Alexandria Quantum Computing Group (AleQCG)

Day1: Introduction to Quantum Computing

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5th Summer School and Internship Programme at CTP
CTP - BUE (7-17 July 2025)

TECHNEWS

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TECHNOLOGY

Google's New Quantum Chip (Willow) Completes 10-Septillion-Year Tasks In Five Minutes

Google has built a new quantum computing chip (Willow) measuring 4cm squared that takes just five minutes to complete tasks that would take 10,000,000,000,000,000,000,000,000 years for some of the world's fastest conventional computers to complete. That's 10 septillion years.

Matthew Giannelis

Last updated: December 10, 2024 1:20 pm

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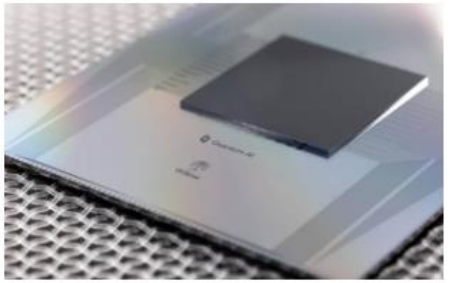
On Monday Google unveiled a ground-breaking quantum computing chip, "Willow," capable of solving problems in just five minutes that would take the world's fastest conventional supercomputers a staggering 10 septillion years—a number far beyond the age of the known universe.

Ten septillion years is a timescale that is longer than the universe is old, and the findings demonstrate for the first time that quantum computers are able to complete tasks beyond classical computers.



Tech Articles

- **Septillion**: 10^{24} (1,000,000,000,000,000,000,000,000)

System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
Frontier - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE Cray OS, HPE DOE/SC/Oak Ridge National Laboratory United States	9,066,176	1,353.00	2,055.72	24,607

Computing

China achieves quantum supremacy claim with new chip 1 quadrillion times faster than the most powerful supercomputers

News By Alan Bradley published March 13, 2025

This new superconducting prototype quantum processor achieved benchmarking results to rival Google's new Willow QPU.

Comments (0)

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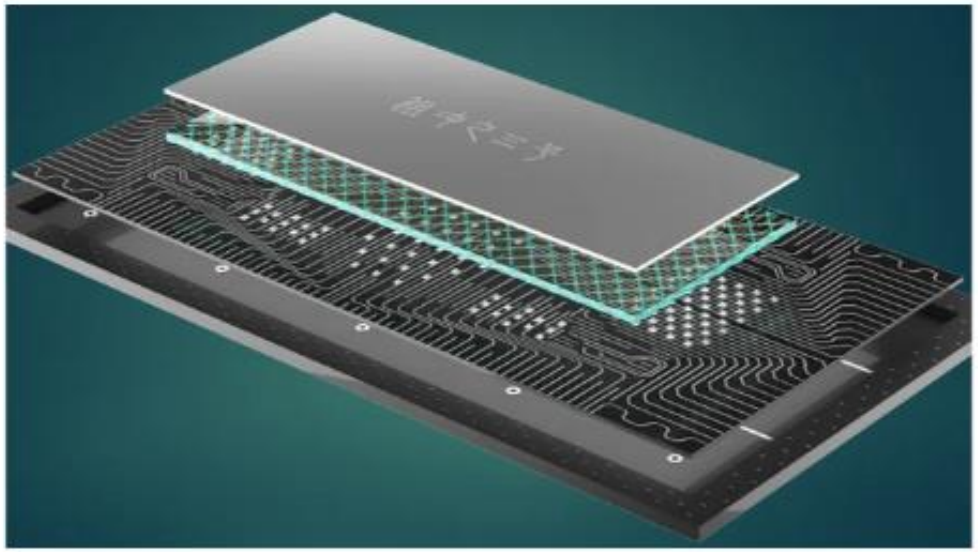


The latest iteration of Zuchongzhi includes 105 transmon qubits — devices made from metals like tantalum, niobium, and aluminum that have reduced sensitivity to noise. (Image credit: D. Gao et al. [2])

- **Quadrillion**: 10^{15} (1,000,000,000,000,000)

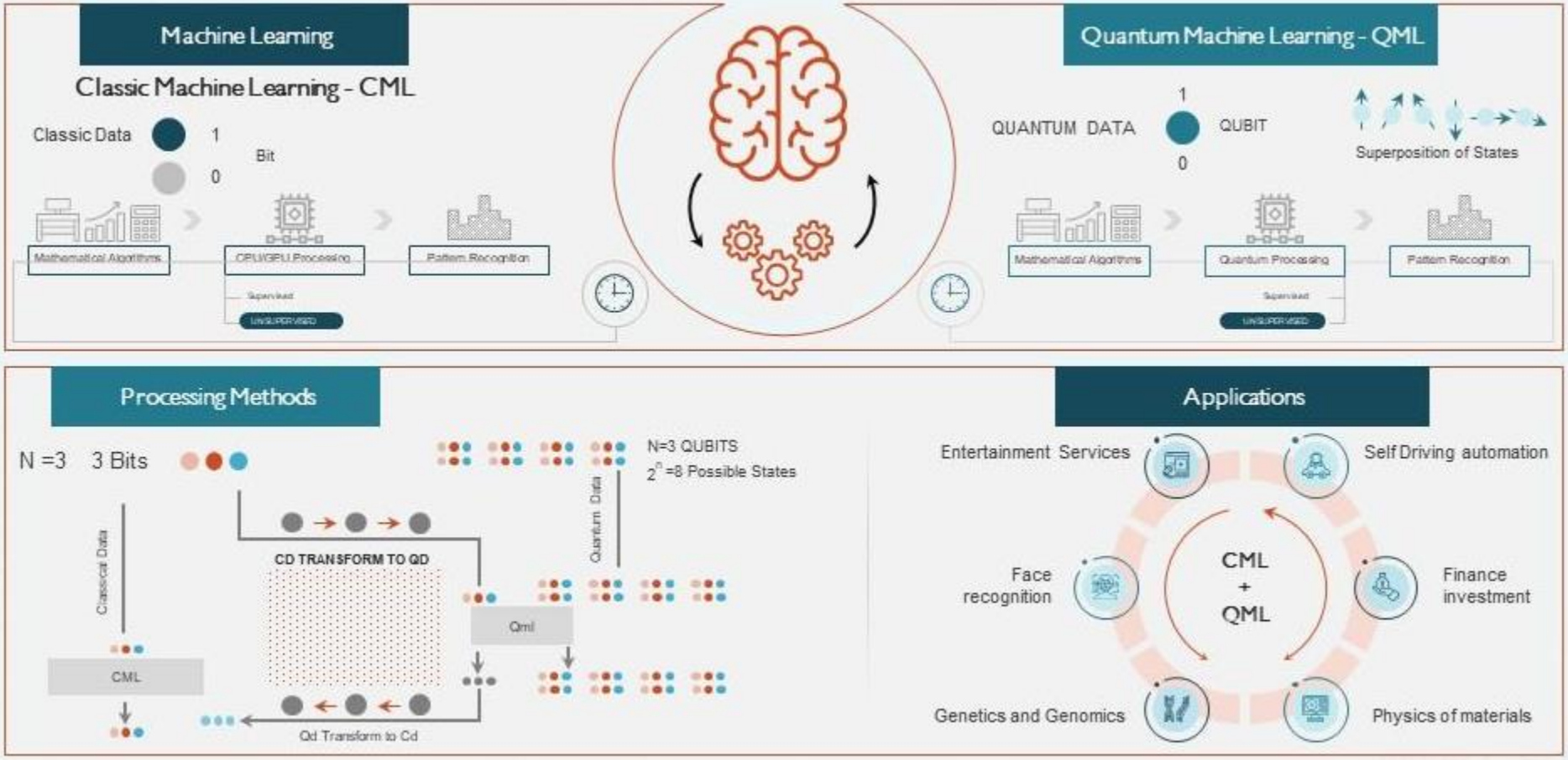
El Capitan has 11,039,616 cores

Key Applications

https://fractal.ai/quantum-computing-is-here-is-your-business-ready/

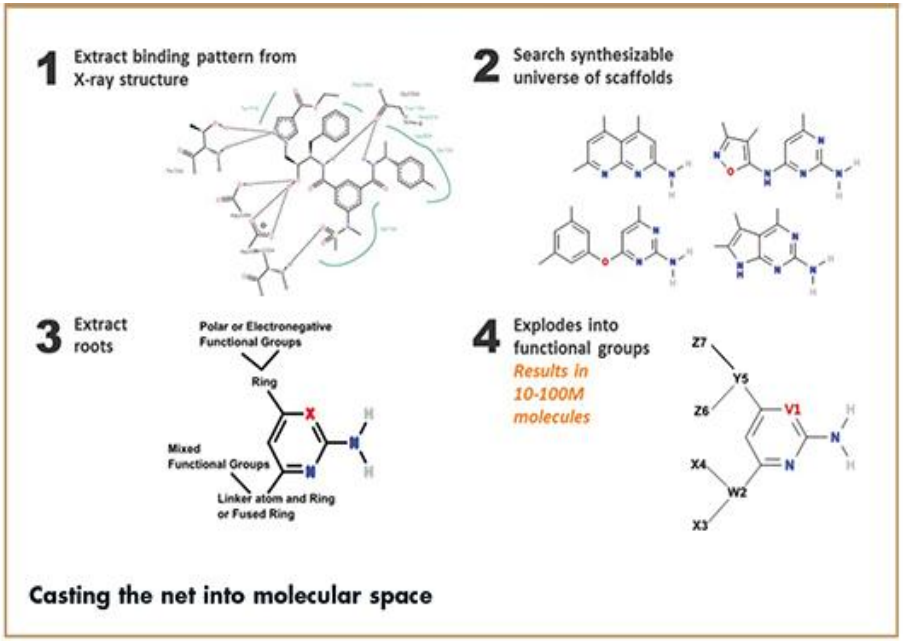
Quantum Machine Learning

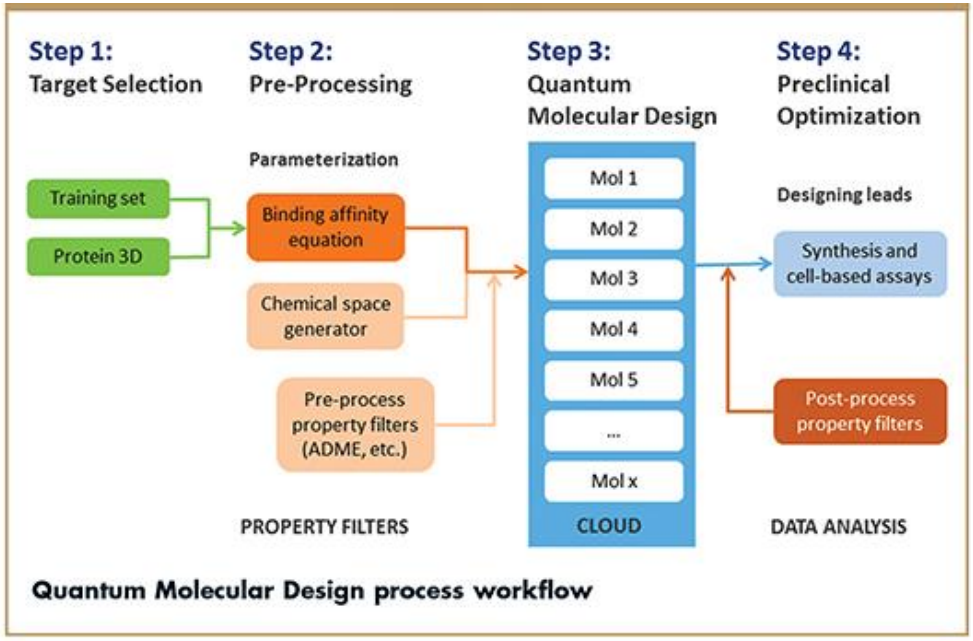
- AI and machine learning are growing fields.
- Quantum machine learning is the integration of quantum algorithms within machine learning programs.
- The most common use of the term refers to machine learning algorithms for the analysis of classical data executed on a quantum computer.



Drug Design & Development

- The costs and timelines to develop effective medicines using traditional drug discovery methods are much too high, exacerbated by outrageous failure rates.



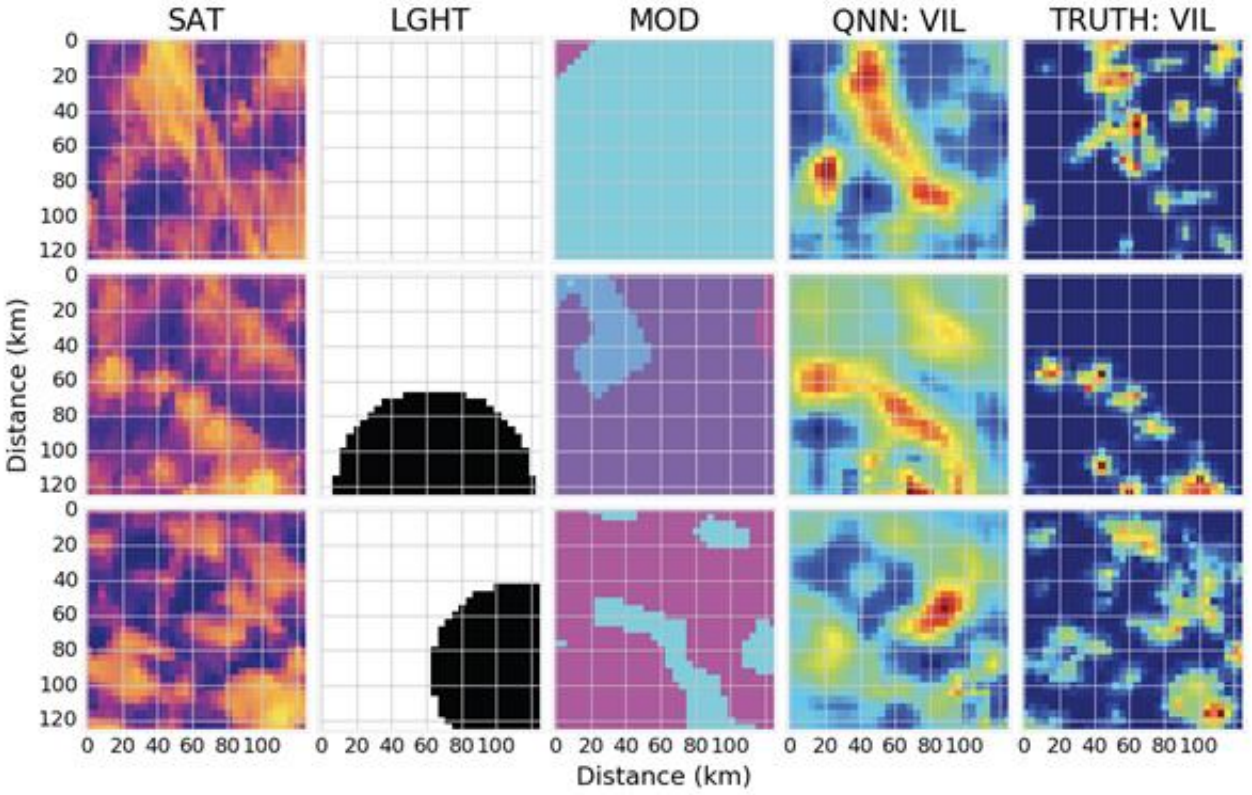


https://drug-dev.com/cloud-computing-using-quantum-molecular-design-cloud-computing-to-improve-the-accuracy-success-probability-of-drug-discovery/

Financial Modelling

Weather Forecasting

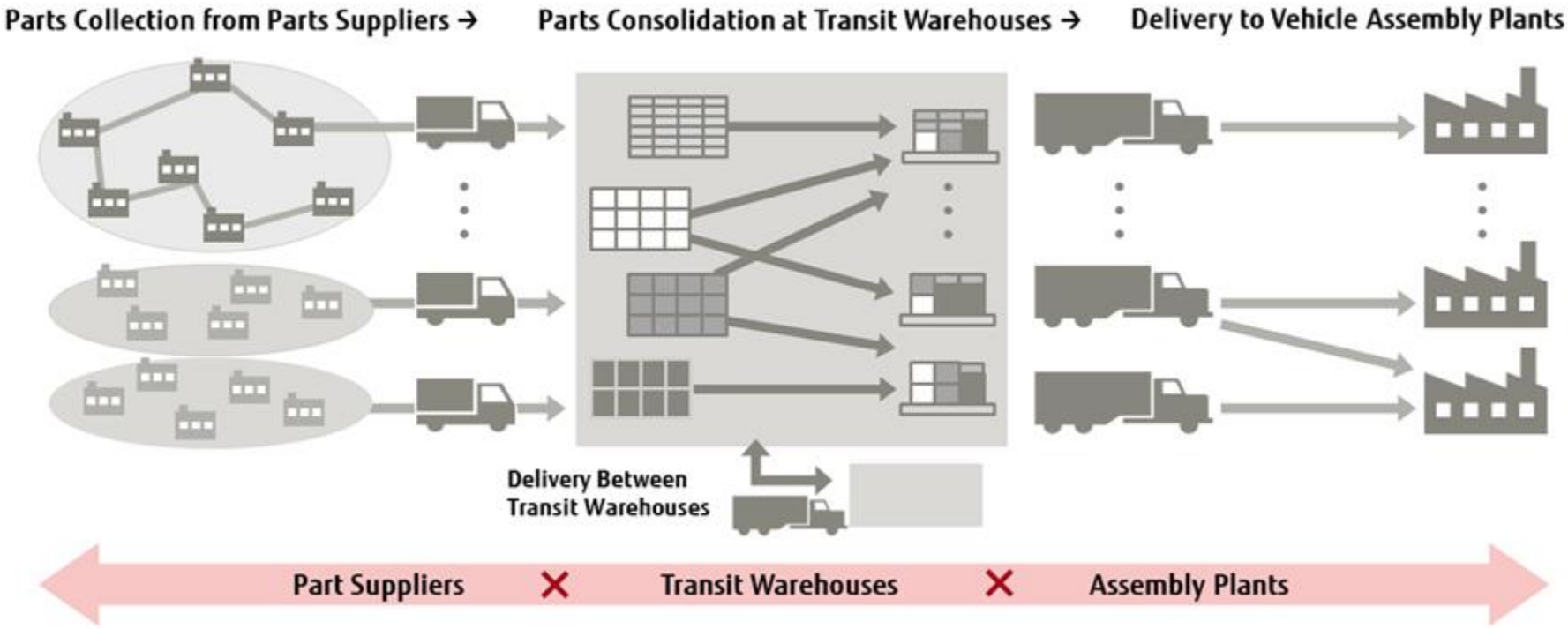
- Currently, the process of analyzing weather conditions by traditional computers can sometimes take longer than the weather itself does to change.



https://analyticsindiamag.com/top-applications-of-quantum-computing-everyone-should-know-about/
https://www.rigetti.com/news/rigetti-enhances-predictive-weather-modeling-with-quantum-machine-learning

Logistics Optimization

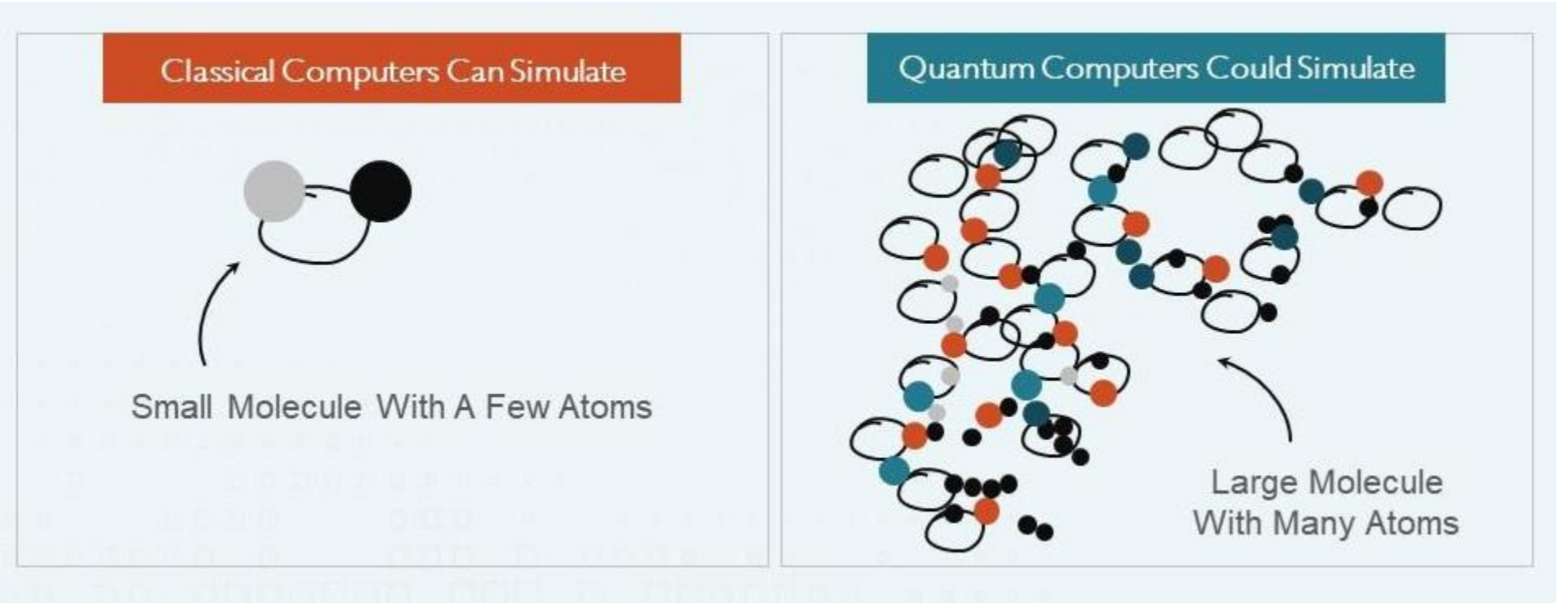
- Improved data analysis and robust modelling will indeed enable a wide range of industries to optimize their logistics and scheduling workflows associated with their supply-chain management.
- The operating models need to continuously calculate and recalculate optimal routes of traffic management, fleet operations, air traffic control, freight and distribution, and that could have a severe impact on applications.



https://www.fujitsu.com/global/about/resources/news/press-releases/2020/0910-02.html

Computational Chemistry

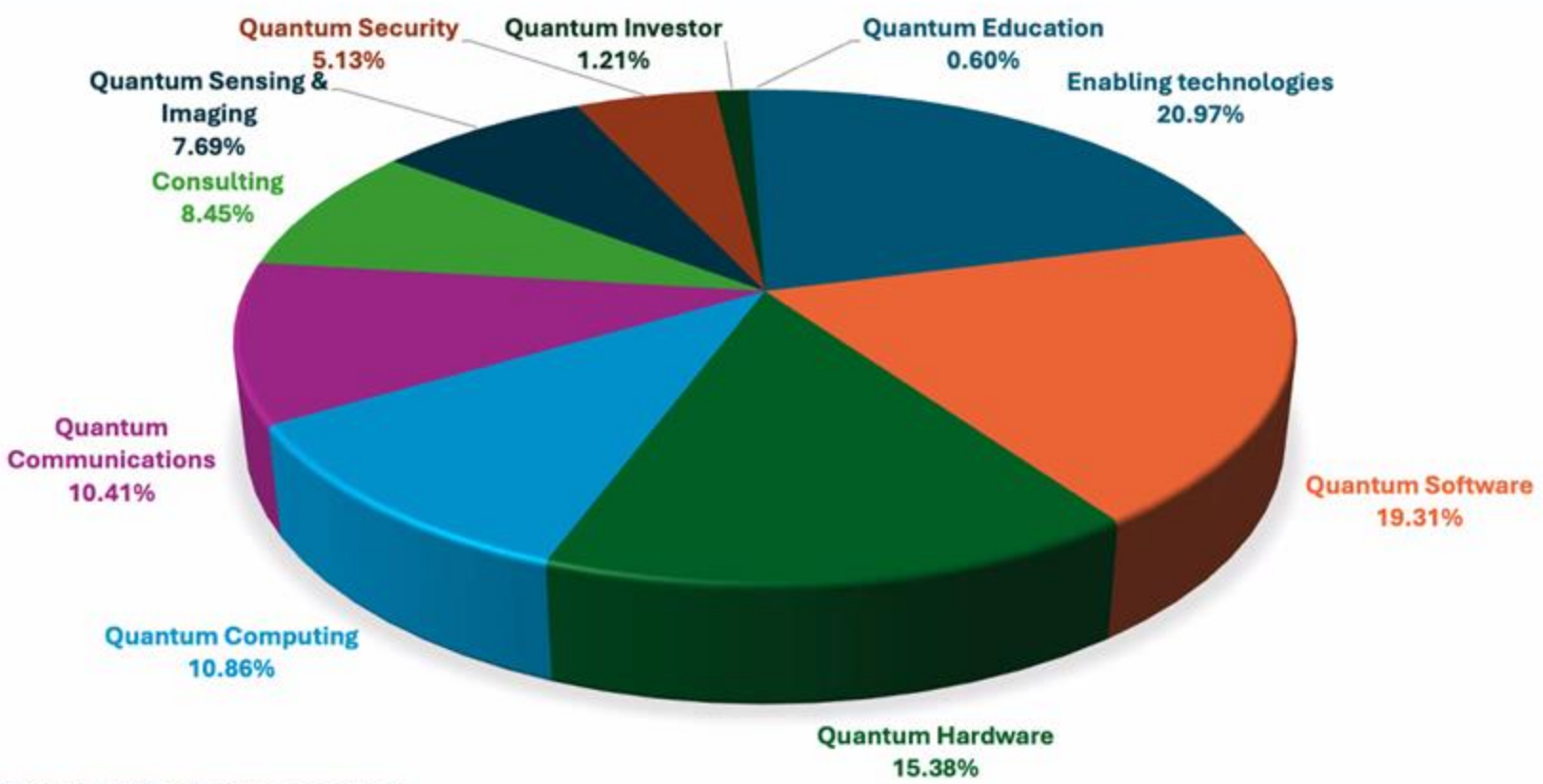
- The number of quantum states, even in a tiniest of a molecule, is extremely vast, and therefore difficult for conventional computing memory to process that.



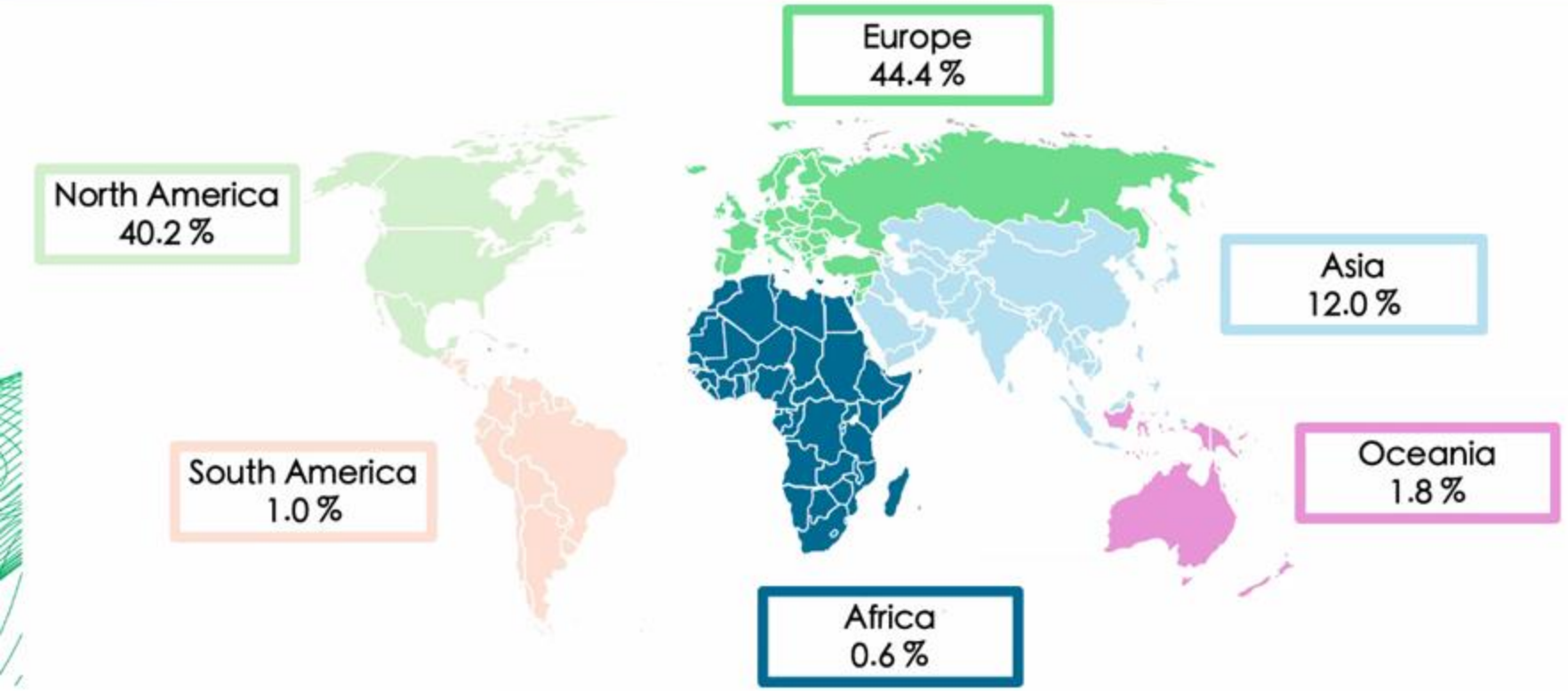
Activities of companies in quantum

- Quantum sensors
- Quantum communication
- Quantum computing hardware
- Quantum algorithms and applications
- Facilitating technologies

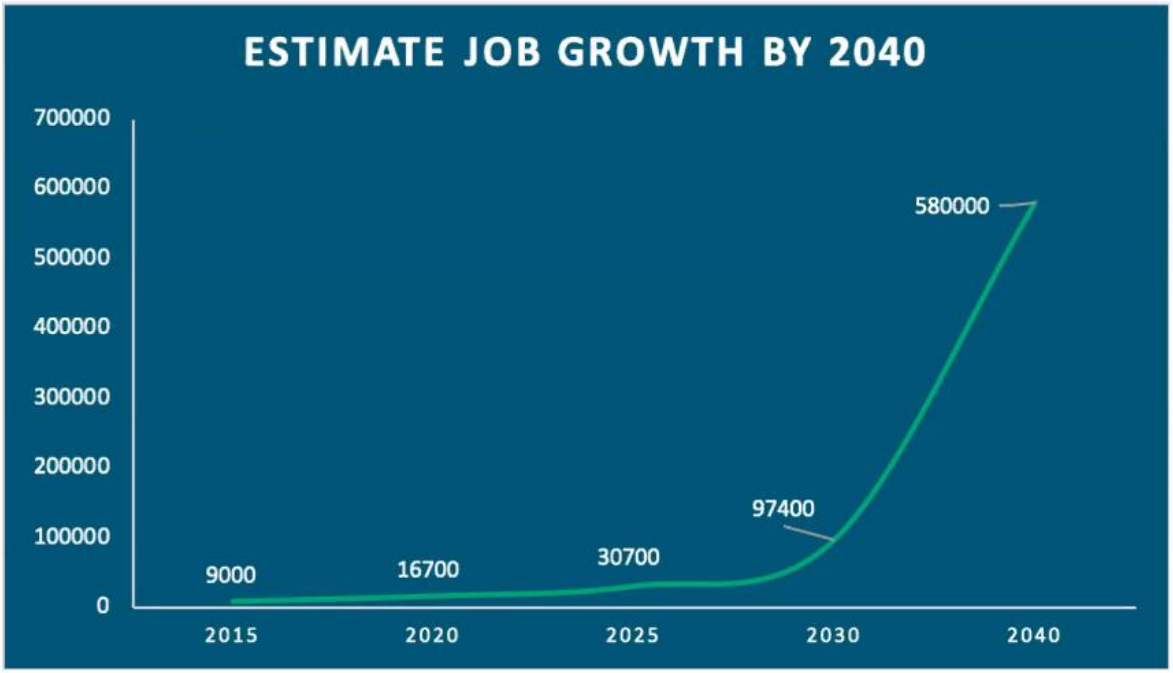
Quantum Companies Sector Distribution



Quantum Companies per Region



Quantum Jobs Market Size



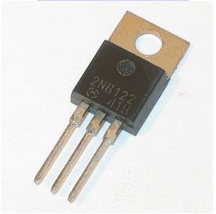
We need to train NOW the *workforce of the present* and the *workforce of the future*

PhotonicsViews, 17: 34-38, 2020. https://doi.org/10.1002/phvs.202000044

https://qubitsok.com/

History

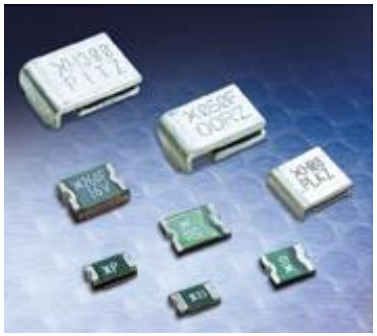
- The true computer we know nowadays came to life when J. Barden, W. Brattain and W. Shockley invented Transistor in 1947.



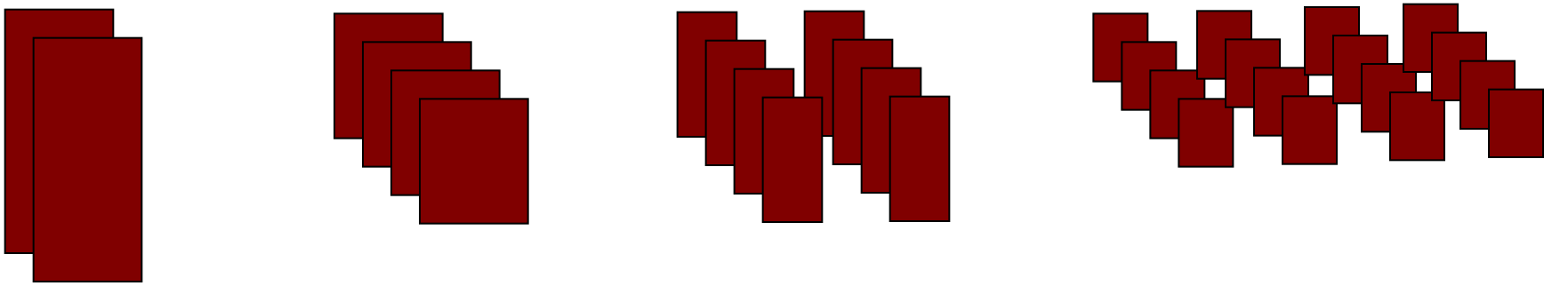
Transistor

- To invent new families of computers with more capabilities, it was necessary to increase the number of transistors used on approx. the same physical space by decreasing the size of the components. (Miniaturization)
- Moore's Law, 1965:

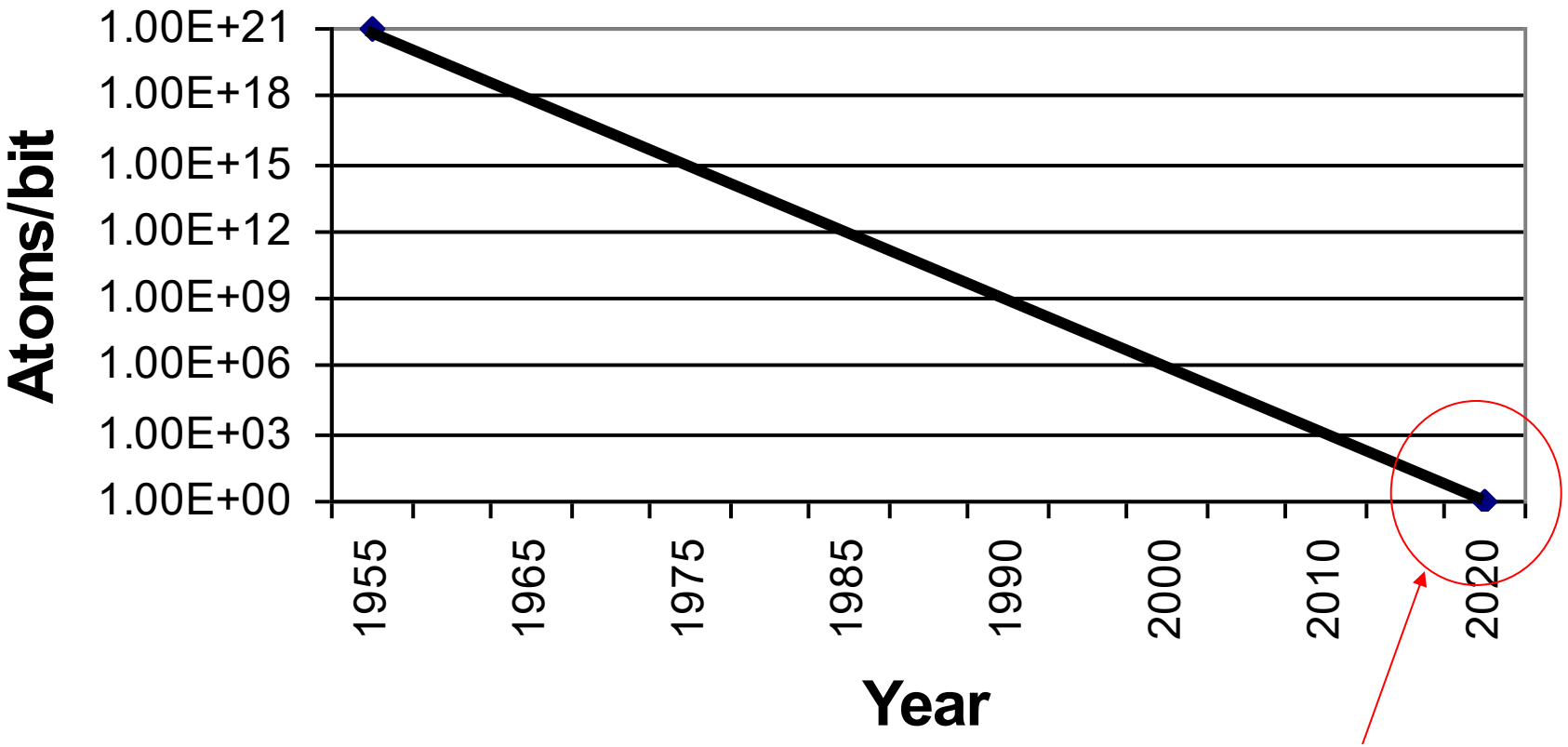
  "The number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented."



Miniaturization



Moore's Law



We need Alternatives !!!

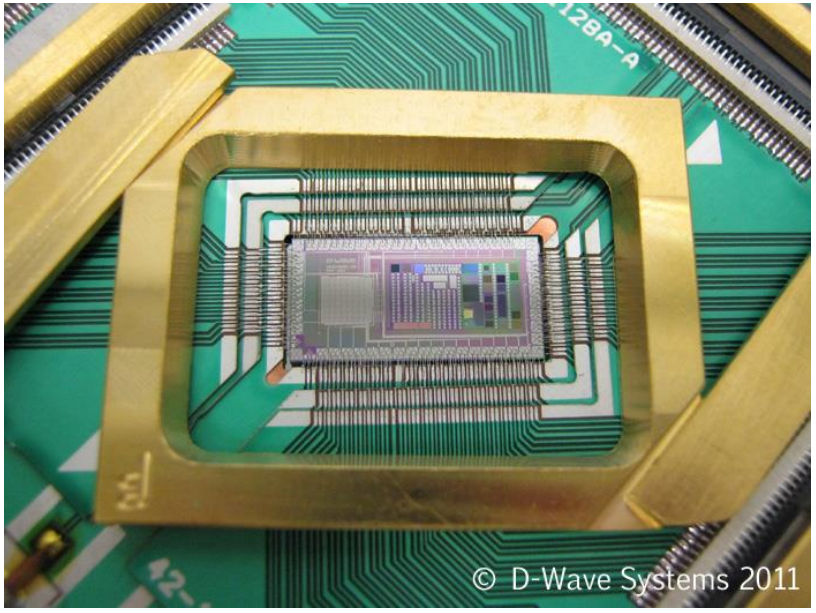
Intel CPUs 2009- 2021

CPU Name	Cores/Threads	Clock	Cache
Core i9-11980HK	8/16	2.6 GHz	24 MB
Core i9-11900H	8/16	2.5 GHz	24 MB
Core i7-11800H	8/16	2.4 GHz	24 MB
Core i5-11400H	6/12	2.7 GHz	12 MB
Core i5-11260H	6/12	2.6 GHz	12 MB
Core i7-11370H	4/8	3.3 GHz	12 MB
Core i5-11300H	4/8	3.1 GHz	12 MB
Core i7-1185G7	4/8	3.0 GHz	12 MB
Core i7-1165G7	4/8	2.8 GHz	12 MB
Core i5-1135G7	4/8	2.4 GHz	8 MB
Core i3-1125G4	4/8	2.0 GHz	8 MB
Core i3-1115G4	2/4	3.0 GHz	6 MB
Core i7-1160G7	4/8	1,2 GHz	12 MB
Core i5-1130G7	4/8	1.1 GHz	8 MB
Core i3-1120G4	4/8	1.1 GHz	8 MB
Core i3-1110G4	2/4	1.8 GHz	6 MB

What is a Quantum Computer?

- A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behavior of particles at the sub-atomic level.

In 1982, Richard P. Feynman proposed if a computer operating with the laws of quantum mechanics will perform more efficient.



Public-key Cryptography is no Longer Safe!

- Shor's Algorithm, 1995:
  - Integer Factorization Problem:
    - On classical computers the best is the Multiple Polynomial Quadratic Sieve algorithm and runs in

$$O\left(\exp\left((64/9)^{1/3}(\ln N)^{1/3}(\ln \right.\right.$$

It means that this algorithm scales exponentially with the number of the digits *N* of the integer number to be factorized.

Given integer n such that $n=p*q$ where p,q are prime numbers.

Find p and q.

This problem is the main problem used to secure online transactions (http vs https)

Factorization Problem RSA – 129 *

- RSA-129 =
  114381625757888867669235779976146612010218296721242362562561842935706935245733897830597123563958705058989075147599290026879543541 [n]

=

  3490529510847650949147849619903898133417764638493387843990820577 [p]

×

  3276913299326670954996198819083446141317764296799294253979828853 3 [q]

http://en.wikipedia.org/wiki/RSA_numbers

Public-key Cryptography - 2

- For instance, in 1994 a 129 digit number (known as RSA-129) was successfully factored using this algorithm on approximately 1600 workstations scattered around the world, the entire factorization took 8 months.

- It needs 800,000 years to factor 250 digit number and 10^{25} years (significantly longer than the age of the universe) to factor 1,000 digit number.

Factorization Problem RSA – 2048 *

- RSA-2048 =
  25195908475657893494027183240048398571429282126204032027777137836043662020707595556264018525880784406918290641249515082189298559149176184502808489120072844992687392807287776735971418347270261896375014971824691165077613379859095700097330459748808428401797429100642458691817195118746121515172654632282216869987549182422433637259085141865462043576798423387184774447920739934236584823824281198163815010674810451660377306056201619676256133844143603833904411952634432190114657544541784240209246165157233507787077498171257724679629263863563728991215483143816789988504044536402352738195137863656439121201039712282212072035 7

Cash Prize Offered: 200,000 USD

Public-key Cryptography - 3

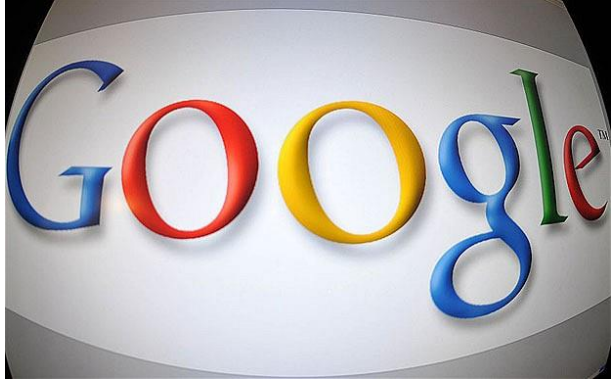
- Shor's algorithm taking the advantage of *quantum parallelism* by using a quantum analogue of the Fourier transform runs in

$$O\left(\left(\log N\right)^{2+\varepsilon}\right)$$

where ε is small.

It means a 1,000 digit number requires about 20 min on a quantum computer.

Quantum Search Engine



- L. Grover, 1996:
  - Describes a very efficient algorithm for database search.
  - Classical search algorithm for unsorted list of *n* records requires $O(N)$.
  - His algorithms runs in $O\left(\sqrt{N}\right)$.

Quantum Search Engine

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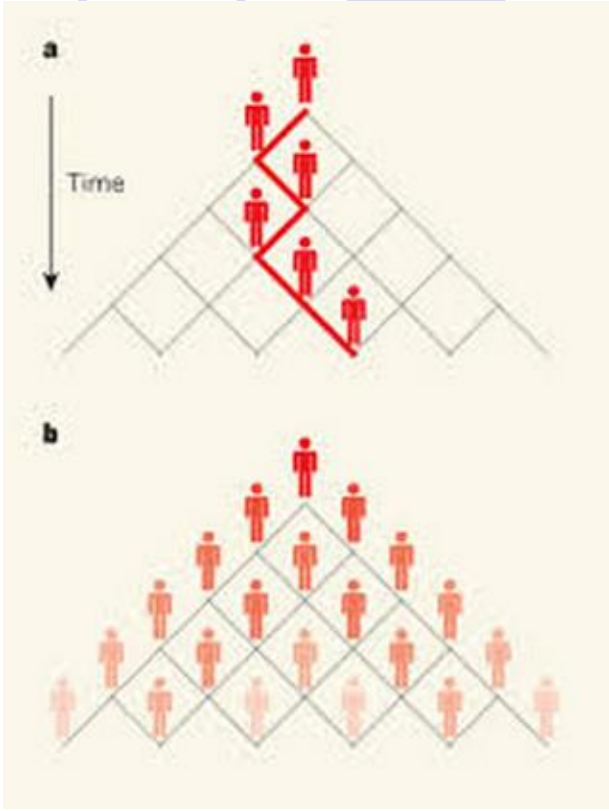
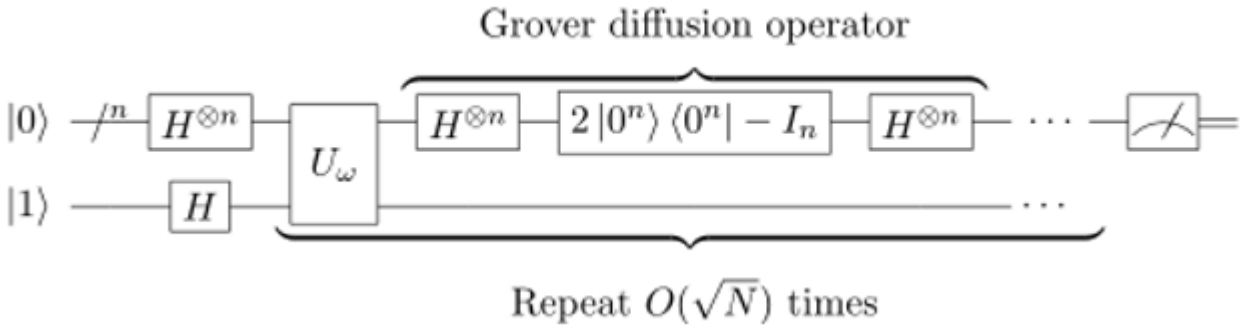




Quantum Computer Science

- Quantum Circuits.
- Quantum Algorithms.
- Quantum Complexity Theory.
- Quantum Neural Network.
- Quantum Pattern Recognition.
- Quantum Relational Databases.
- Quantum Images Recognition.
- Quantum Genetic Information.
- Quantum Cryptography.
- Quantum Programming Languages.
- Quantum Route Finding.
- Quantum Machine Learning.
- Quantum Image Processing.
- Quantum NLP.
- Quantum Origin cybersecurity.

Universities

Quantum Algorithms Vs. Classical Algorithms

Algorithm Name	Speedup
Quantum Fourier Transform, Simon's Algorithm, Quantum Phase Estimation, HHL Algorithm, Quantum Principal Component Analysis, Quantum Support Vector Machine, Quantum Linear Systems Algorithm, Quantum Eigenvalue Estimation, Quantum Matrix Inversion, Quantum Singular Value Transformation	Exponential
Quantum Walks	Polynomial
Grover's Search, Quantum Counting, Quantum Amplitude Amplification, Quantum Amplitude Estimation,Quantum Minimum Finding, Quantum Mean Estimation	Quadratic
Factoring, Discrete-log, Pell's Equation	Superpolynomial

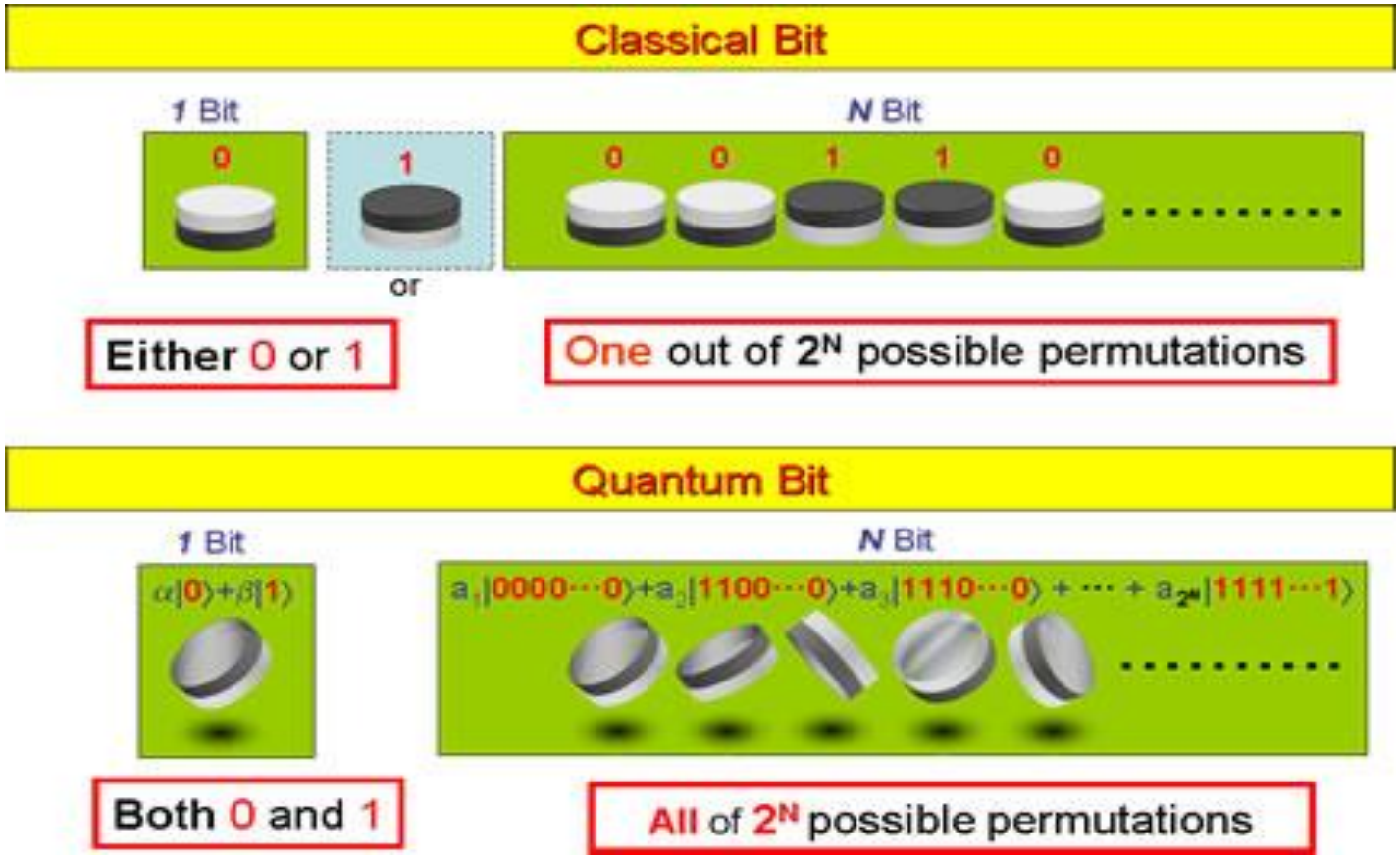
https://math.nist.gov/quantum/zoo/

local

Basics of Quantum Computing

Quantum Data (qubit)

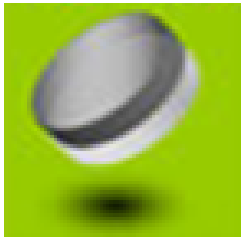
A quantum bit of data is represented by a single atom that is in one of two states denoted by **|0>** and **|1>**. A single bit of this form is known as a ***qubit***



Superposition - 1

$|0\rangle$

$|1\rangle$



$$\text{Prob}(|0\rangle) = |a|^2 = a.a^*$$

$$\text{Prob}(|1\rangle) = |b|^2 = b.b^*$$

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

$$\left(a|0\rangle + b|1\rangle\right)$$

Superposition - 2


$$|0\rangle \qquad (a|0\rangle + b|1\rangle)$$

$$a|00\rangle + b|01\rangle$$


$$(a|0\rangle + b|1\rangle) \qquad |1\rangle$$

$$a|01\rangle + b|11\rangle$$

$$(a_0|0\rangle + b_0|1\rangle) \otimes (a_1|0\rangle + b_1|1\rangle)$$

$$a_0a_1|00\rangle + a_0b_1|01\rangle + b_0a_1|10\rangle + b_0b_1|11\rangle$$

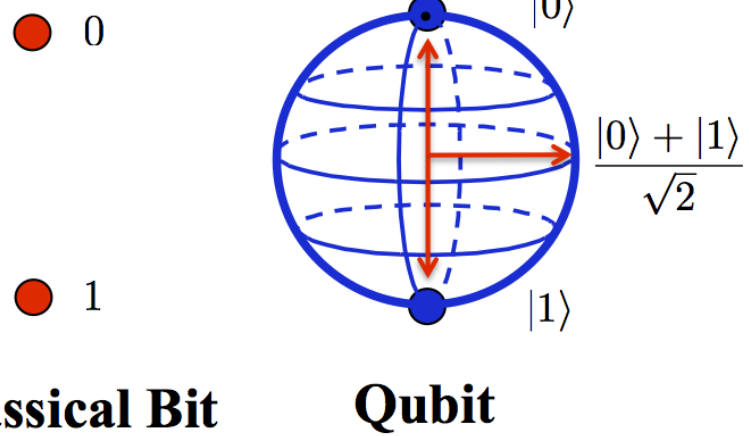
$$(\alpha_0|00\rangle + \alpha_1|01\rangle + \alpha_2|10\rangle + \alpha_3|11\rangle)$$

Representation of Quantum Data - Superposition

A single qubit can be forced into a ***superposition*** of the two states denoted by the addition of the state vectors:

$$|\psi\rangle = a\ |0\rangle + b\ |1\rangle$$

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

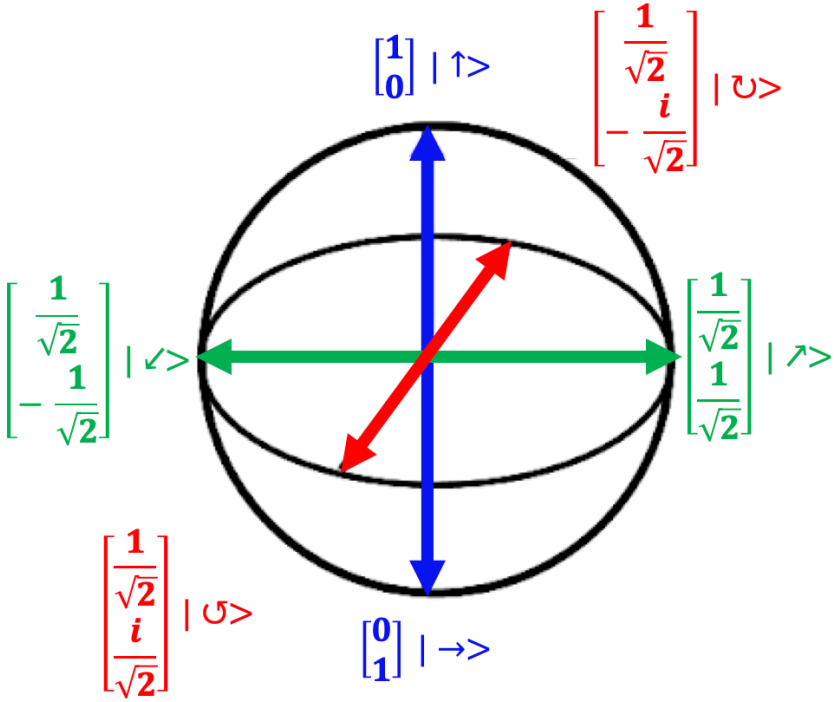


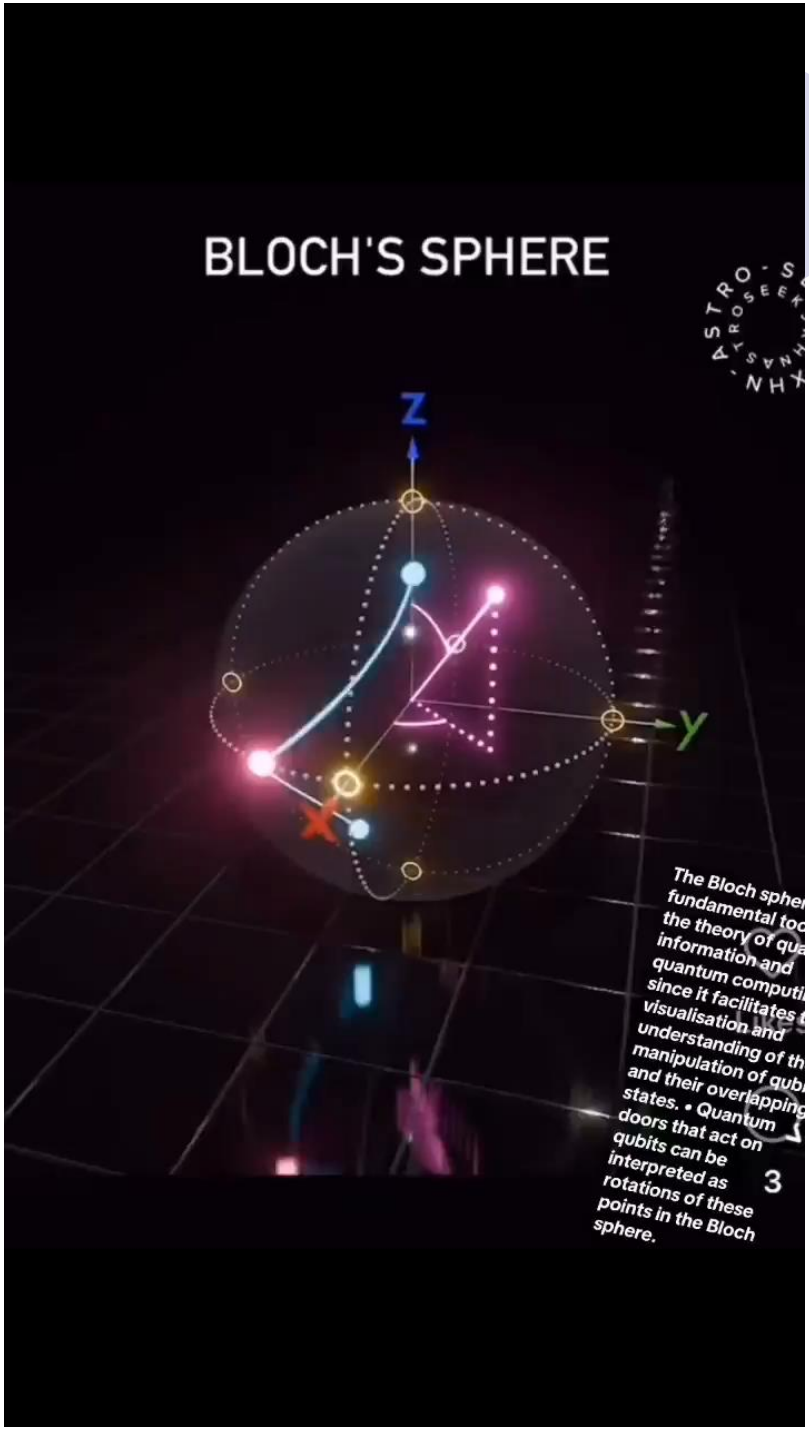
Classical Bit **Qubit**

Where ***a*** **and** ***b*** are complex numbers and $|a|^2 + |b|^2 = 1$

A qubit in superposition is in both of the states |1> and |0> at the same time

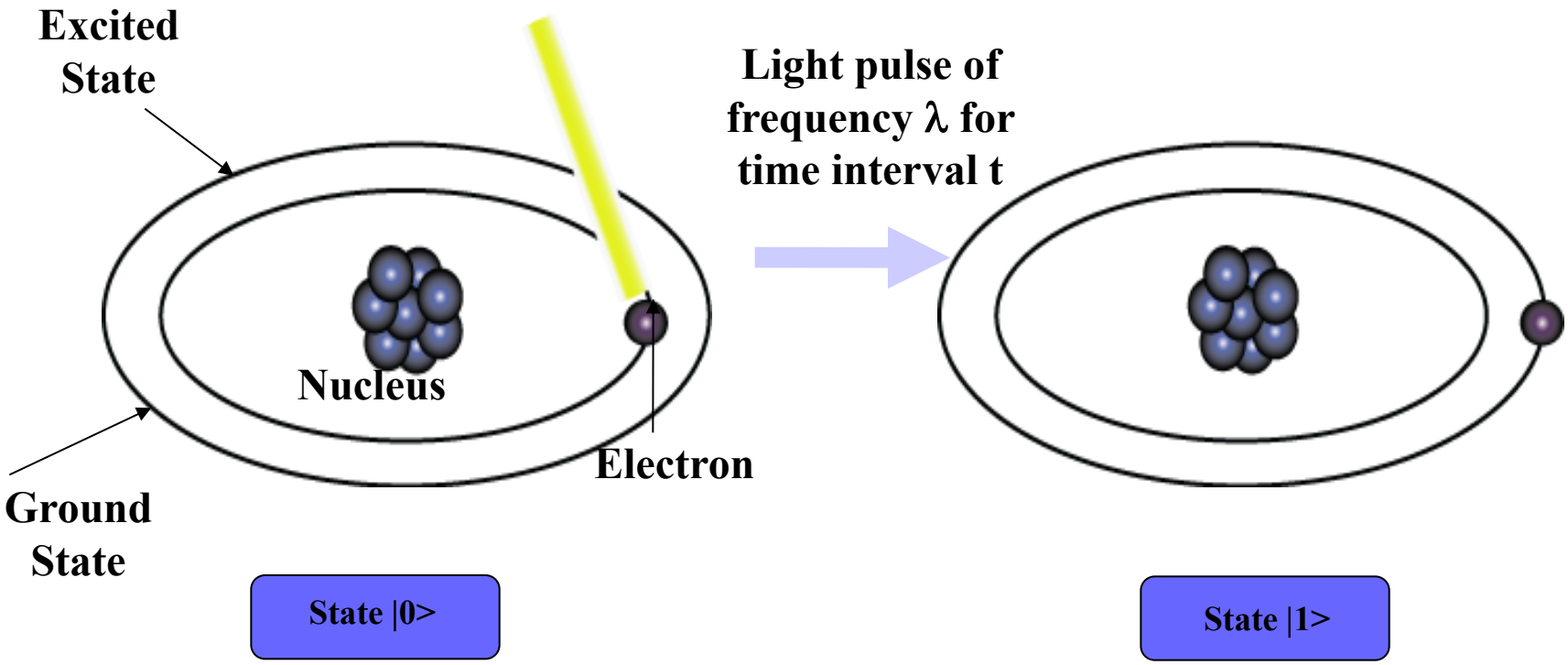
Bloch Sphere



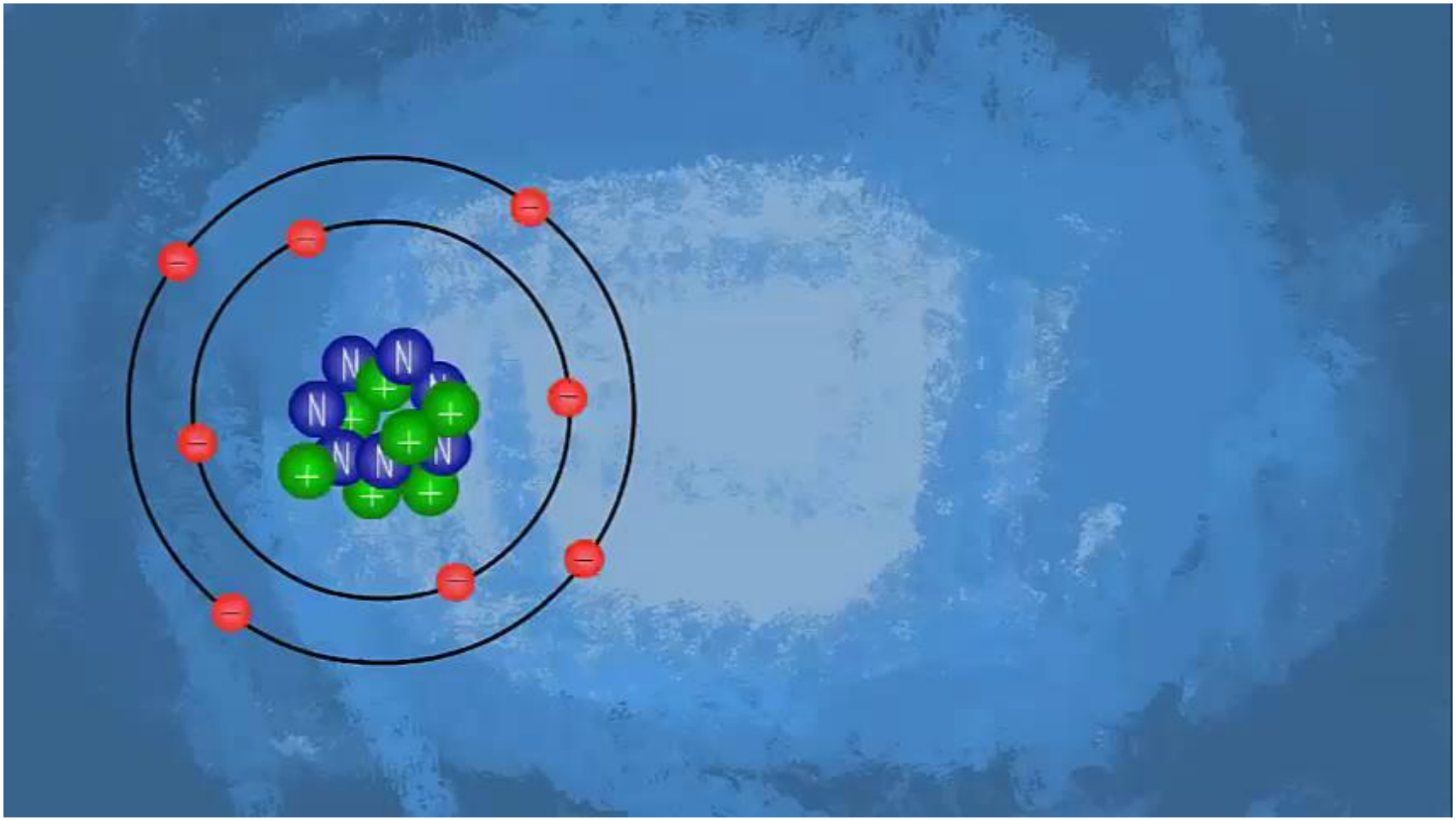


Physical Qubit (Trapped Ions)

A physical implementation of a qubit could use the two energy levels of an atom. An excited state representing |1> and a ground state representing |0>.

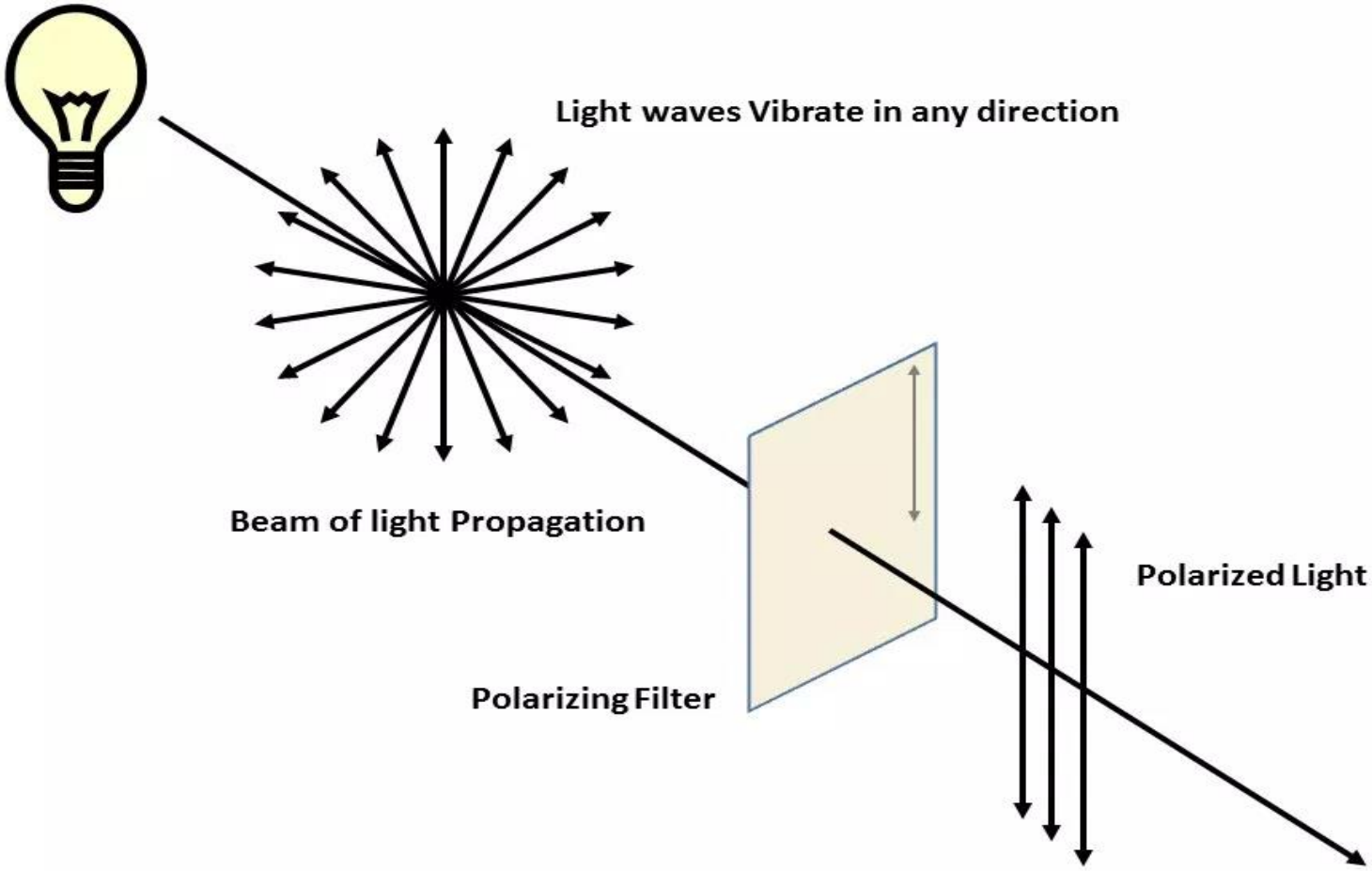


Trapped Ions

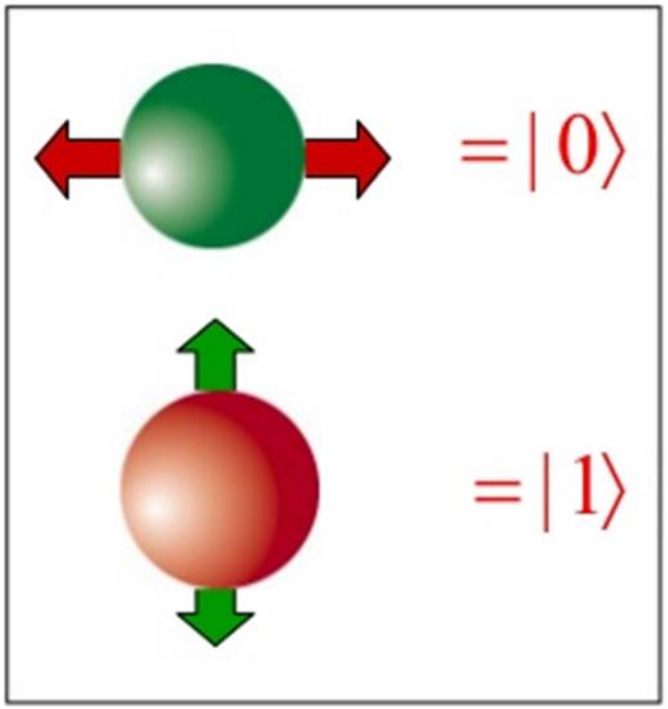


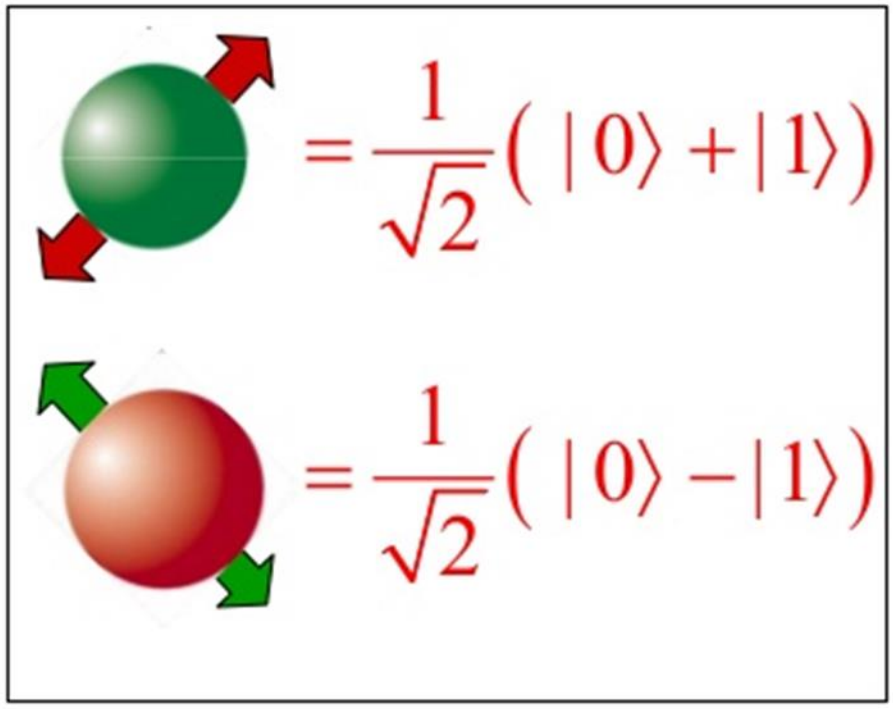
Superconducting Qubits

Light Polarization



Photon polarization as a qubit





Physical support	Name	Information support	$\|0\rangle$	$\|1\rangle$
Photon	Polarization encoding	Polarization of light	Horizontal	Vertical
	Number of photons	Fock state	Vacuum	Single photon state
	Time-bin encoding	Time of arrival	Early	Late
Coherent state of light	Squeezed light	Quadrature	Amplitude-squeezed state	Phase-squeezed state
Electrons	Electronic spin	Spin	Up	Down
	Electron number	Charge	No electron	One electron
Nucleus	Nuclear spin addressed through NMR	Spin	Up	Down
Optical lattices	Atomic spin	Spin	Up	Down
Josephson junction	Superconducting charge qubit	Charge	Uncharged superconducting island (Q=0)	Charged superconducting island (Q=2e, one extra Cooper pair)
	Superconducting flux qubit	Current	Clockwise current	Counterclockwise current
	Superconducting phase qubit	Energy	Ground state	First excited state
Singly charged quantum dot pair	Electron localization	Charge	Electron on left dot	Electron on right dot
Quantum dot	Dot spin	Spin	Down	Up
Gapped topological system	Non-abelian anyons	Braiding of Excitations	Depends on specific topological system	Depends on specific topological system

Essential Mathematical Topics

Math. Topic	Quantum Computing Topics
Linear Algebra:	Dirac notation, quantum gate is unitary matrix, quantum data is a normalized vector.
Differential Equations:	Adiabatic quantum computing, quantum annealing.
Statistics/Probability Theory:	Quantum computers are probabilistic devices, quantum measurement, quantum amplitude amplifications.
Complex Analysis:	Amplitudes of quantum states are complex numbers.
Information Theory:	Quantum information theory, quantum noise, quantum error correction, quantum compression entropy.

Essential Mathematical Topics (cont.)

Math. Topic	Quantum Computing Topics
Topology:	Topological quantum computing.
Group Theory:	Stabilizer codes, Quantum error Correction, reversible computing, permutation group, universal quantum gates.
Graph Theory:	Graph state quantum computing, quantum walk on a graph.
Algebraic Geometry:	Quantum annealing.
Boolean Algebra:	Quantum Boolean circuits, quantum logic, quantum gates.

Essential Mathematical Topics (cont.)

Math. Topic	Quantum Computing Topics
Coding Theory:	Quantum error correcting codes.
Number Theory:	Quantum cryptography and Shor's Algorithm.
Differential Geometry:	Quantum information theory and quantum gravity.
Formal Language Theory:	Quantum computation models, quantum complexity, quantum computability, quantum Turing machines.
Fractional Calculus:	Fractional quantum calculus, generalization of quantum mechanics, fractional Schrödinger equation.

Computation with Qubits - 1

How does the use of qubits affect computation?

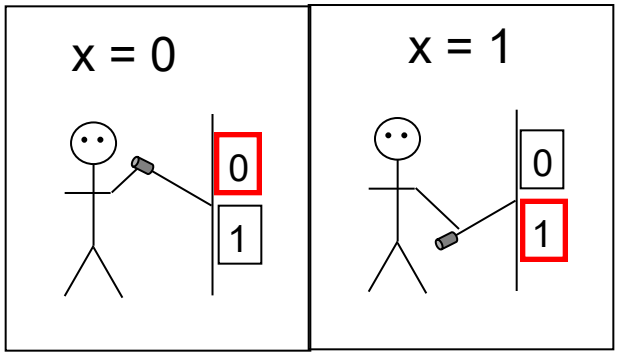
Classical Computation

Data unit: bit

● = '1' ○ = '0'

Valid states:

x = '0' or '1'



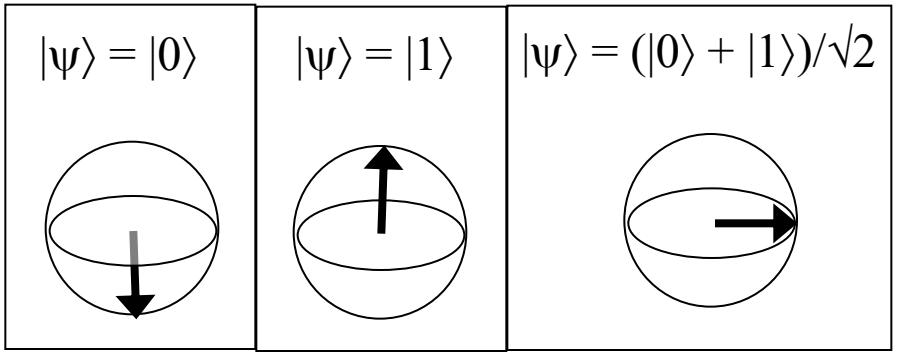
Quantum Computation

Data unit: qubit

$|1\rangle$ $|0\rangle$

Valid states:

$|\psi\rangle = c_1|0\rangle + c_2|1\rangle$



Computation with Qubits - 2

How does the use of qubits affect computation?

Classical Computation

Operations: logical

Valid operations:

NOT =

	in: 0	in: 1
out	1	0

1-bit

AND =

in	in: 0	in: 1
0	0	0
1	0	1

(out)

2-bit

Quantum Computation

Operations: unitary

Valid operations:

1-qubit

$$\sigma_X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\sigma_y = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix} \qquad H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

2-qubit

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

Computation with Qubits - 3

- Computation in quantum systems must be *reversible*, so that *no loss in energy* during the computation process.
- Quantum gates are represented as square matrices U that satisfy the *unitary* condition:

$$U^{\dagger} = U^{-1}$$
$$U^{\dagger}U = UU^{\dagger} = I.$$

Computation with Qubits - 4

- Single qubit gates:

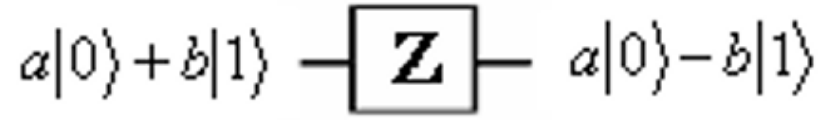
Identity gate:

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

NOT gate:

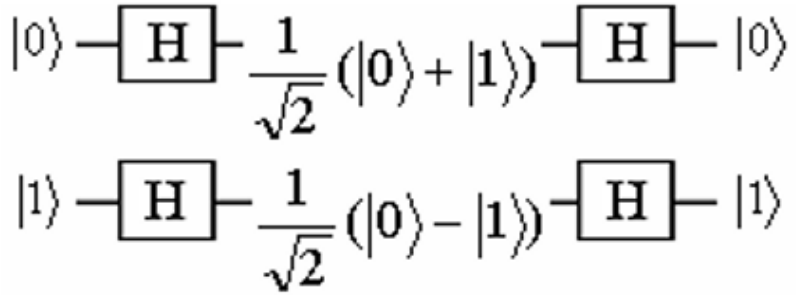
$$X=\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$$

Phase Shift Gate:



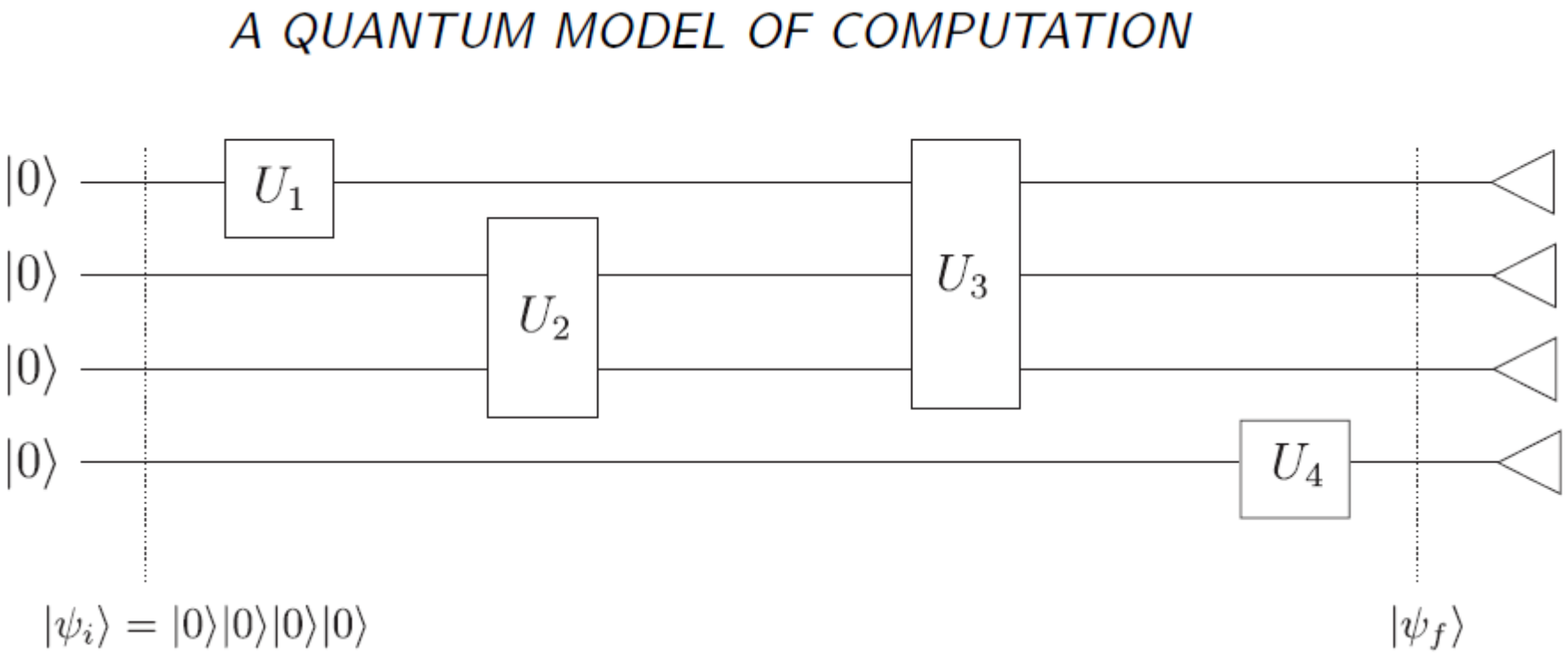
$$Z=\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$$

Hadamard Gate:

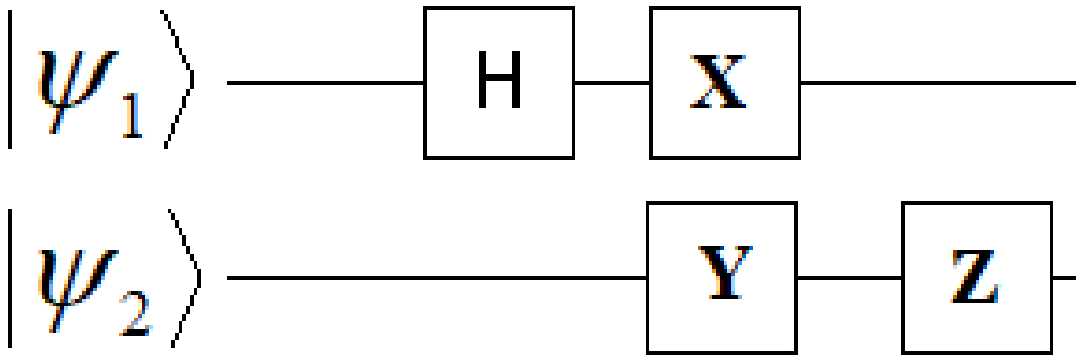


$$H=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$$

Quantum Circuit Model



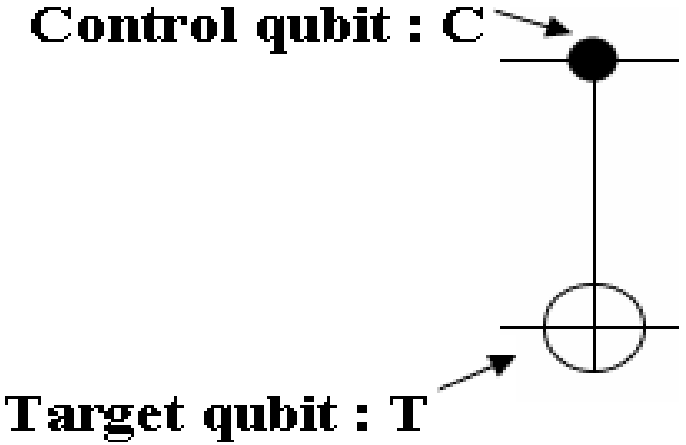
Tracing a Quantum Circuit



- What is the truth table?

Two qubit gates

- **The Controlled-NOT Gate (C_{not})**
- If C=0 then no change
- Else If C=1 then T is flipped



Diagonal representation,

$$C_{not} = |0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes X.$$

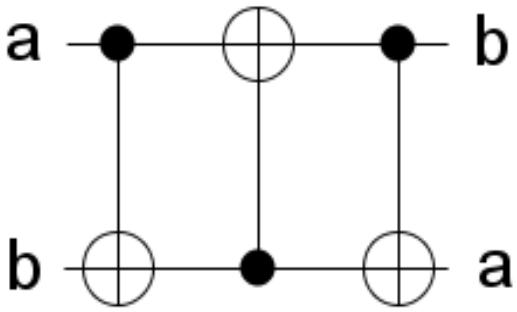
$$C_{not} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Input	Output
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$\|01\rangle$
$\|10\rangle$	$\|11\rangle$
$\|11\rangle$	$\|10\rangle$

The C_{not} gate truth table.

Examples

Swap Circuit:



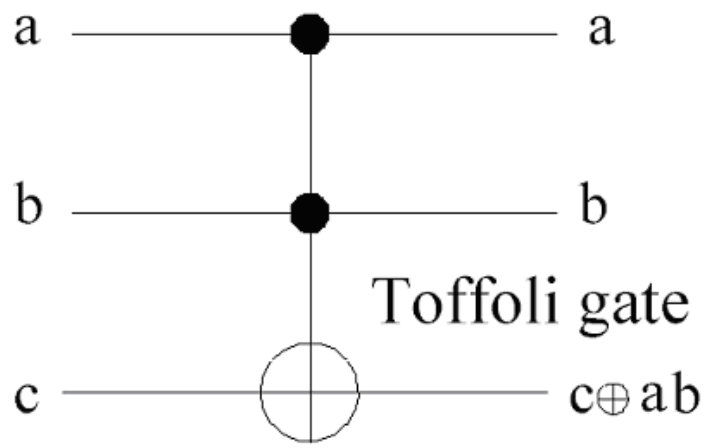
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Three qubit gates

Toffoli gate :

Is considered to be universal…

Setting C=1 will convert it to classical *NAND* gate which is universal from classical point of view.

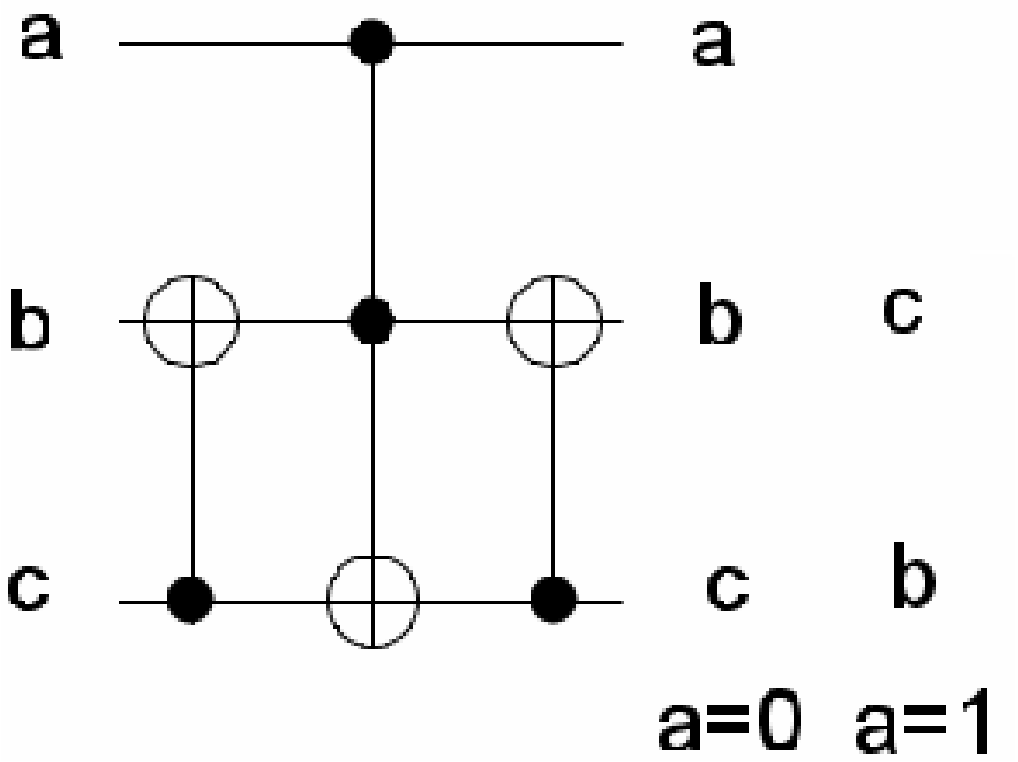


Input	Output
$\|000\rangle$	$\|000\rangle$
$\|001\rangle$	$\|001\rangle$
$\|010\rangle$	$\|010\rangle$
$\|011\rangle$	$\|011\rangle$
$\|100\rangle$	$\|100\rangle$
$\|101\rangle$	$\|101\rangle$
$\|110\rangle$	$\|111\rangle$
$\|111\rangle$	$\|110\rangle$

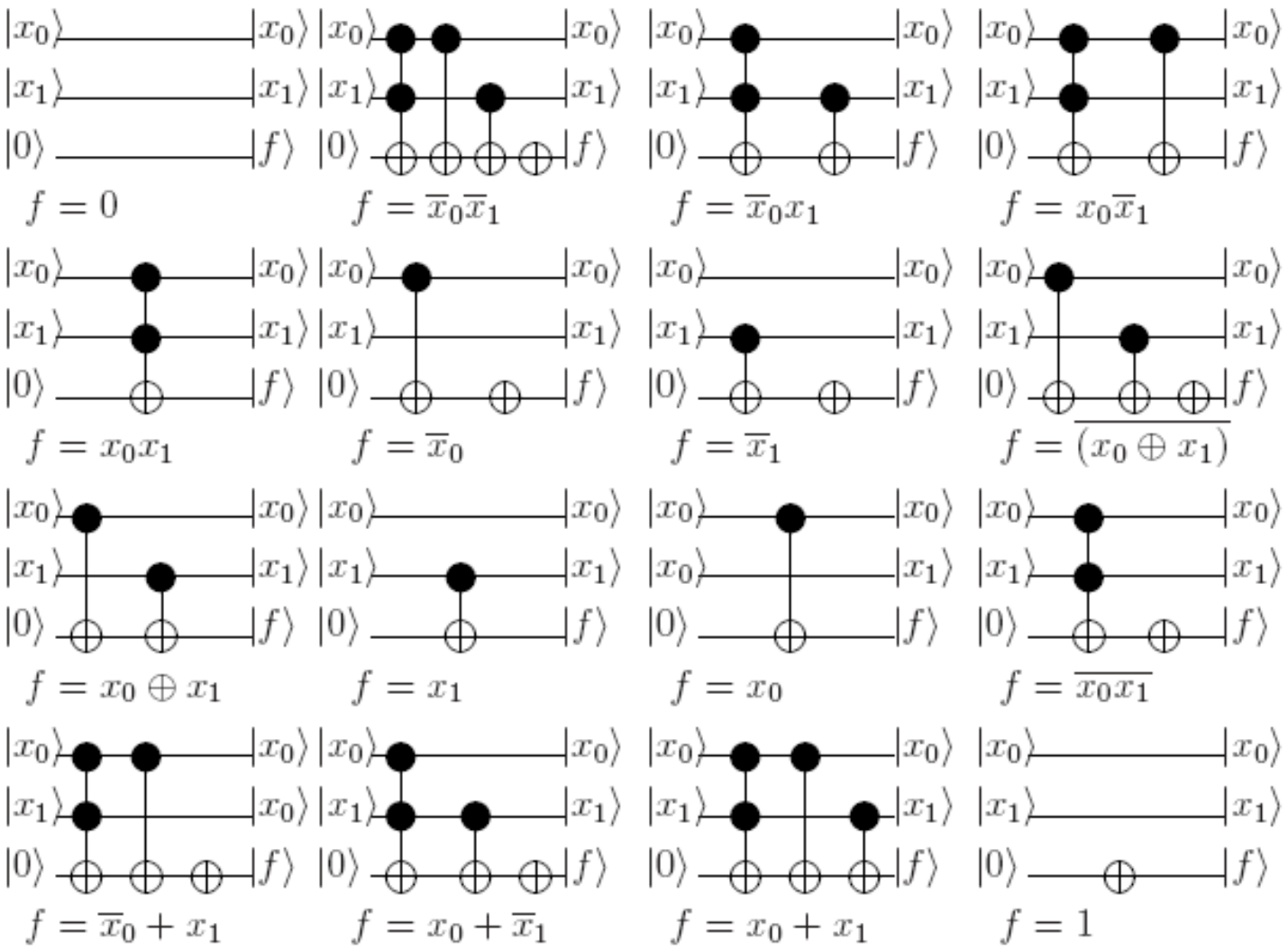
truth table.

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

Controlled Swap Circuit (Fredkin Gate)

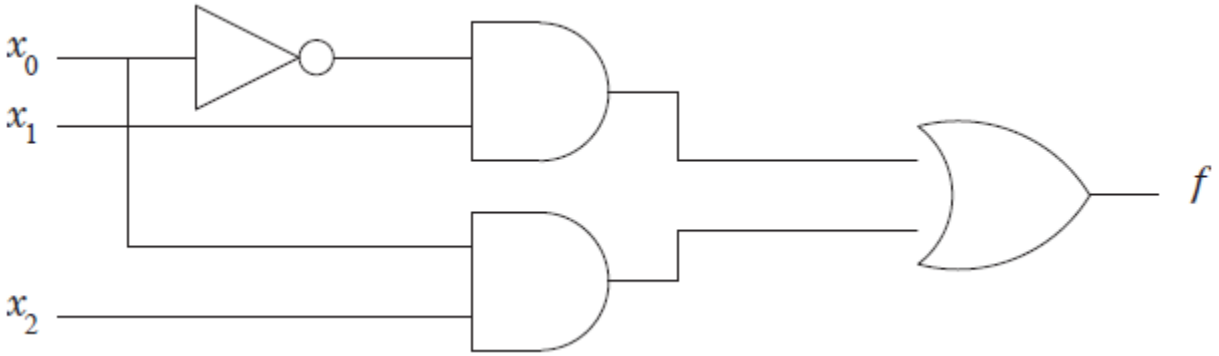


Two-qubits Boolean Circuits

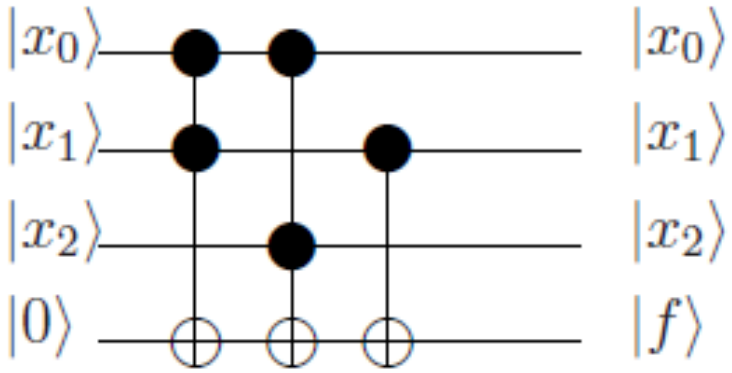


Boolean Quantum Circuits

$$f = \overline{x_0} x_1 + x_0 x_2$$



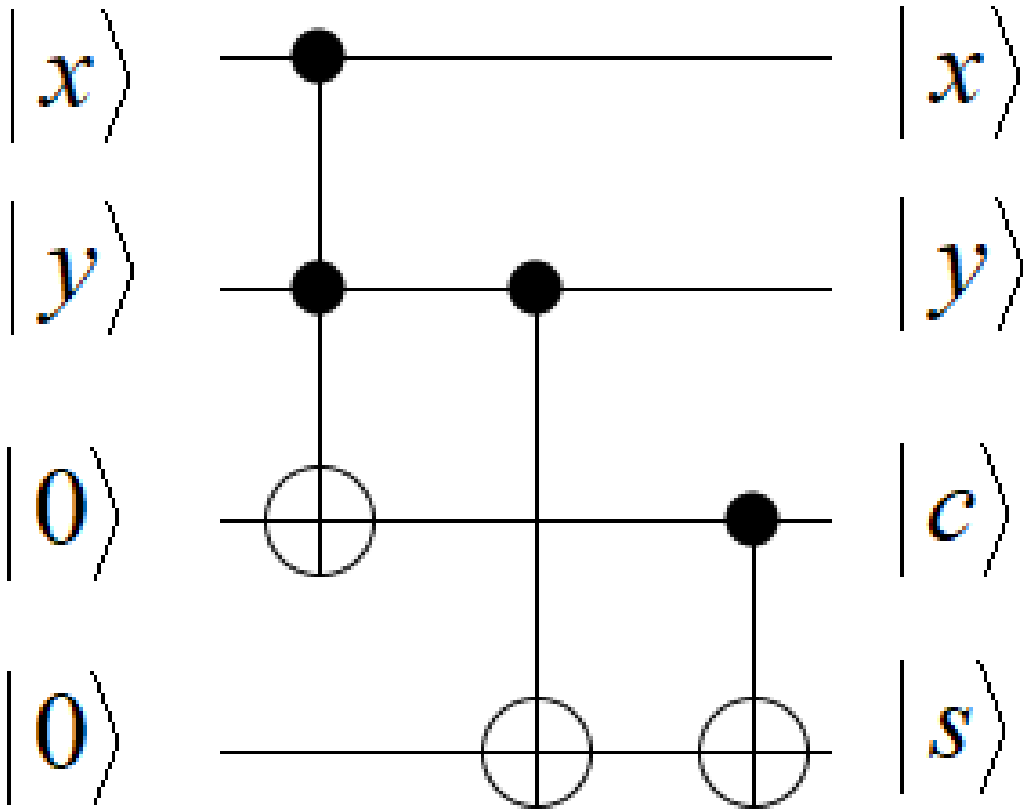
Digital circuit



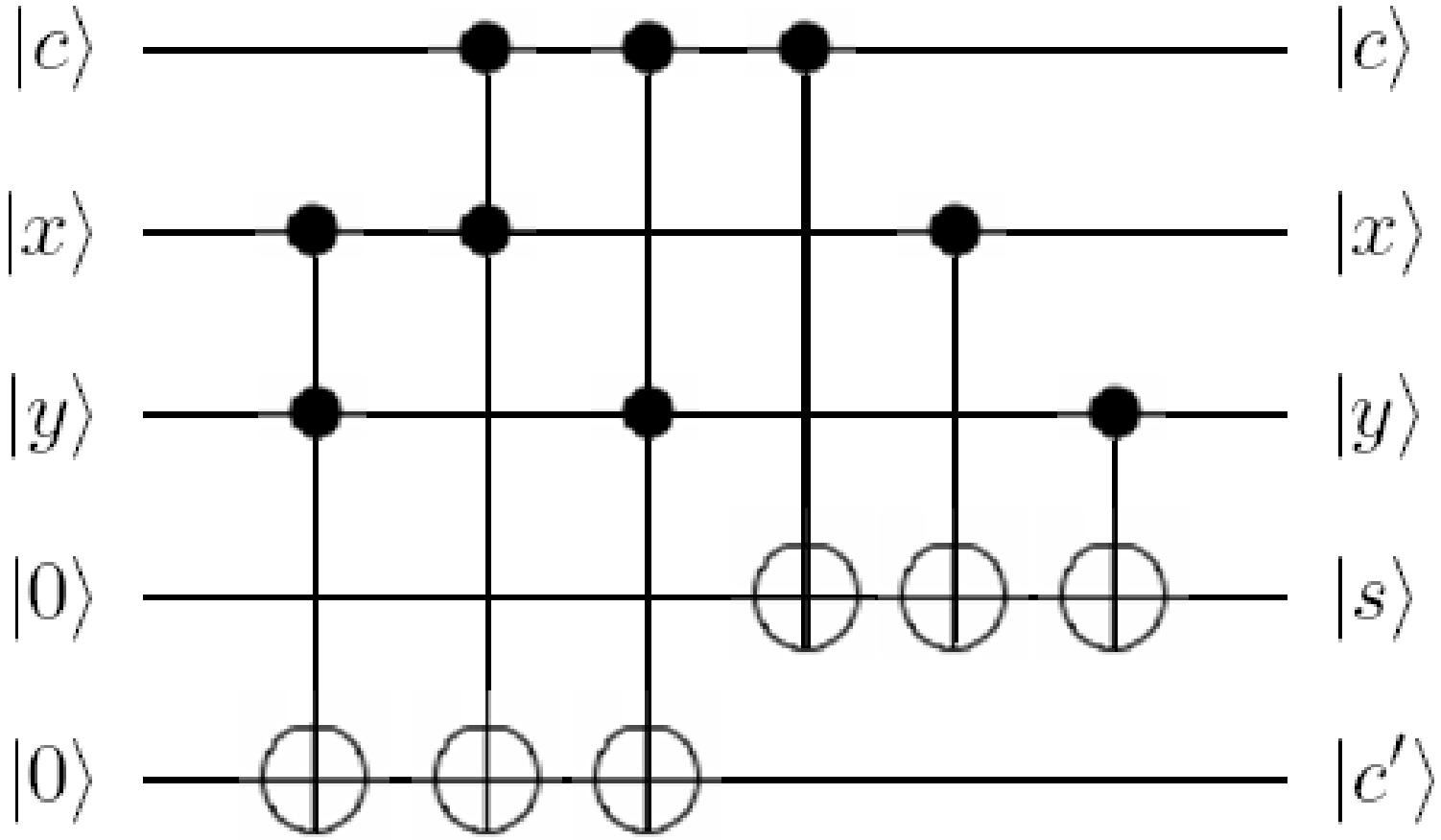
Quantum circuit

x_0	x_1	x_2	f
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

1-bit Half Adder



1-bit Full Adder



Let |c> = |1>, |x> = |0>, |y> = |1>
Then |s> = |0>, |c'> = |1>

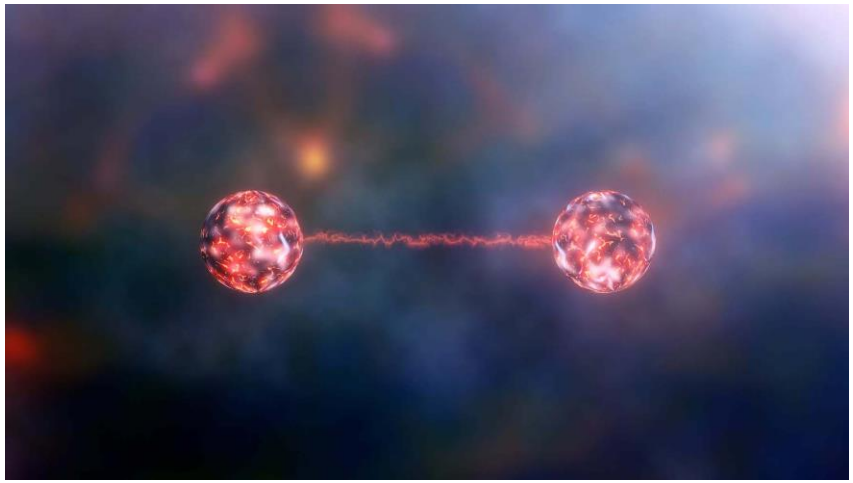
Entanglement

$$\alpha_2|10\rangle + \alpha_3|11\rangle \rightarrow$$

$$\alpha_0|00\rangle + \alpha_2|10\rangle \rightarrow$$

$$\left(\alpha_0|00\rangle + \alpha_1|01\rangle + \alpha_2|10\rangle + \alpha_3|11\rangle\right) \rightarrow$$

$$\alpha_0|00\rangle + \alpha_3|11\rangle \rightarrow$$



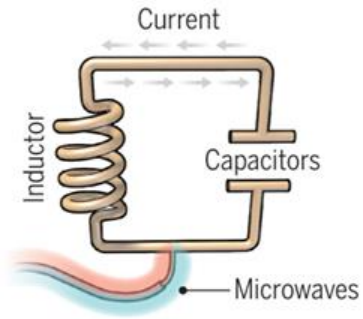
Hidden correlation between qubits -
spooky action at a distance

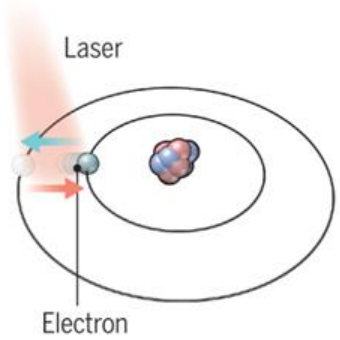
Communication with Entanglement

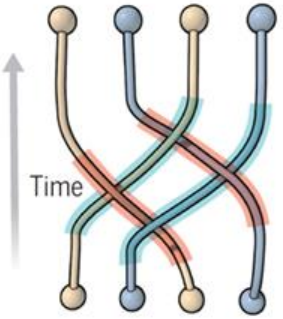
Quantum Computing in Market

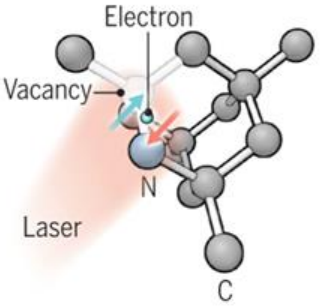
A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.







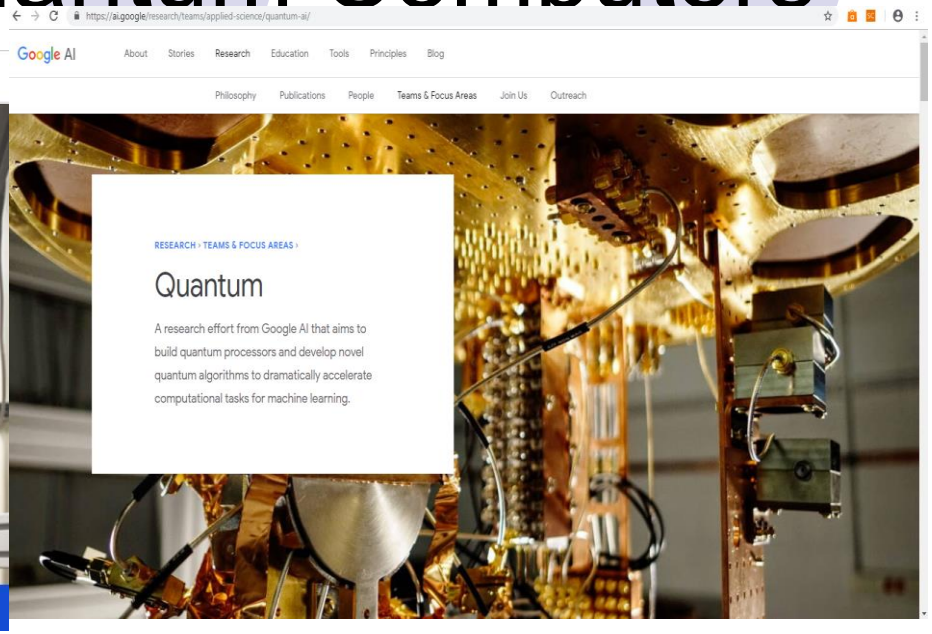


	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	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.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

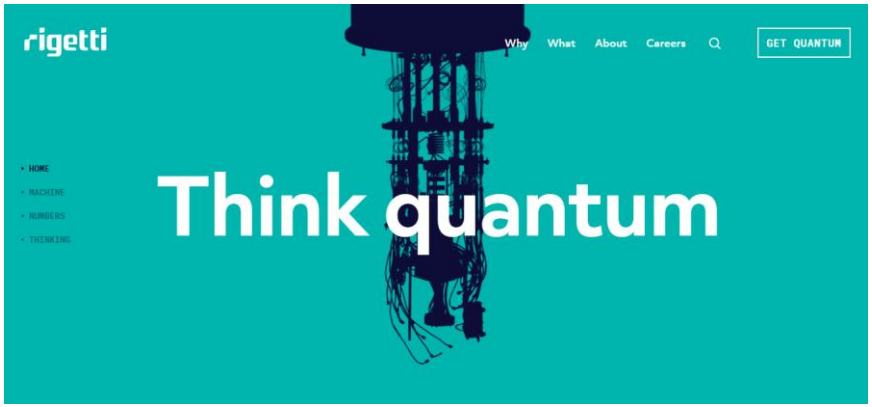
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Superconductor Quantum Computers

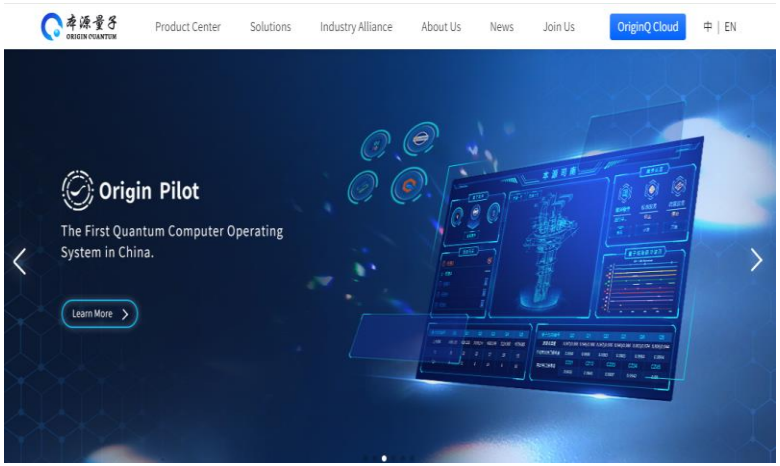
https://www.research.ibm.com/ibm-q/



https://quantumai.google/

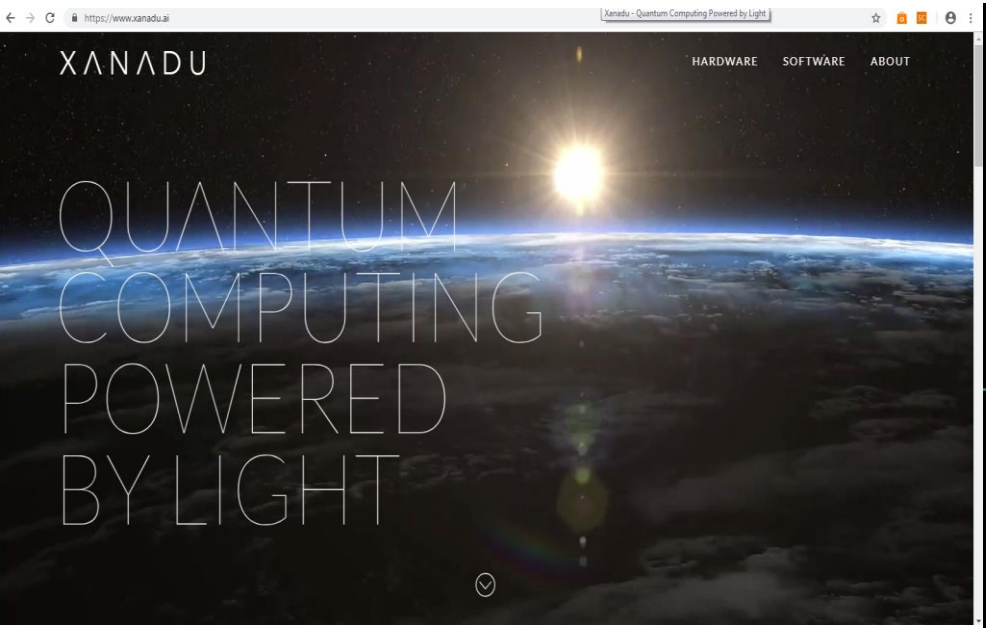


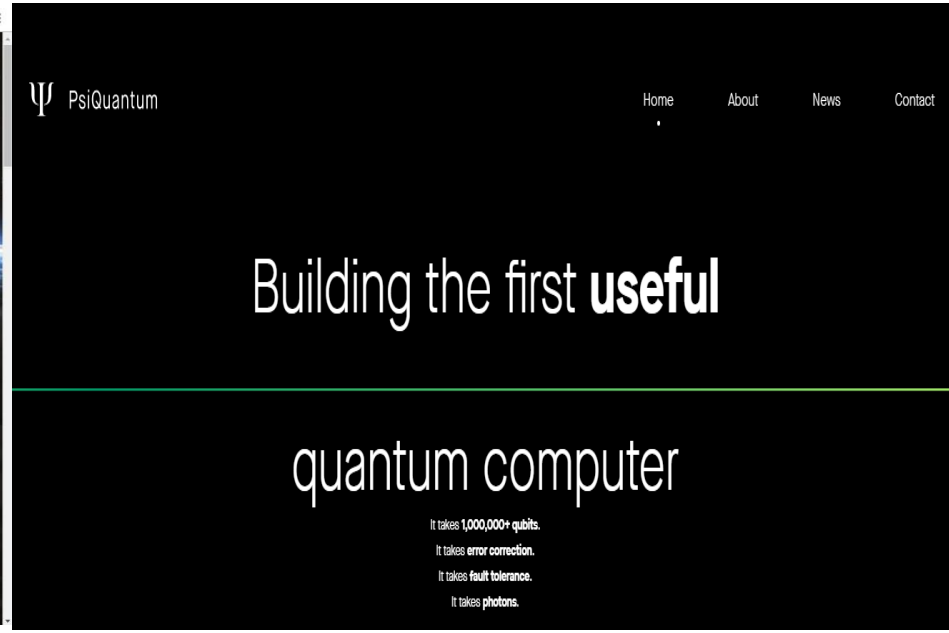
https://www.rigetti.com/



https://originqc.com.cn/en/

Photonics Quantum Computers

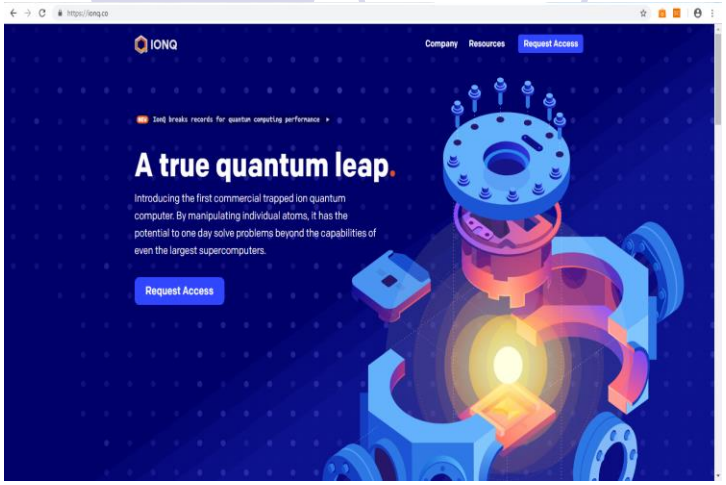




https://www.xanadu.ai/

https://psiquantum.com/

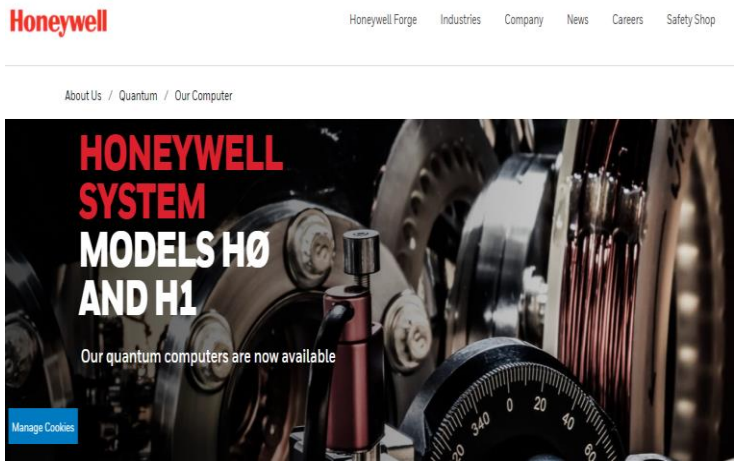
Ion Traps Quantum Computers



https://ionq.com/

OXFORD IONICS

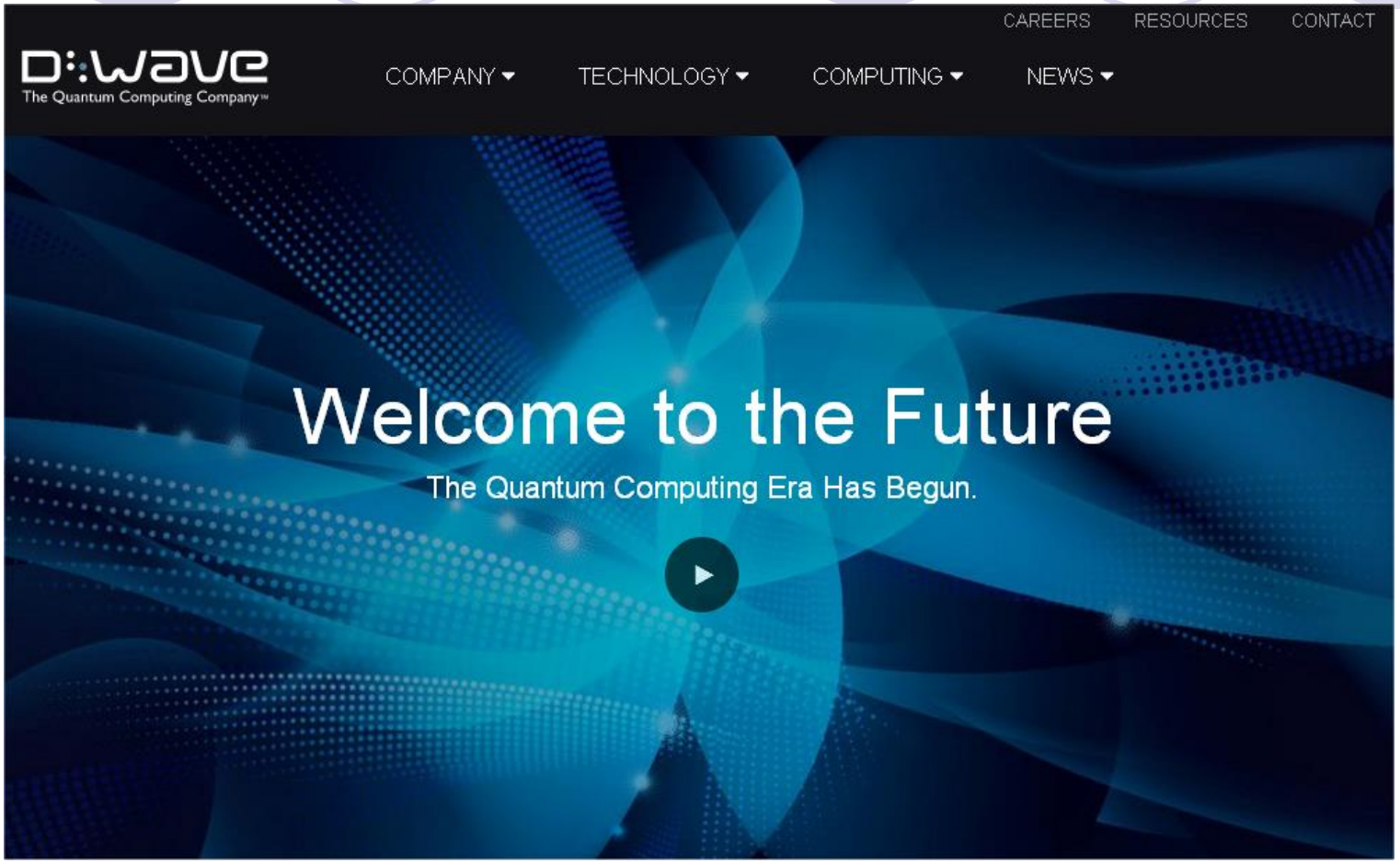
https://www.oxionics.com/



https://www.honeywell.com/us/en/company/quantum/quantum-computer

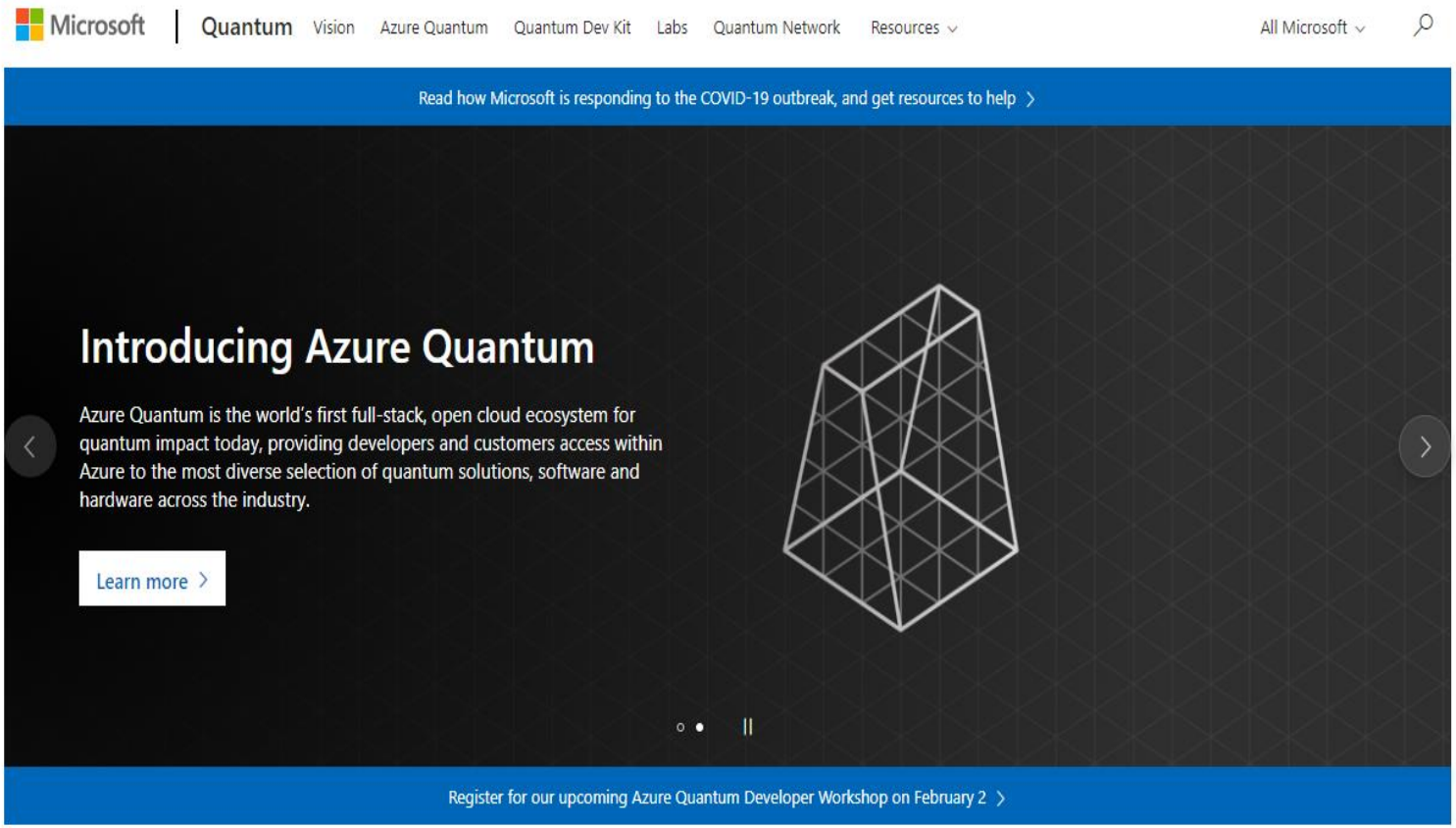
https://www.sandia.gov/quantum/

Adiabatic Quantum Computers



www.**dwave**sys.com/

Topological Quantum Computers



https://www.microsoft.com/en-us/quantum

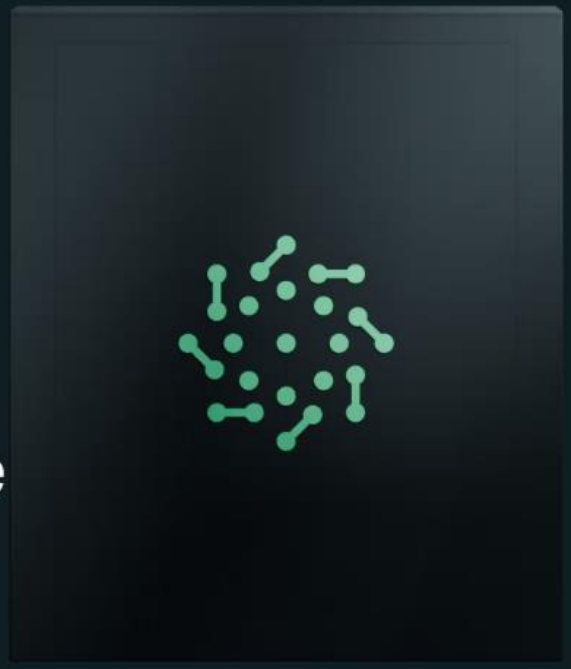
Neutral Atoms Quantum Computers

Pasqal

Contact us

01

Quantum computing has transcended the realm of theory.



It is now a viable technology with a track record of powering transformation. Advances in neutral-atom technology are now translating into tomorrow's "everyday applications." Businesses everywhere must harness this infinite potential to step into the next phase of their development.

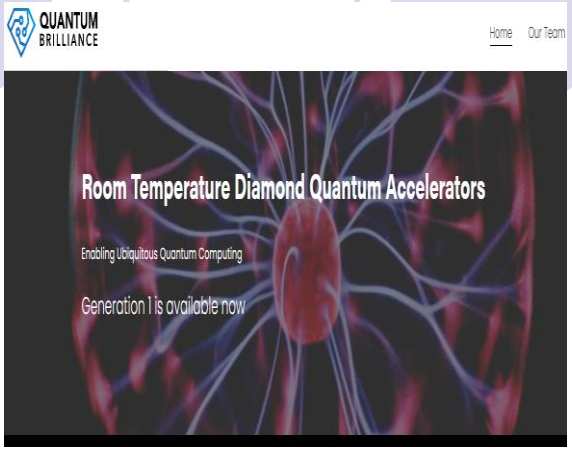
Our ambition is to breakthrough the limits of computing by leading the delivery of state-of-the-art quantum computing. At Pasqal, we have built much of the foundation that allows us to guide you through this new era. Have a look at some of the case uses that make use of the power of quantum computing. Let quantum computing find concrete solutions to your real-world challenges.

Desktop Quantum Computer

More Quantum Computers

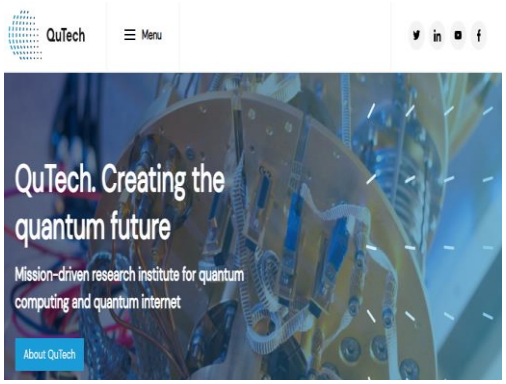
TU Delft University and Intel

https://www.tudelft.nl/en/2015/tu-delft/qutech-quantum-institute-enters-into-collaboration-with-intel



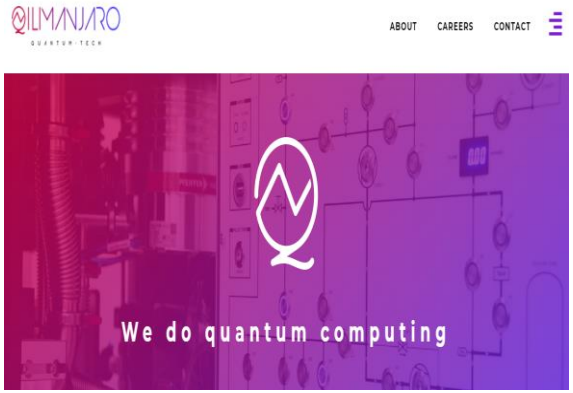
Quantum Brilliance

https://quantumbrilliance.com/



QuTech

https://qutech.nl/



Qilimanjaro

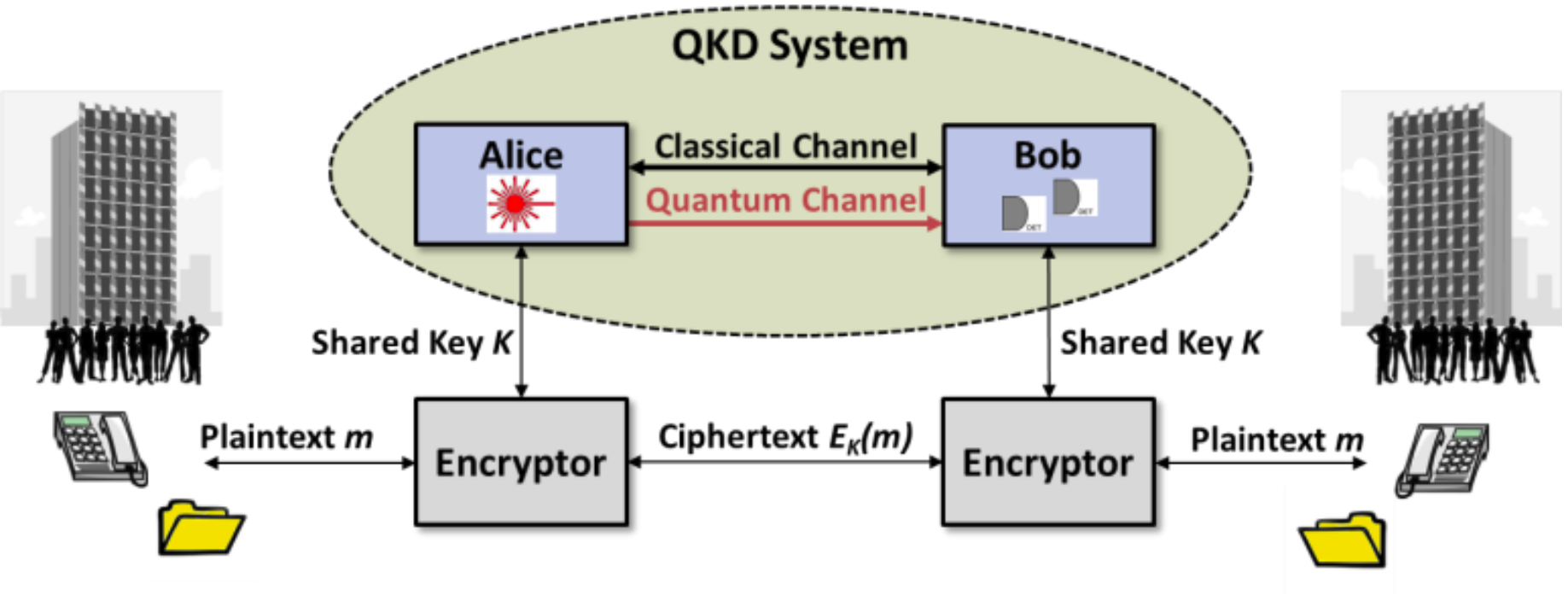
https://www.qilimanjaro.tech/

Open-Source Quantum Software Tools

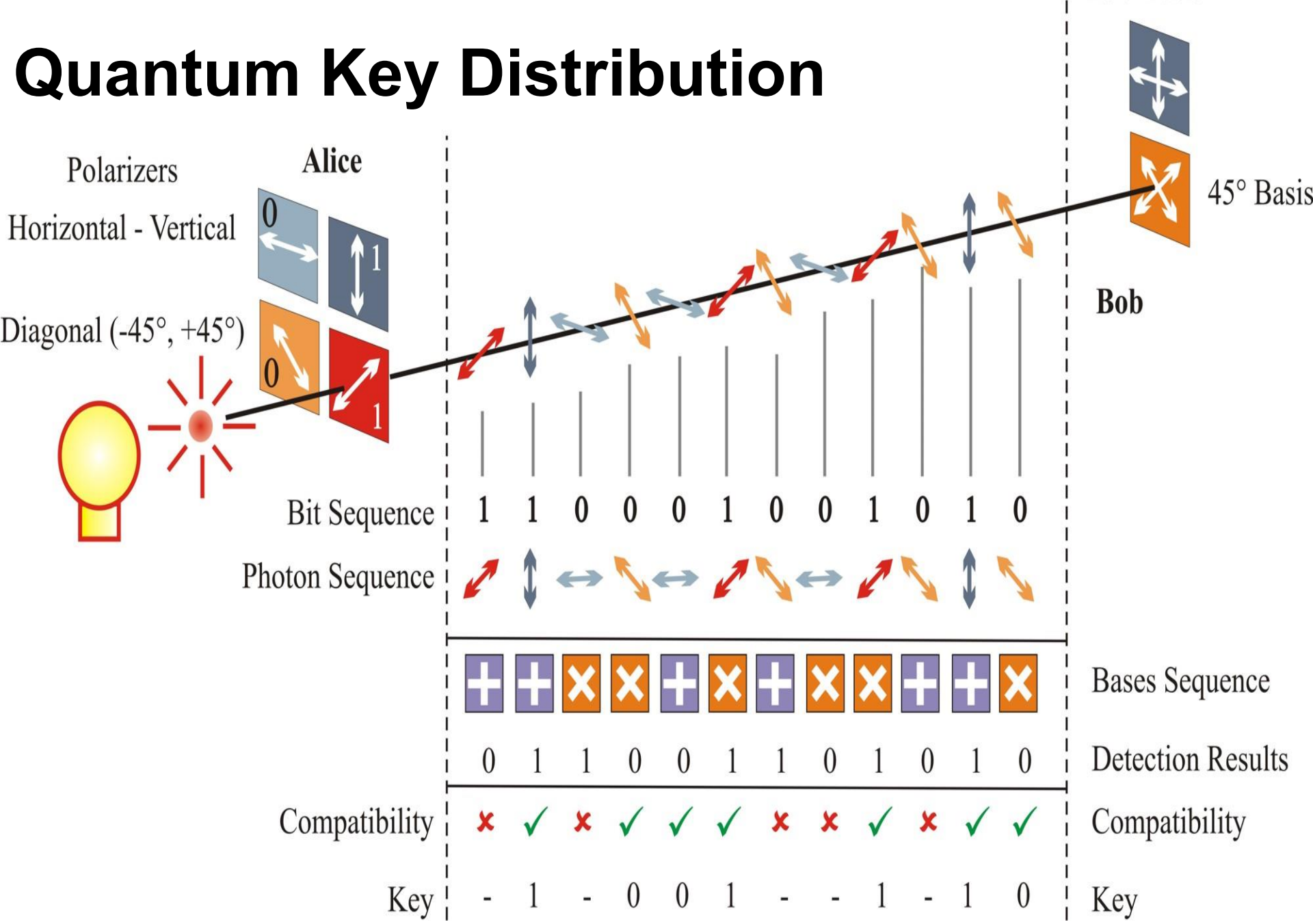
- IBM Quantum Experience (QISKIT)
- Microsoft Quantum Development Kit (Q#)
- Cirq (Google AI Quantum Team)
- PennyLane and Strawberry Fields from Xanadu
- Intel Quantum Simulator
- CAS-Alibaba Quantum Computing Laboratory
- ProjectQ
- Open Controls from Q-CTRL
- Silq
- Tequila
- Quantum User Interface (QUI)
- Quirk
- QuEST
- QuTiP: Quantum Toolbox in Python

https://quantumcomputingreport.com/tools/

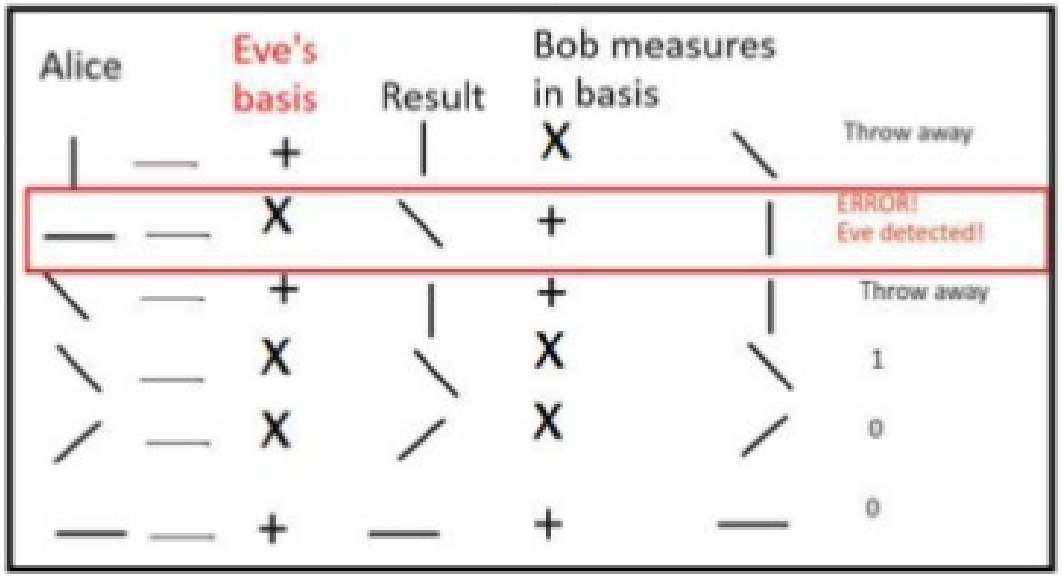
Quantum Key Distribution



Quantum Key Distribution



Eavesdropping detection:



$$P_d = 1 - \left(\frac{3}{4}\right)^n$$

$P_d = 0.99999999$ Alice and Bob need to compare $n = 72$ key bits.

- Error rate < E max → No eavesdropping
- Error rate > E max → Eavesdropping or the channel is noisy.

Alice and Bob should then discard the whole key and start over.

phy Companies

Post-Quantum

Private Cor

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United King

Post-Quantum e
authenticity and
the future. Prod
authentication,
deterrence; PQ
Chat - Ultra-secu
- Future-proof e

INCUBATOR

VENTURE FU

https://p

Single Quantum

Private Company

Founded date unknown

Netherlands

Wij leveren betrouwbare en gebruiksvriendelijke complete detectiesystemen gebaseerd op 'superconducting nanowire singl detectors' (SNSPDs), die gevoelig golflengtegebied van UV tot het r infrarood. Wij zijn het eerste bed

INCUBATOR / ACCELERATOR BACK

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NuCrypt LLC

Private Company

Founded 2003

USA

tical encryption
mmunications and
product,
ced
with quantum
, and high-speed

.net

Lattice

Private Company

Founded date unknown

Estonia

The era of quantum computer is already in front of me. In the cryptography used in the current cryptographic currency, it is broken by the quantum computer, and its cryptographic currency becomes useless. In the quantum era, we developed a cryptographic currency that can be safely used. By using the quantum

http://www.lattice.com/

CUBE

Private Company

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AET, Inc.

n/a

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Crypta Consultancy

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Founded 2015

United Kingdom

Crypta Consultancy is a cybersecurity advisory service in Cybersecurity, Cryptography and Quantum Cryptography. We specialises in Automotive, Financial Services, Oil & Gas, Online Gaming & Gambling, Print & Digital, Media, Research, Shipping, Logistics & Transportation, Telecommunications, and

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Quantum Resistant Ledger

Found

The QRL wi
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Private Company

Founded 2003

Switzerland

ID Quantique (IDQ) is the leader in high-performance multi-protocol network encryption based on conventional and quantum technologies. The company provides network security solutions and services to the financial industry, defence and government organizations and other enterprises globally. It

SPIN-OFF

http://www.idquantique.com/

Founded in 2001, Geneva based startup ID Quantique has taken in around **$5.6 million** in funding to develop an entire suite of quantum cryptography solutions that are divided into three areas. The first area is quantum random number generators (QRNGs) that can plug into a PCI slot or USB port. You would actually need 60 of these PCI QRNG devices to equal 1 of the qStream devices from Quintessence Labs we discussed earlier. The second business area of IDQ is photon counting hardware like the appliances seen below:

ID100 VIS BEST DARK COUNT RATE

- Silicon Avalanche Photodiode
- 350-900nm
- Free-Running
- 40ps Timing Resolution
- Low Dark Count Rate <5Hz
- 35% Quantum Efficiency
- Highly Reliable

PRODUCT DETAILS

ID230 NIR BEST DARK COUNT RATE

- InGaAs/InP APD
- 900-1700nm
- Free-Running
- Best dark count rate (<50Hz)
- 200ps Timing Resolution (<100ps on request)
- Single mode or multimode fiber connection

PRODUCT DETAILS

ID110 VIS 100MHZ PHOTON DETECTOR

- Silicon Avalanche Photodiode
- 350-900nm
- Free-Running and Gated
- Adjustable Deadtime
- 200ps Timing Resolution
- Low Dark Count Rate
- 25% Quantum Efficiency

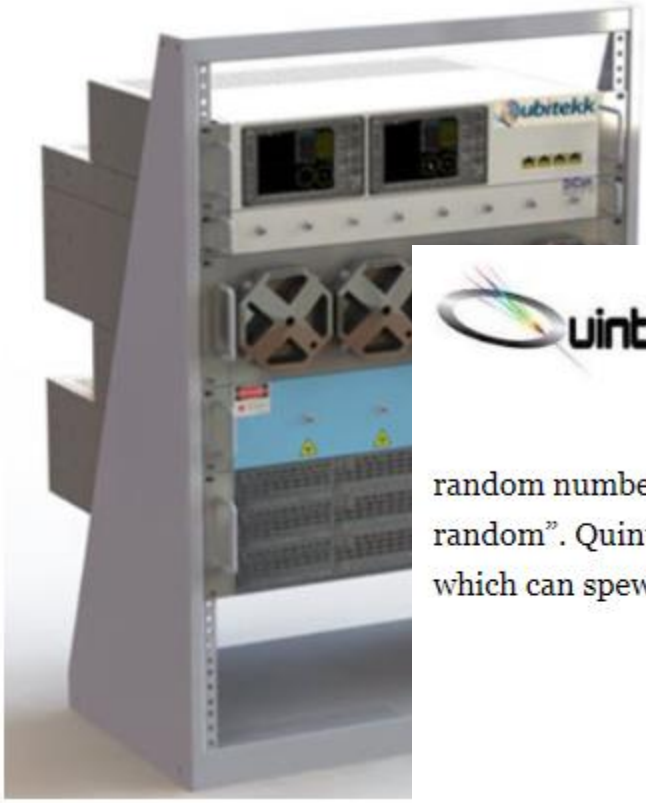
PRODUCT DETAILS

ID210 NIR 100MHZ GATED DETECTOR

- InGaAs/InP APD
- 900-1700nm
- Gated and Free-Running
- 100MHz Trigger Rate
- Lowest Dark Count Rate
- 30% Quantum Efficiency
- Most Versatile Device

PRODUCT DETAILS

Founded in 2012, Qubitekk has taken in at least **$2 million** in funding (in additions to various grants) in order to develop a machine-to-machine communication device that can help protect critical infrastructure like electrical grids or oil pipelines. Their solution works as follows:



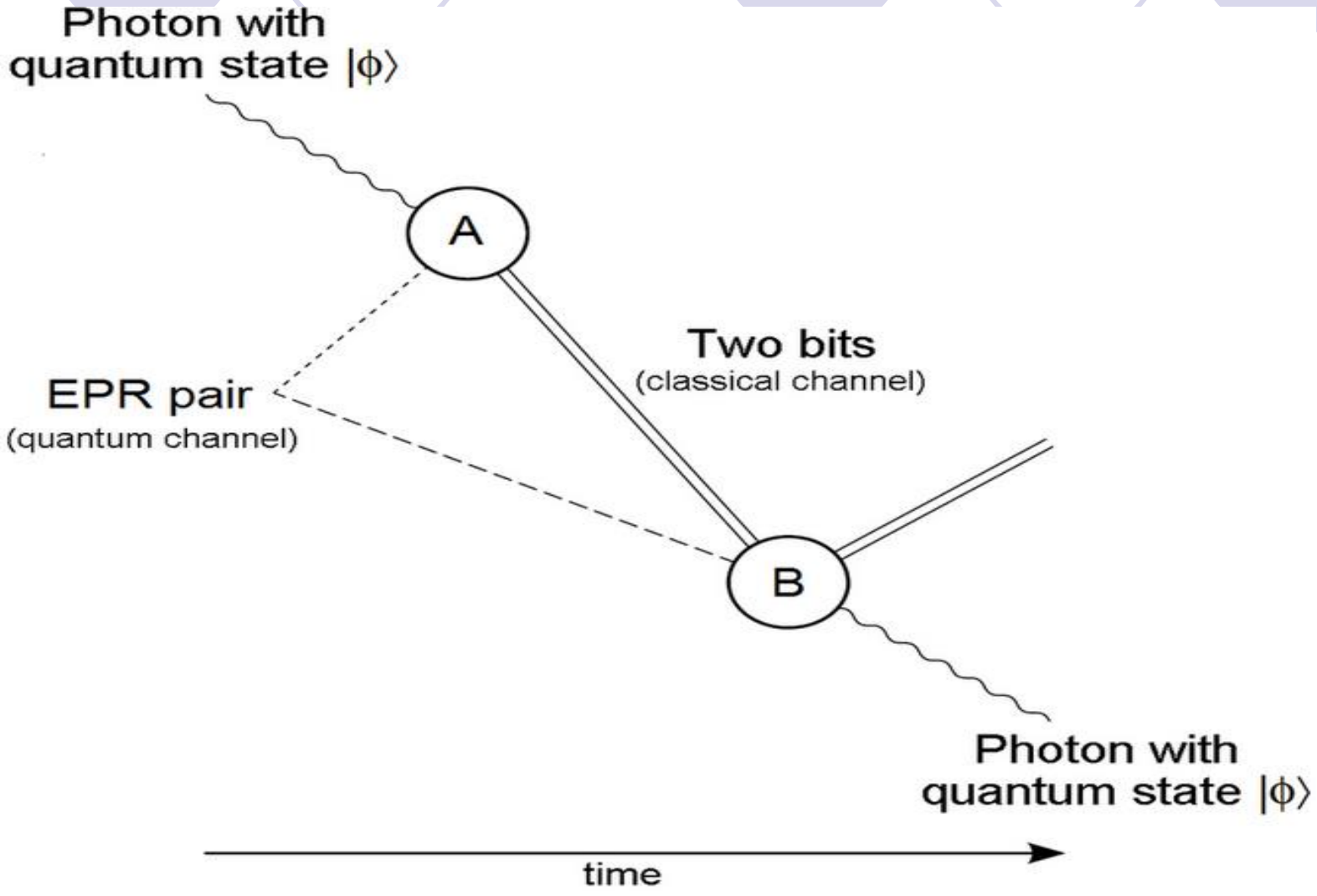
4 Controller – Randomly configures switch

3 Fiber Optic Switch – Routes entangled photons

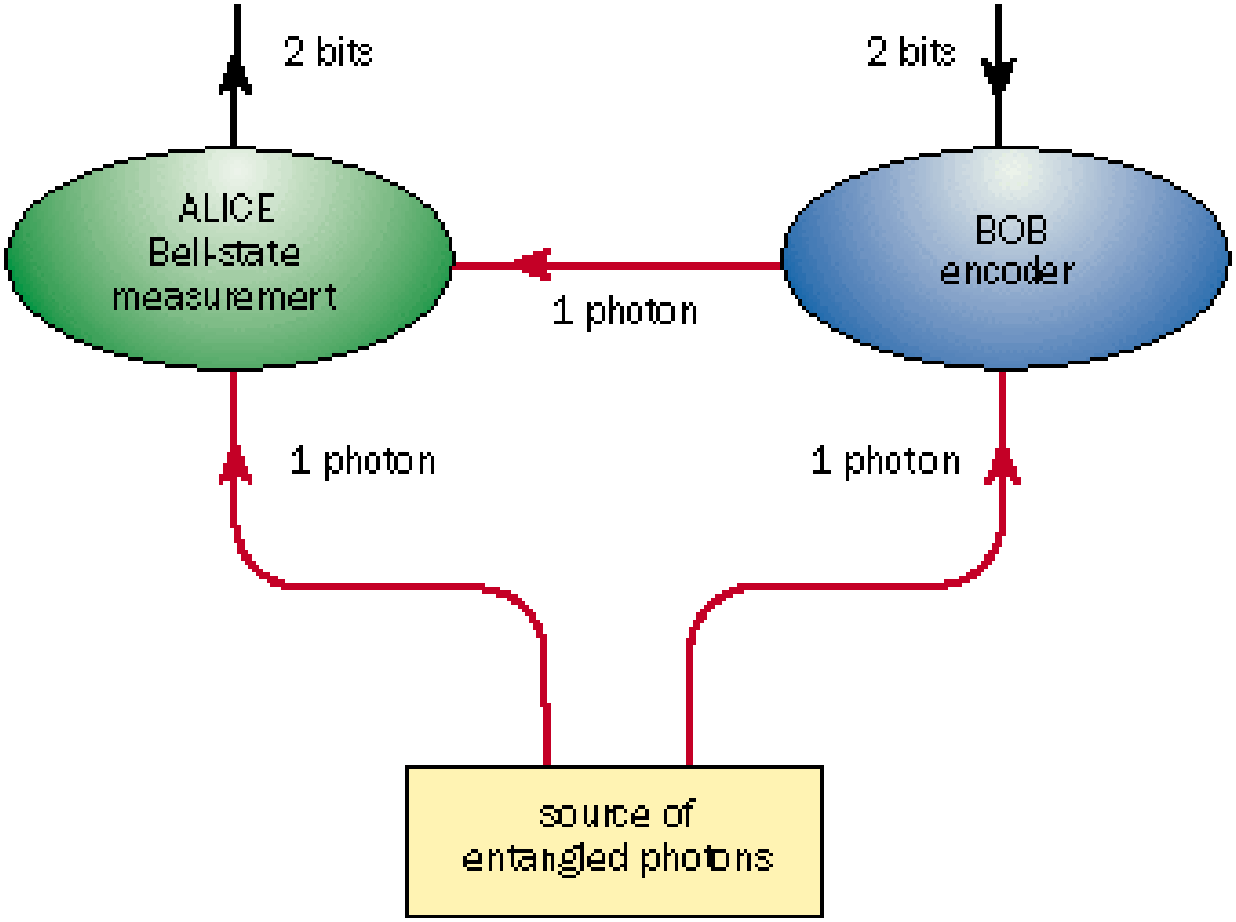
Founded in 2006, Australian firm Quintessence labs has taken in an **undisclosed** amount of funding to develop an entire suite of quantum security products. In the world of computer programming, and particularly in cryptography, there are many ways to generate a random number. Present random number generation uses algorithms so that they are not "truly random". Quintessence Labs has built a Quantum Random Number Generator (QRNG) called qStream which can spew forth random numbers at a rate of 1 gigabit per second.

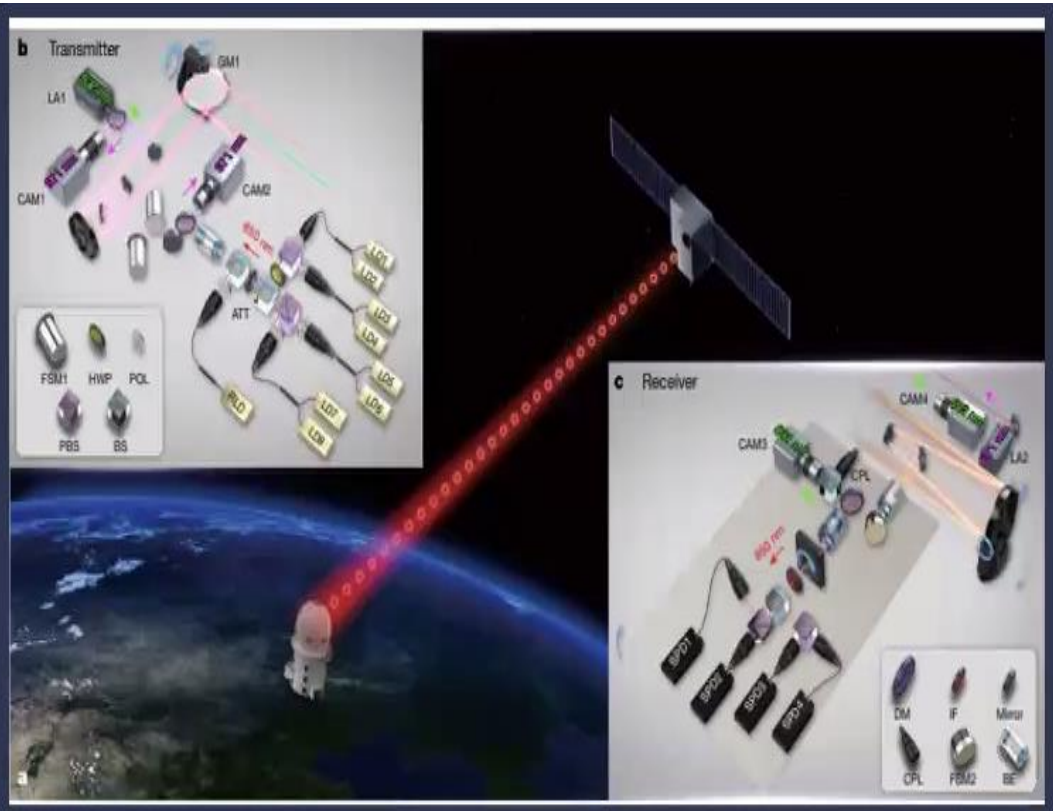
qStream™

Quantum Teleportation

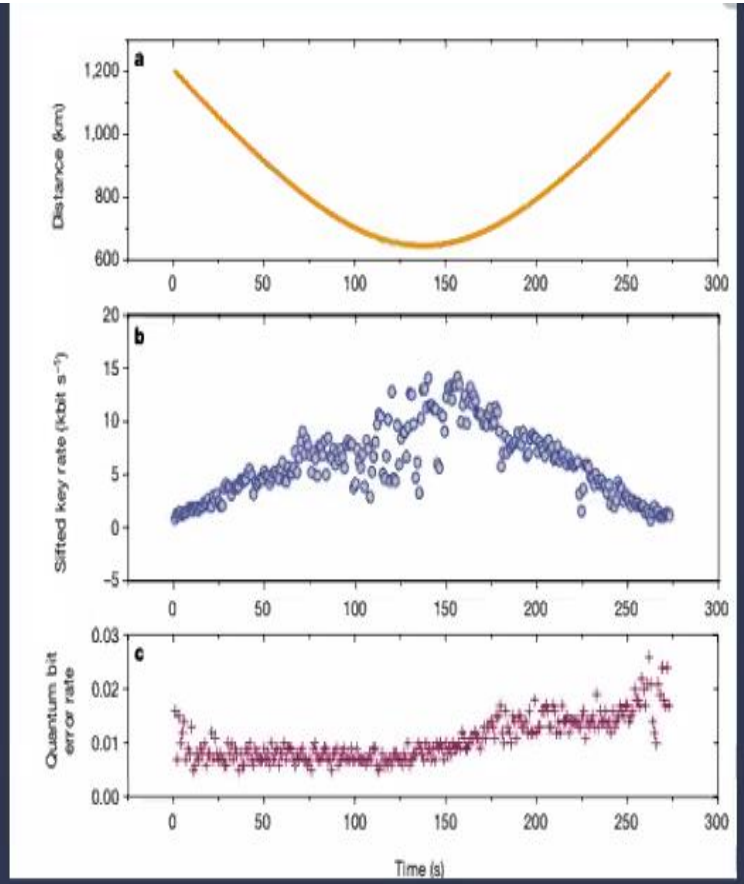


Quantum Dense Coding

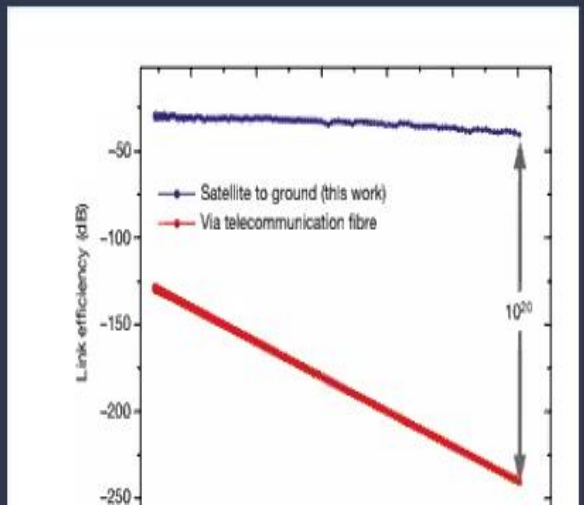


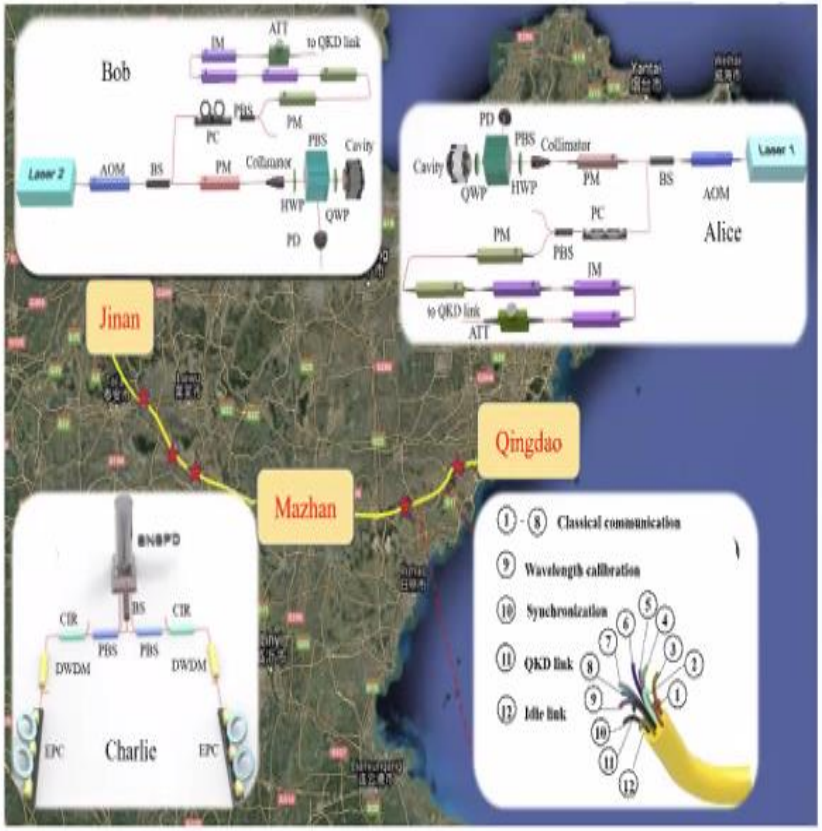


Liao et al. 2017

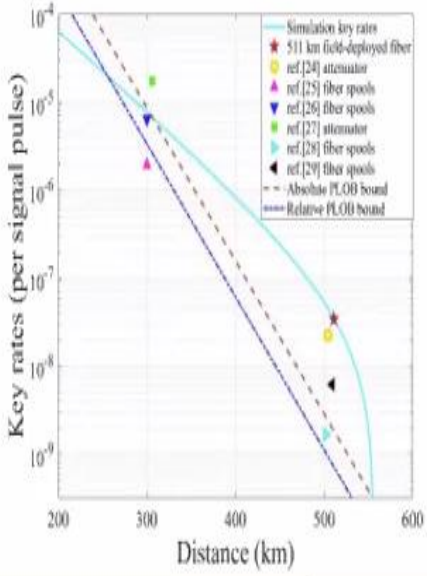


BB84 QKD using a satellite link





Chen et al . 2021

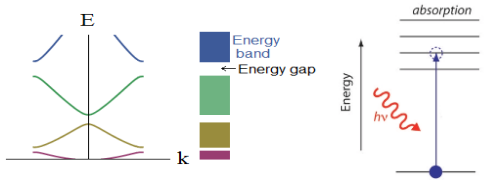


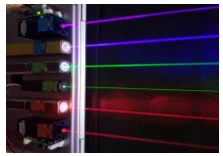
TF-QKD

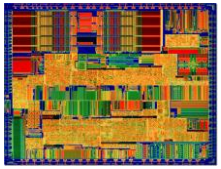
INTERNATIONAL YEAR OF
Quantum Science and Technology

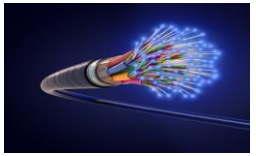
100 Years of Quantum Mechanics is just beginning…

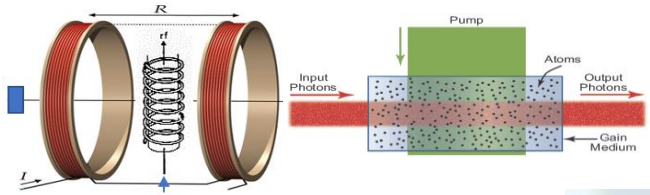
1925 → 2025

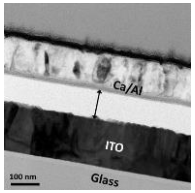


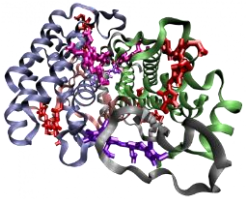


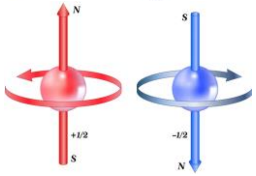


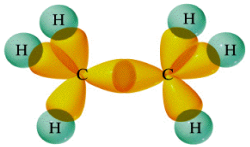


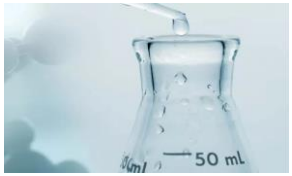


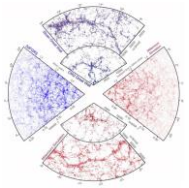












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www.quantum2025.org

100 years of quantum is just the beginning...