\hat{H}$ is a Hermitian operator and E is a real value.

Example: $\hat{H}$ can be the fermionic Hamiltonian for electronic-structure problem.

Variational principle and variational method.

The optimization problem to find the ground state of a Hamiltonian:

$$E_0 = \min_{|\Phi\rangle \in \mathcal{H},\ \langle\Phi|\Phi\rangle = 1} \langle\Phi|\hat{H}|\Phi\rangle$$

- Variational quantum eigensolver (VQE)

In summary, the linear variational method is a procedure for finding the best possible approximate solutions to the eigenvalue problem

$$\mathscr{H}|\Phi\rangle = \mathscr{E}|\Phi\rangle \qquad (1.172)$$

given a fixed set of orthonormal functions $\{|\Psi_i\rangle, i = 1, 2, \ldots, N\}$. The procedure entails forming the matrix representation of the operator $\mathscr{H}$ in the finite basis $\{|\Psi_i\rangle\}$, i.e. $(\mathbf{H})_{ij} = \langle\Psi_i|\mathscr{H}|\Psi_j\rangle$ and solving the matrix eigenvalue problem

$$\mathbf{H}\mathbf{c} = E\mathbf{c} \qquad (1.173)$$

that is, diagonalizing the $N \times N$ matrix $\mathbf{H}$.

We derived this result by explicitly minimizing the expectation value of the Hamiltonian. However, we can obtain Eq. (1.173) in an alternate way, which we will find useful. In an attempt to solve (1.172), let us approximate $|\Phi\rangle$ as

$$|\Phi\rangle = \sum_{j=1}^{N} c_j|\Psi_j\rangle \qquad (1.174)$$

and substitute this expansion into (1.172)

$$\sum_j c_j\mathscr{H}|\Psi_j\rangle = \mathscr{E}\sum_j c_j|\Psi_j\rangle \qquad (1.175)$$

Multiplying (1.175) by $\langle\Psi_i|$ on the left and replacing $\mathscr{E}$ by E as a reminder that the expansion (1.174) is approximate, we find

$$\sum_j c_j\langle\Psi_i|\mathscr{H}|\Psi_j\rangle = E\sum_j c_j\langle\Psi_i|\Psi_j\rangle = Ec_i$$

or

$$\sum_j H_{ij}c_j = Ec_i \qquad (1.176)$$

which in matrix notation is identical to Eq. (1.173). If we had used a *complete* orthonormal basis $\{|\Psi_i\rangle, i = 1, 2, \ldots, N, N+1, \ldots\}$, we would have obtained an equation identical to (1.173) except, of course, $\mathbf{H}$ would have been an infinite matrix. The eigenvalues of this matrix are exactly equal to the eigenvalues of the operator $\mathscr{H}$. Thus the linear variational method is equivalent to solving the eigenvalue equation, (1.172) in a finite subspace spanned by $\{|\Psi_i\rangle, i = 1, 2, \ldots, N\}$.

Szabo, Attila, and Neil S. Ostlund. *Modern quantum chemistry: introduction to advanced electronic structure theory*. Courier Corporation, 2012.

Communication, Sensing, Metrology

QUANTUM INFORMATION & QUANTUM CONTROL

Qunatum computing

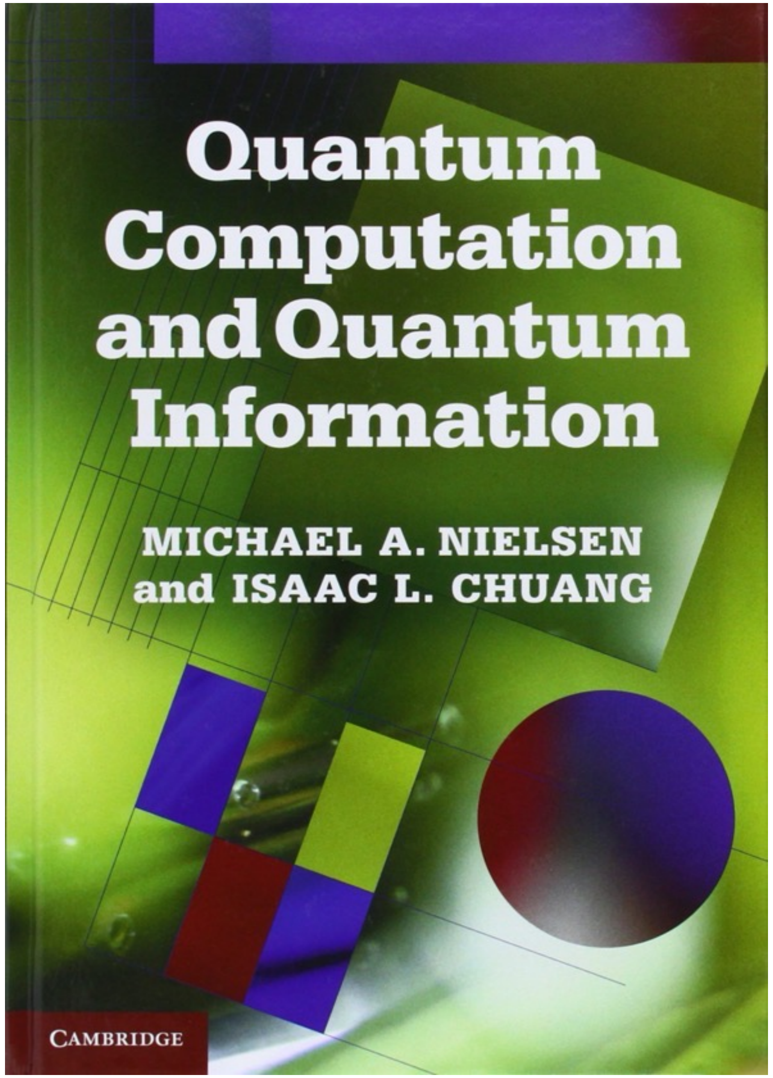
- Using quantum effects to perform computation.

Qunatum information theory

- Analysis, processing and transmission of information with quantum effects.
  - E.g., Quantum Error Correction, Quantum Communication

Qunatum control theory

- Control of physical systems that have quantum behavior.
  - E.g., building quantum computing devices
  - Dong, Daoyi, and Ian R. Petersen. "Quantum control theory and applications: a survey." IET Control Theory & Applications 4, no. 12 (2010): 2651-2671.



Quantum Communication & Cryptography

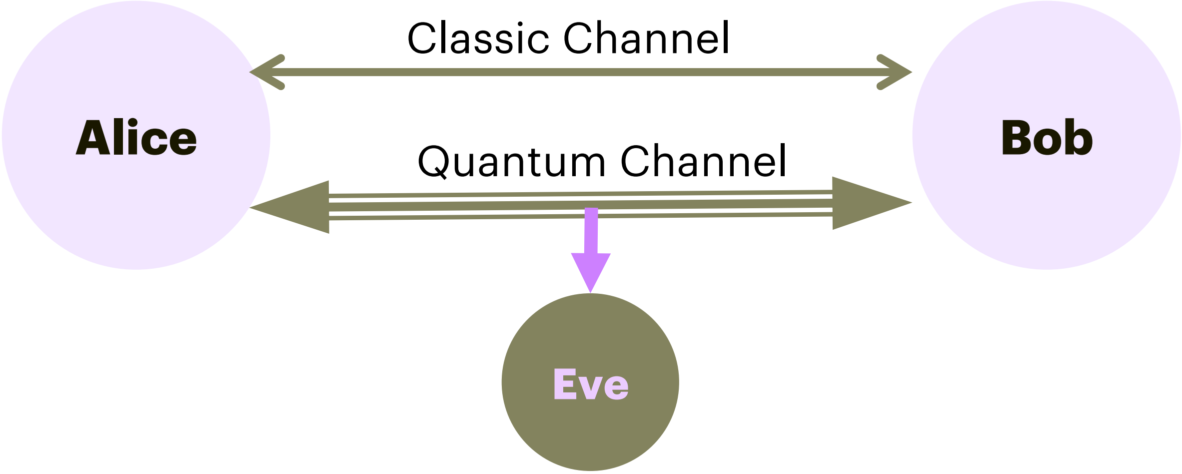
Quantum communication transfers a quantum state from one place to another.

- **Quantum Channel (capacity, fidelity, etc.)**
- **Entanglement Forging, Quantum Networks**

Cryptography Threat: Shor's algorithm on a large QC can break **RSA cryptosystem.**

Quantum key distribution (QKD)

- Entanglement provides a mechanism to distribute tamper proof encryption keys.
- Currently available over long distances.



Example: BB84 protocol, Charles H. Bennett and Gilles Brassard (1984)
The security of the protocol comes from **encoding the information in non-orthogonal states**.

Quantum Sensing and Metrology

Using quantum mechanical effects for precise measurement. [Not very new]

A large variety of quantum sensors have been developed for a wide range of applications.

- Quantum Magnetic Imaging, Neuro-Imaging
- Quantum Gravity Sensors
- Quantum Radar
- Photonic sensors, microscopy, gravitational wave detectors
- Atomic Clocks, Magnetometers, etc.

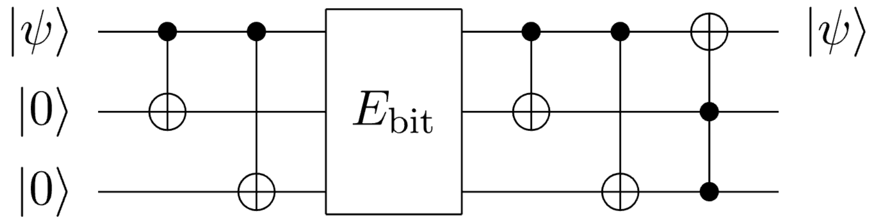
Fault-tolerant qunatum computing

Quantum information is prone to errors due to decoherence and noise.

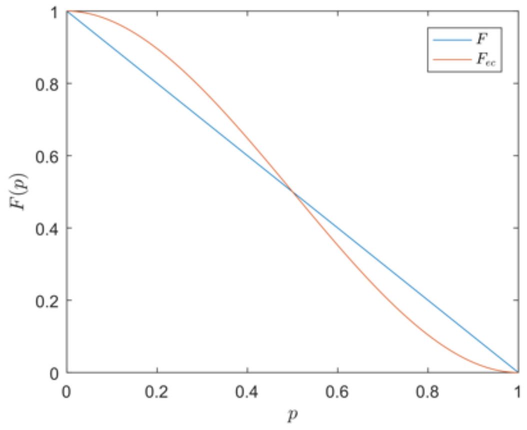
Quantum error correction codes are different.

For example, copying quantum information is not possible due to the no-cloning theorem.

Quantum error correction (QEC) enables fault-tolerant quantum computation by making elementary operations meets a certain fidelity threshold.



Quantum circuit of the bit flip code



Output fidelities with and without error correction via three qubit bit flip code.

Lidar, Daniel A., Isaac L. Chuang, and K. Birgitta Whaley. "Decoherence-free subspaces for quantum computation." Physical Review Letters 81, no. 12 (1998): 2594.

4

Quantum Ecosystem & Accenture

NORDIC QC LANDSCAPE

SOME MAJOR PLAYERS (NOT ALL-INCLUSIVE)

Wallenberg Center for Quantum technology, Sweden

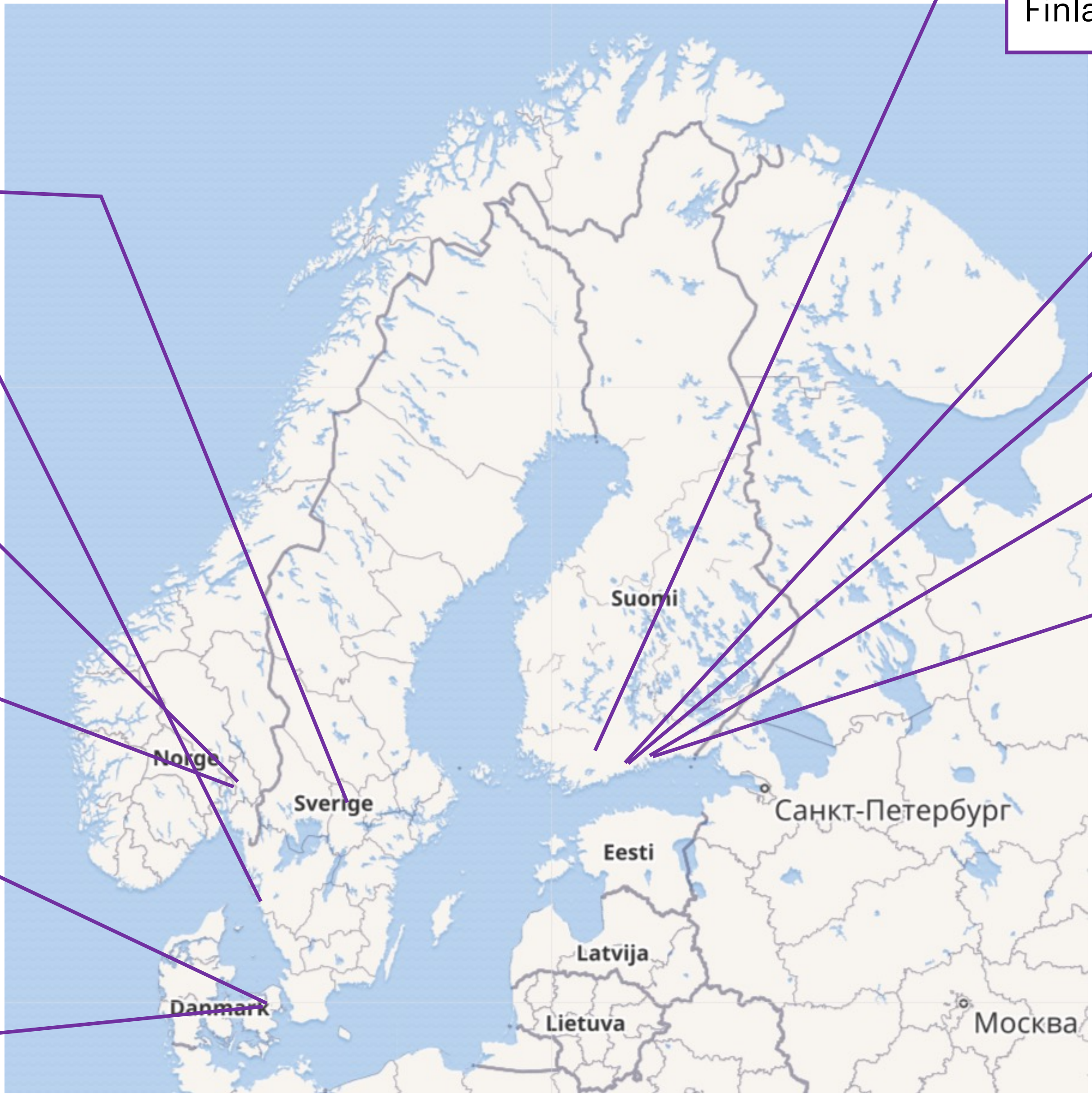
Quantum Technology Laboratory, Chalmers University Gothenburg

Simula/OsloMet, Simula Research Lab, Oslo

Nordic Quantum Computing Group, Oslo

Nils Bohr Institute, Copenhagen

Center for Quantum Technology - DTU, Lyngby



Center of Excellence – Quantum Technology Finland

IQM, Espoo

VTT, Espoo

Centre for Quantum Engineering, Espoo

Bluefors, Helsinki

ROADMAP

https://databaseline.tech/quantum.html

Quantum Advantage Found

Advantage Unlocks Across Industries and Use Cases

TODAY | 2020 | 2025 | 2030 | 2035

Educate and **build software** for future quantum advantages

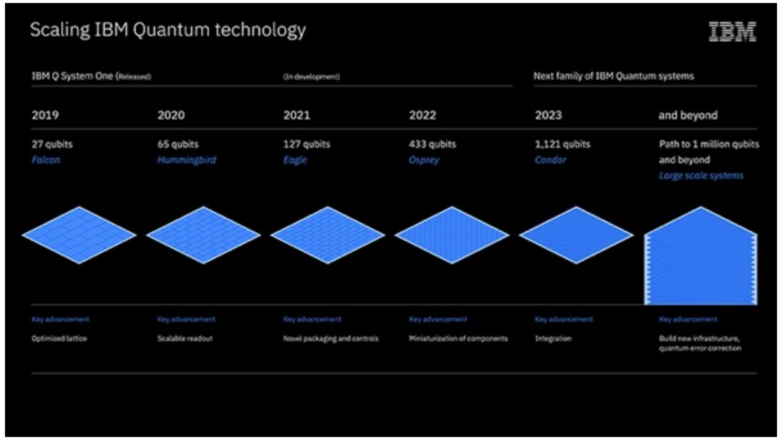
First real-world applications arrive simulating new materials and chemicals

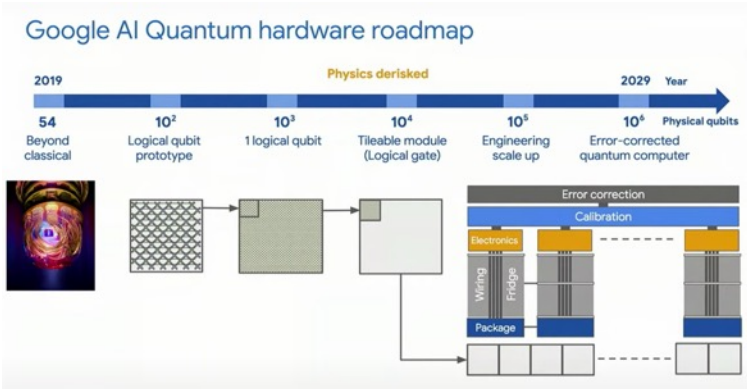
Quantum optimization techniques **viable** for financial trading

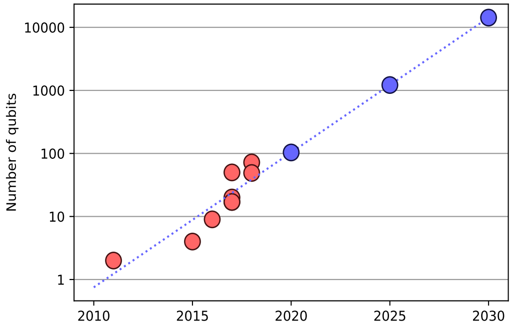
Quantum **supply chain optimization** redefines global manufacturing and trade strategies

Quantum machine learning **supersedes classical approaches**

Quantum computers break security and are capable of decrypting any data that is not using quantum resistant encryption







Superconducting quantum computing growth

accenture

QC HARDWARE ECOSYSTEM

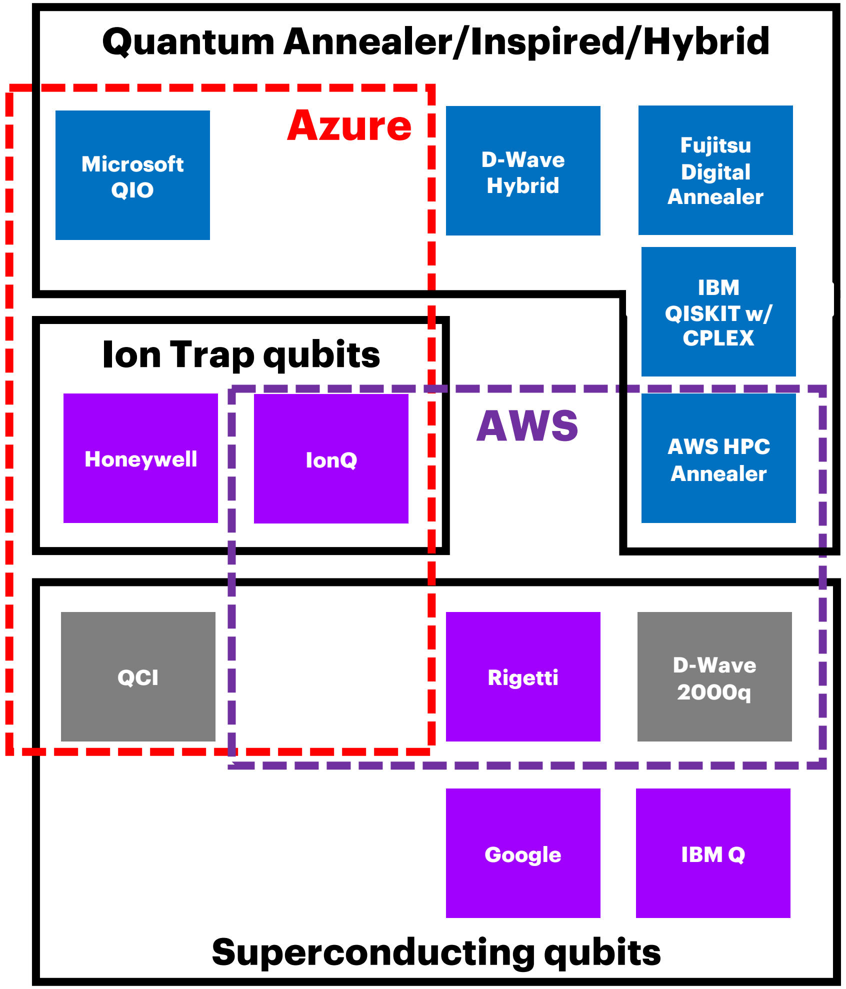
Hardware is in the cloud

Costs vary per vendor between $.5-$1.5 a query. A typical entry level agreement can be roughly $50,000 for roughly 24 hours worth of runtime. Some vendors require a longer-term commitment.

Most software toolkits have amenable open-source licenses however there are methods which could require additional teaming and costs. These factors are included in the selection process before starting the Proof of Concept.

Illustrative Quantum HW Ecosystem

Aug 2020



Focus on Now or Future?

Tactical: Access to only one device is required for a quantum business experiment.

Long Term: Access to at least one purple and one blue system for quantum program coverage considered.

KEY:

Solve complex business optimization problems today

Universal (gate model) computers: Research and learn about provable quantum speed up for future business cases

Use case specific

Quantum Stack

Creating QC applications requires technology across many parts of the ecosystem.

The Q Stack

Multidisciplinary approach to quantum development

Most enterprises need to focus on the top and middle of the stack.

New skills needed:

- Industry Expertise
- Delivery Leadership
- Service Designers
- System Architects
- Quantum Integrators
- Quantum Info Scientists

Frontend UI (React or Angular – *No change in skills*)

- **Select Tests**
- **Run Tests**
- **Add Test**
- **Select Device**

Backend Service (Node.js – *Learn new libraries*)

- **Algorithm Selection**
- **Execution Code**
- **Application Orchestrator**
- **Database / Cache (data model)**

API (Python / C – *Understand Quantum Methods*)

- **Select System**
- **Parameters**
- **Call Function**
- **Return Result**

1QBit Forest Leap <Q#> Cirq PENNYLANE Qiskit STRANGE WORKS

Quantum Computation Hardware

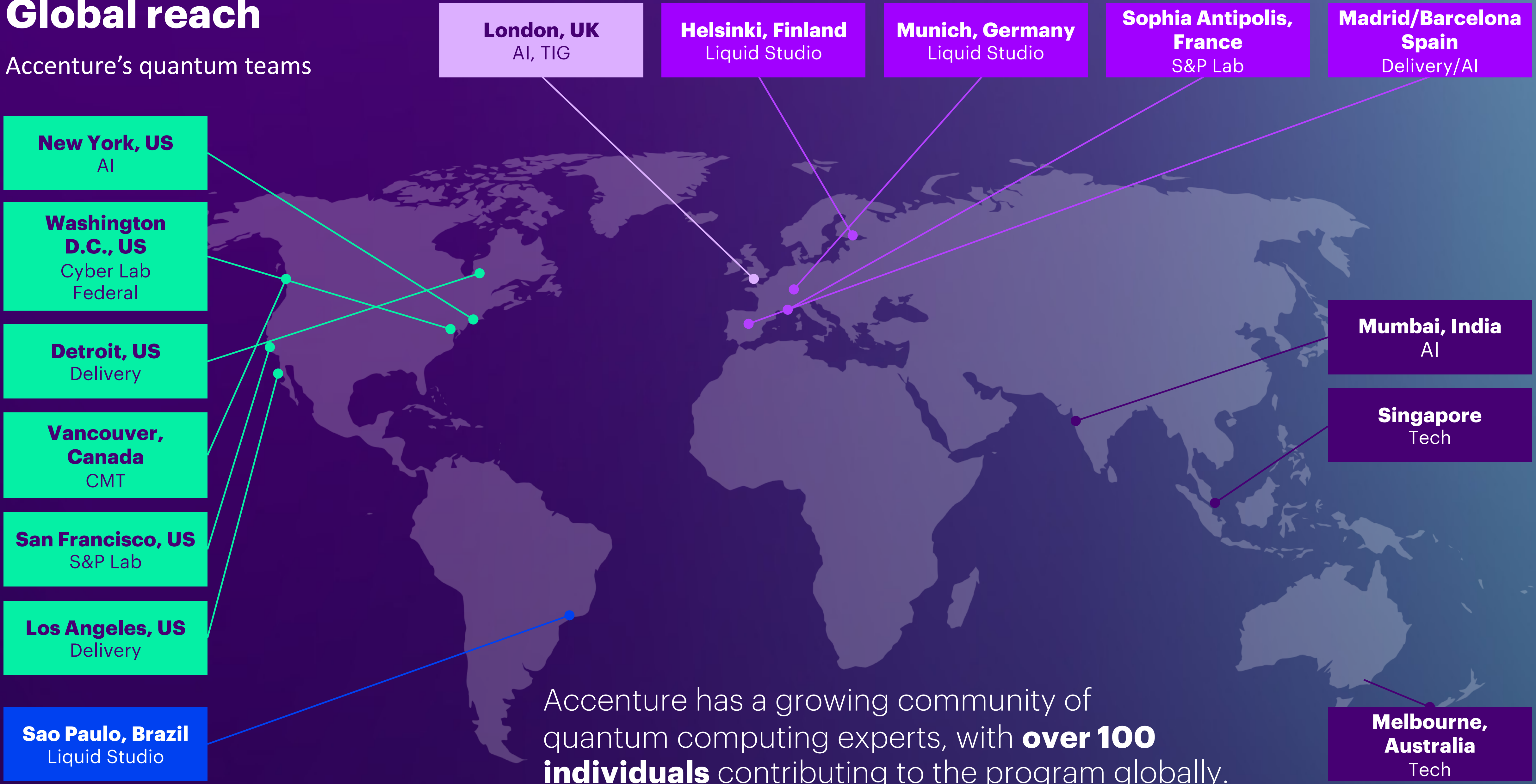
IBM D-Wave intel Honeywell rigetti Google IONQ

Classical Compute Alternatives

Microsoft

Global reach

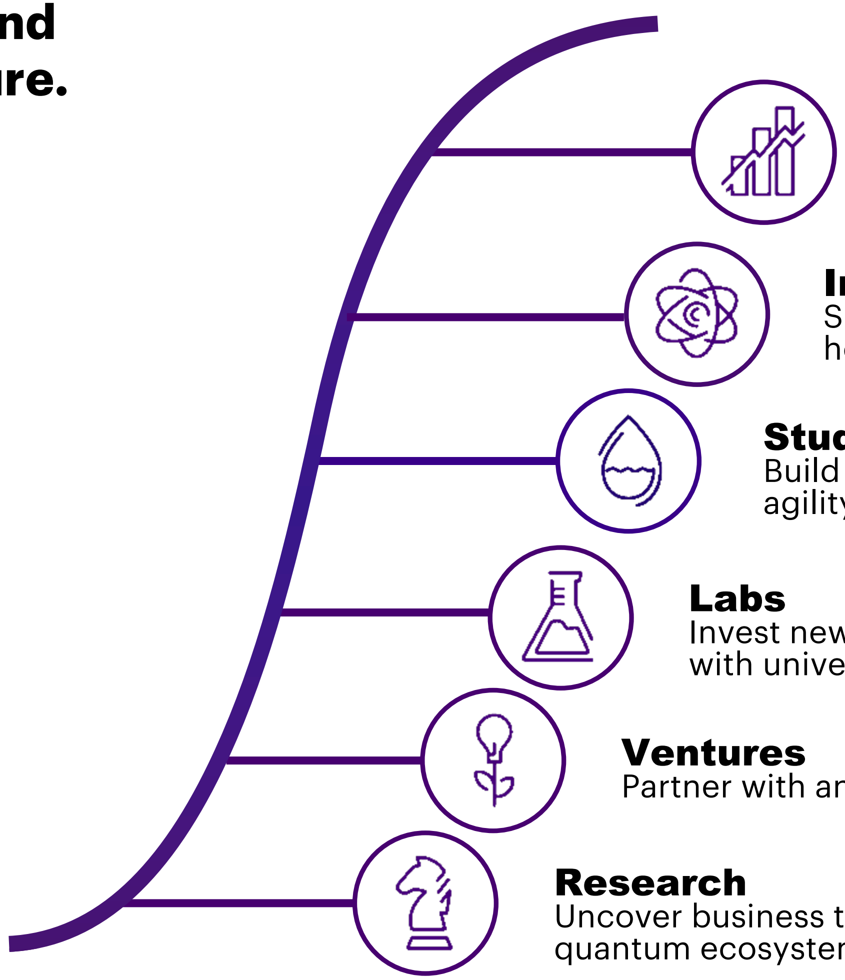
Accenture's quantum teams



Accenture has a growing community of quantum computing experts, with **over 100 individuals** contributing to the program globally.

Quantum @ Accenture: the Innovation Architecture

Accenture's Quantum Program is designed around our Innovation Architecture.



Delivery Centers
Deliver quantum-inspired projects at scale globally

Innovation Centers
Showcase the latest quantum tech, educate, host events and working teams

Studios
Build quantum prototype solutions with speed and agility

Labs
Invest new quantum methods, discover use cases, work with universities and corporate R&D

Ventures
Partner with and invest in growth-stage companies

Research
Uncover business trends and shape data-driven insights into the quantum ecosystem

 59

Since 2010 Accenture has been exploring Next Generation Computing methods and application in real-world scenarios

Accenture Technology Innovation - Next Generation Compute Group

Ecosystem

A market leader, connected to universities, vendors, and consortiums

People

100+ contributors from Accenture Labs, Ventures, Tech. Incubation, and Studios

Research

Large use case library, academic publications, and patent library

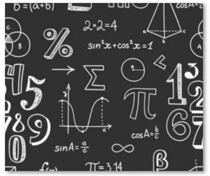
Industry

30+ pilot applications of quantum and next generation HPC across industries

Offerings

Innovative offerings from first steps to scaled up programs

Analytics



Quantum

HPC

Simulations

Neuromorphic

Collective AI

Key Solution Areas

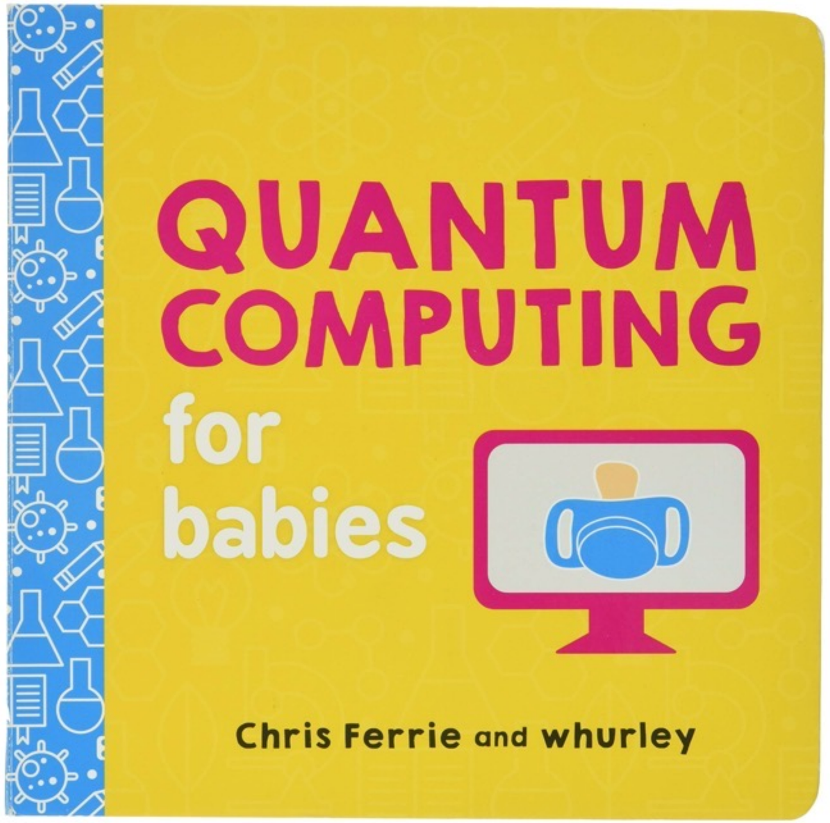
- Mathematical Optimization
- Machine Learning
- Simulations

Digital R&D Technology Stack

Domain Knowledge	Industry, Business	Industry & Business Problem Analysis			
Domain Knowledge	Science, Technology	Chemistry (organic, inorganic, quantum)	Biology, Life Sciences	Digital Twin, Operations Research	Sustainability, Circular Economy
Technical Expertise	Methods, Platforms	Optimization (Mathematical Programming)	Scientific Simulation , Mathematical Modeling	Machine Learning, Data Science, Automation	
Technical Expertise	IT, Compute	IT Infrastructure & Next Generation Computing			

Conclusions

- **Qunatum computing is a large and diverse field.**
- **It is still young. There is plenty of space for innovation, reaserch and development.**
- **You only need linear algebra to start with.**
- **Public sector and many private companies are heavily investing and building the ecosystem.**



THANK YOU