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Quantum Artificial Intelligence

Let Nature Solve the Problem

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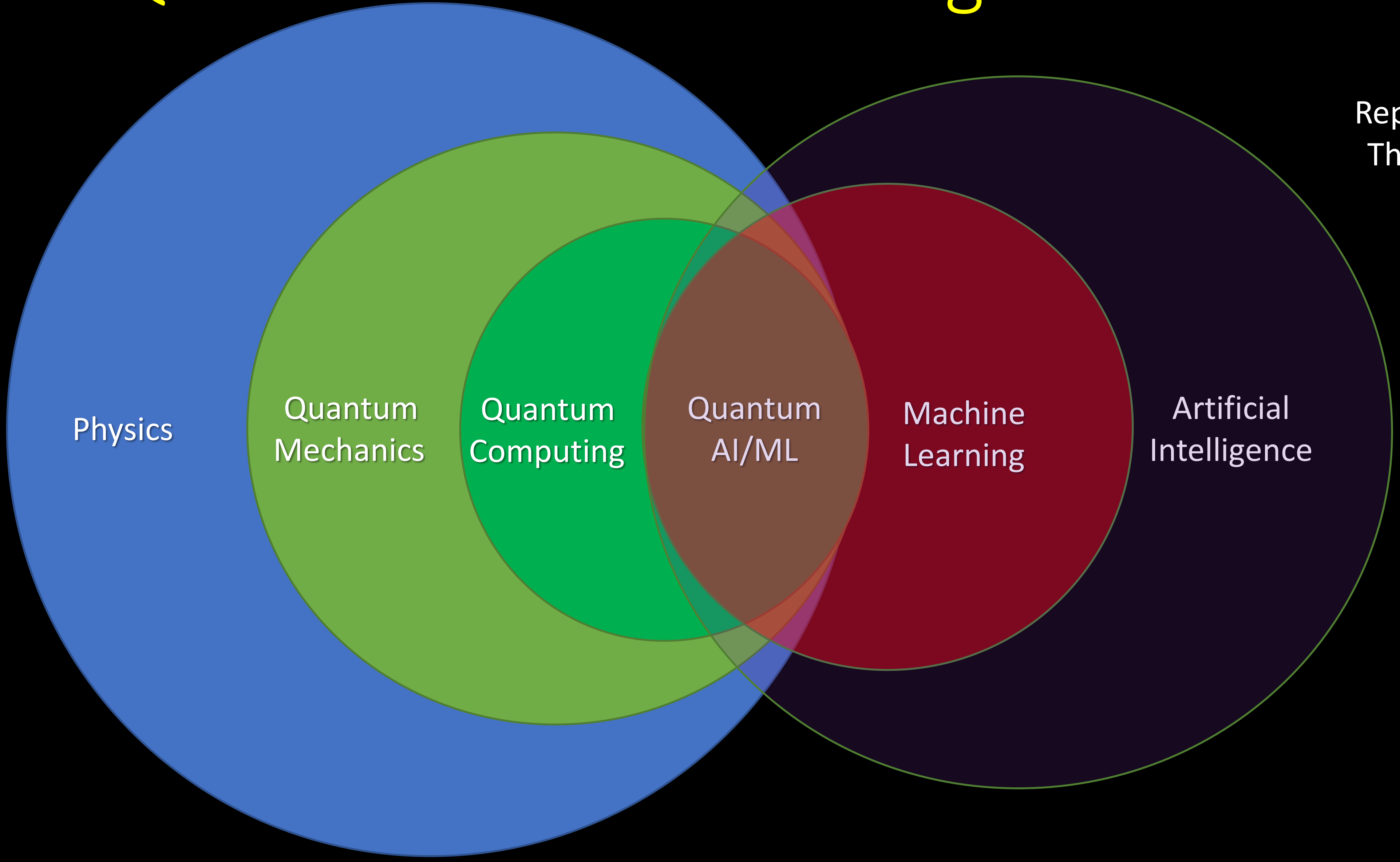
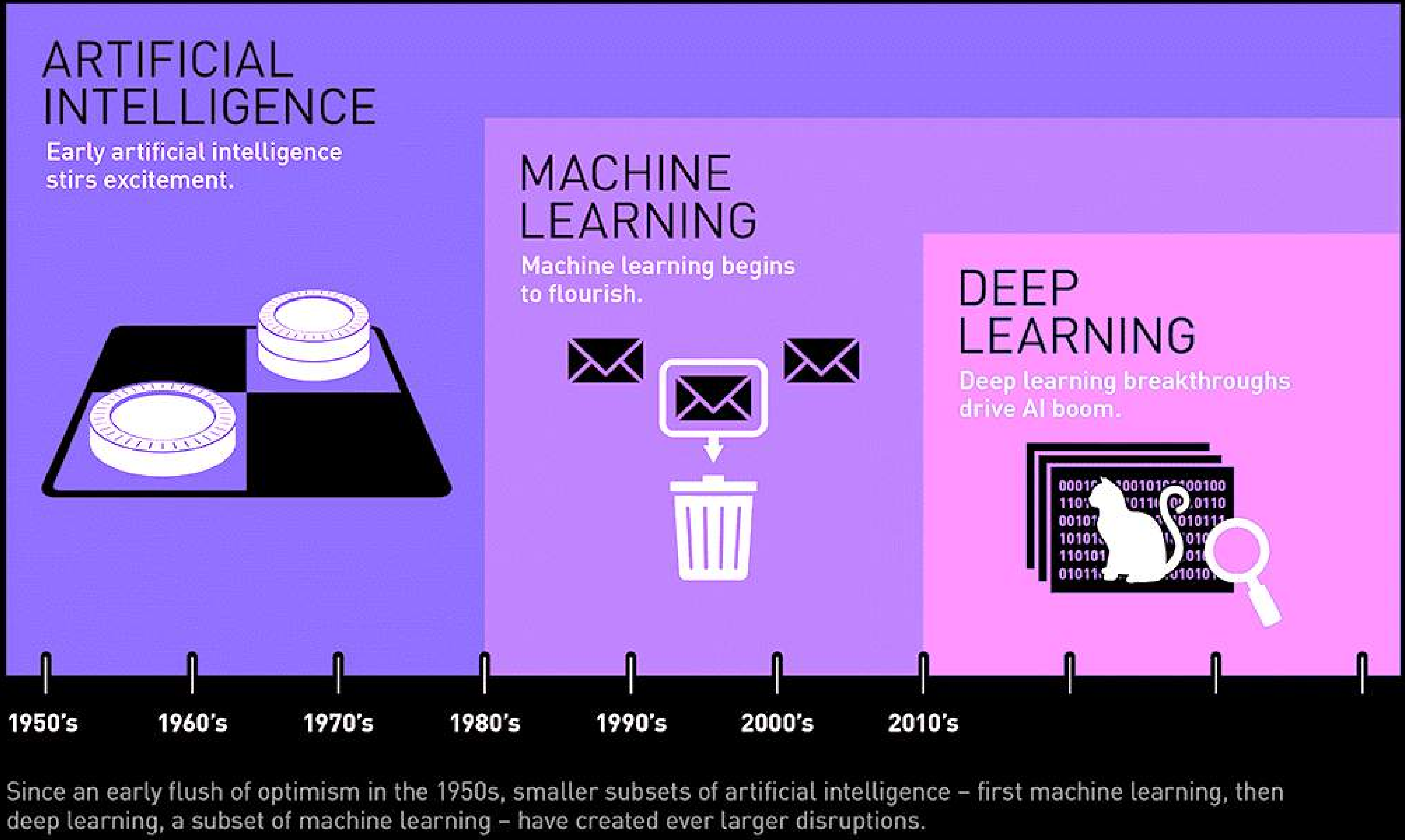
High Performance Computing Research Group
Faculty of Information Technology, Universitas Kristen Maranatha

Quantum Artificial Intelligence



A “rough” Representation of The overlapping fields

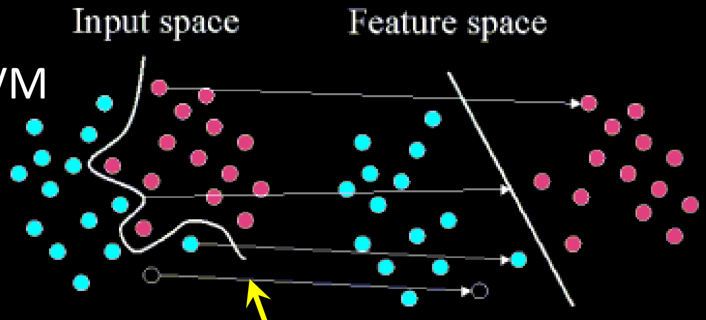
Artificial Intelligence

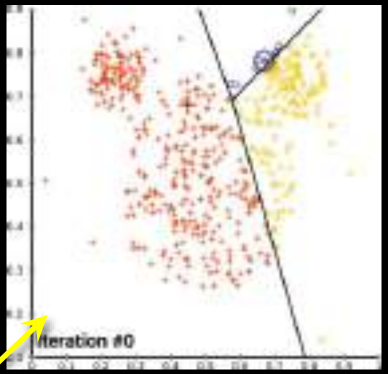


https://blogs.nvidia.com/blog/2016/07/29/whats-difference-artificial-intelligence-machine-learning-deep-learning-ai

Artificial Intelligence: Machine Learning

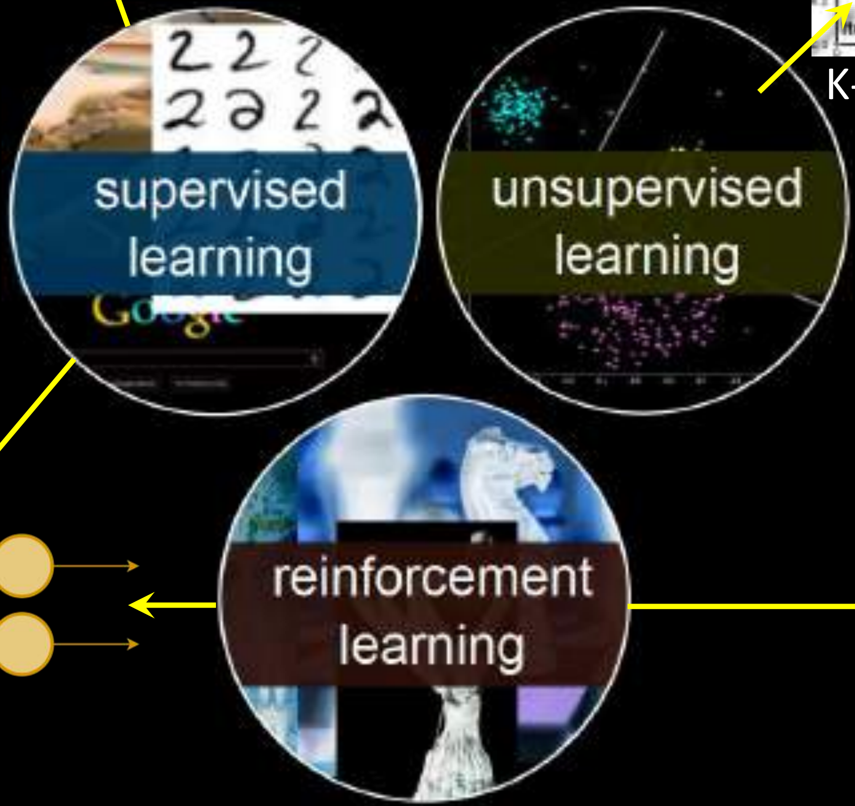
SVM





K-means clustering

Machine (Statistical) Learning algorithm is based on finding suitable statistical models (functions) which map input data into output (predictions)



Deep NN

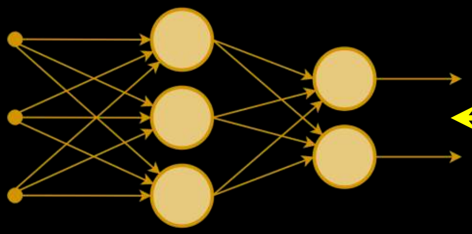


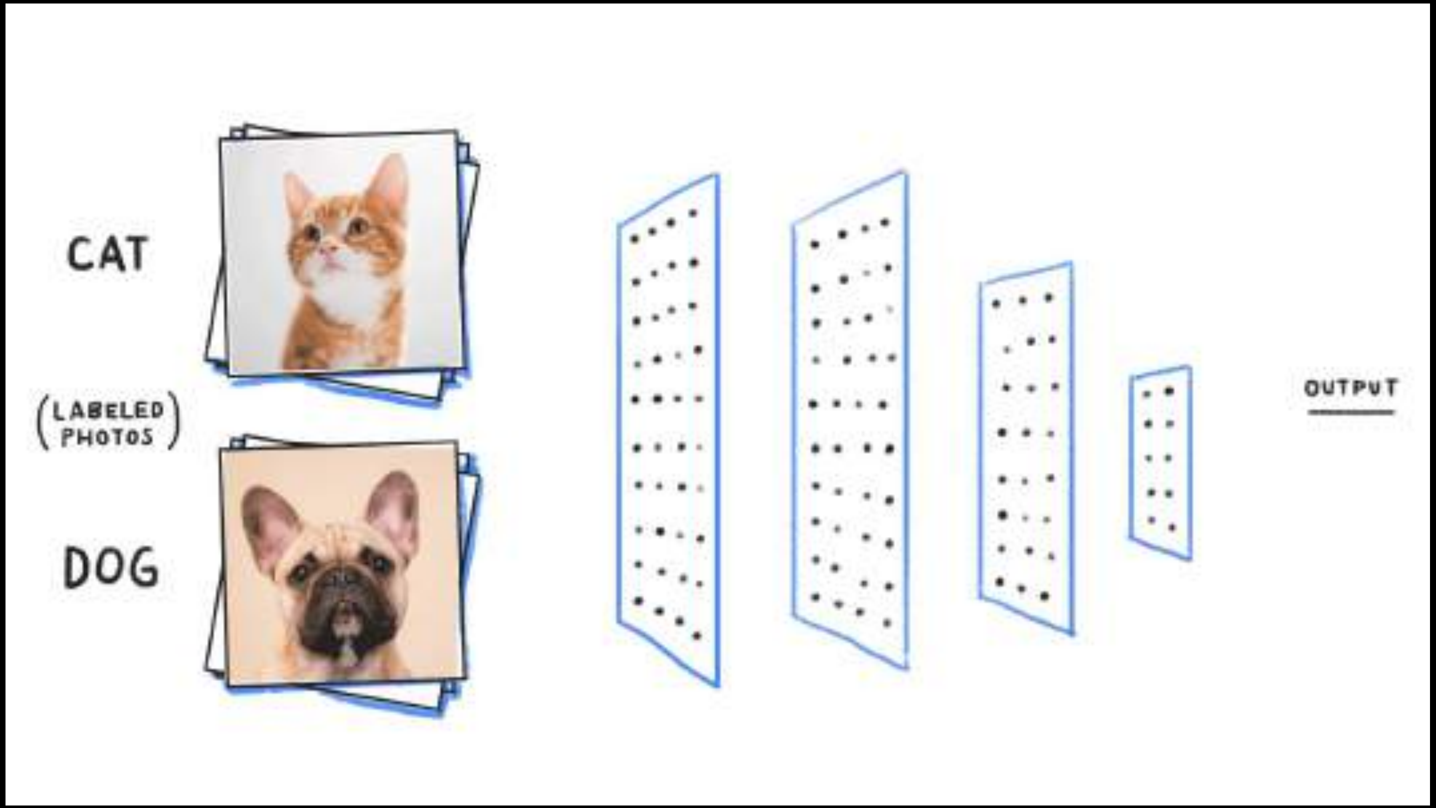
image: https://towardsdatascience.com/enjoy-the-go-with-alpha-go-e1172afdb322

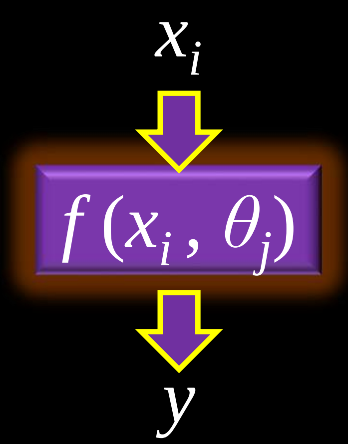
*Silver, D., Schrittwieser, J., Simonyan, K. et al. *Mastering the game of Go without human knowledge*. Nature 550, 354–359 (2017)

Artificial Intelligence: An Example of ML

Supervised Learning:

Simple Image Classification using Convolutional Neural Network[1]





<u>In Principle</u>:

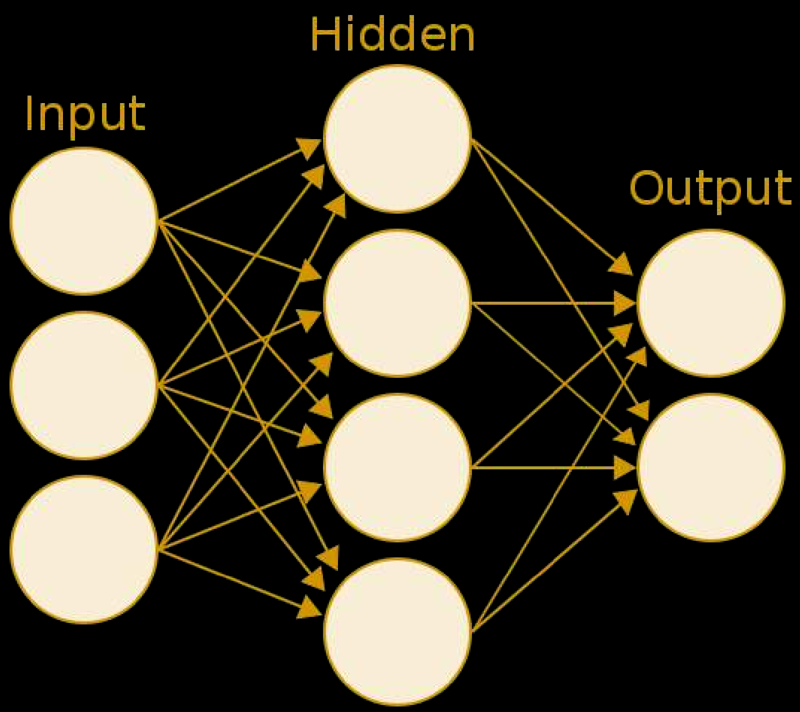
The algorithm learns how f maps x_i into y, on varying parameters θ_j, such that when given x, it can correctly predict y after trained with previously known (x_i, y).

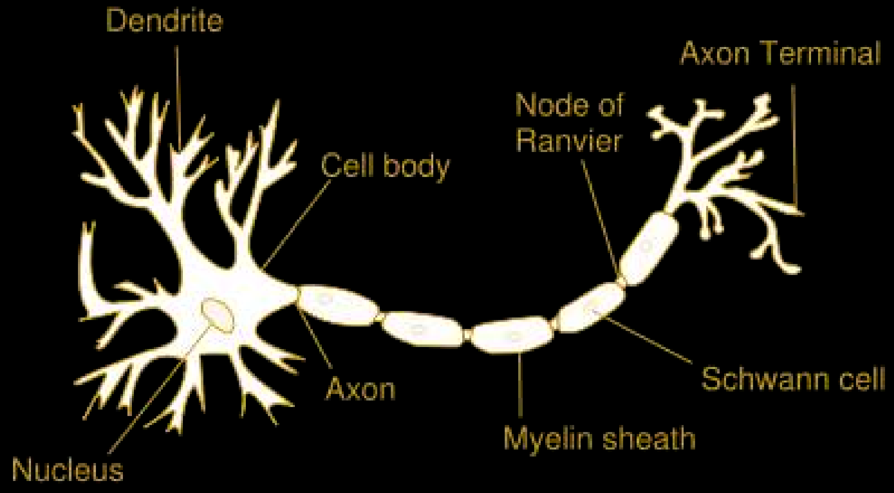
1. https://becominghuman.ai/building-an-image-classifier-using-deep-learning-in-python-totally-from-a-beginners-perspective-be8dbaf22dd8

Artificial Intelligence

Artificial Neural Networks (ANN):

- Basis for some AI algorithms
- Applications in classification, speech recognition, pattern recognition, …
- Every "neuron" is designed to work as functionality of biological neuron.

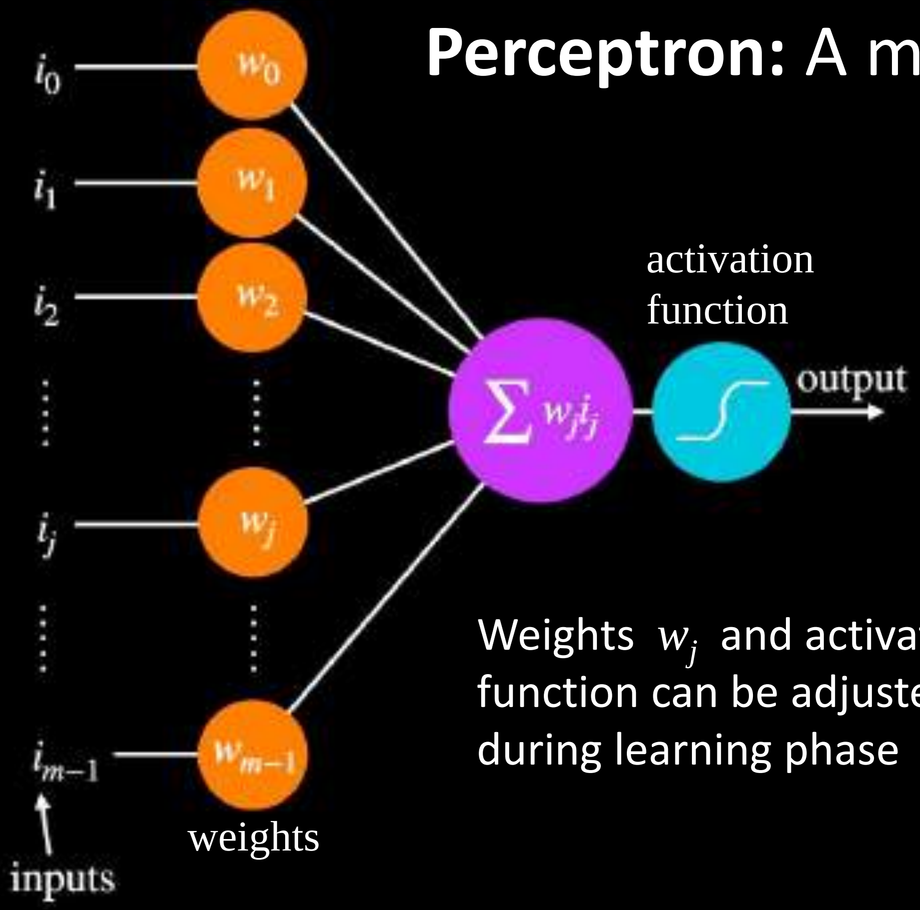




Images: Wikipedia.org

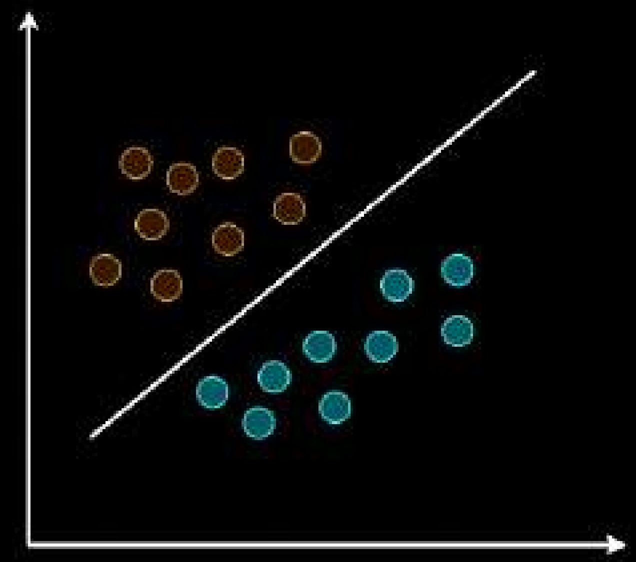
Artificial Intelligence

Perceptron: A model of artificial neuron[1, 2]



Weights w_j and activation function can be adjusted during learning phase

Classical perceptron is the simplest linear classifier



1. Rosenblatt, F. *The perceptron: A probabilistic model for information storage and organization in the brain*. Psychological Review, 65(6), 386–408 (1958)

2. Tacchino, F., Macchiavello, C., Gerace, D. et al. *An artificial neuron implemented on an actual quantum processor*. npj Quantum Inf 5, 26 (2019)

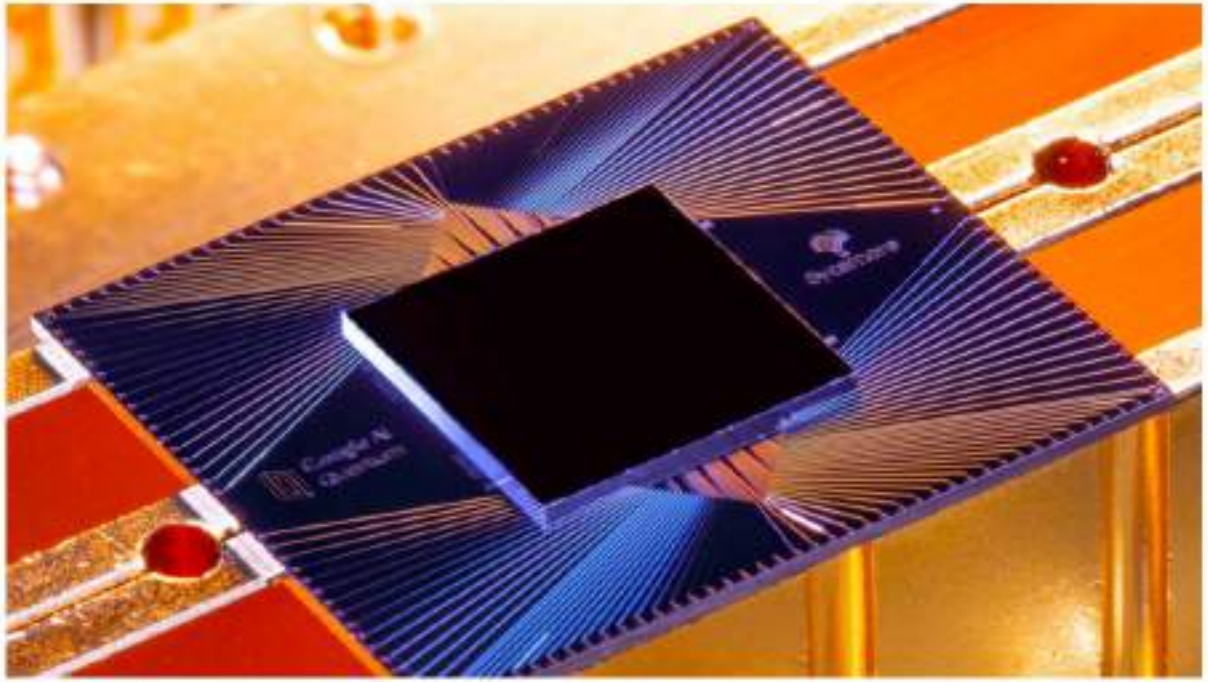
Quantum Computing

sciencenews.org/article/google-quantum-computer-supremacy-claim

NEWS QUANTUM PHYSICS

Google officially lays claim to quantum supremacy

A quantum computer reportedly beat the most powerful supercomputers at one type of calculation



Google researchers report that their quantum computer, Sycamore, has performed a calculation that can't be achieved with any classical computer. The quantum chip (shown) must be cooled to near absolute zero to function.

F. ARUTE ET AL/NATURE 2019

Quantum Computing

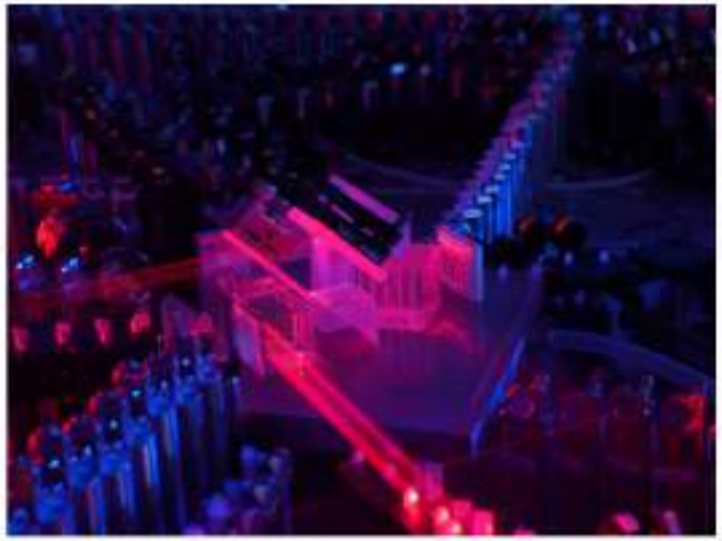
nature.com/articles/d41586-020-03434-7

NEWS · 03 DECEMBER 2020

Physicists in China challenge Google's 'quantum advantage'

Photon-based quantum computer does a calculation that ordinary computers might never be able to do.

Philip Ball



This photonic computer performed in 200 seconds a calculation that on an ordinary supercomputer would take 2.5 billion years to complete. Credit: Hansen Zhong

PDF version

Related Articles

Chaoyang Lu: Quantum wizard

Hello quantum world! Google publishes landmark quantum supremacy claim

Beyond quantum supremacy: the hunt for useful quantum computers

Subjects

Quantum information

Optics and photonics

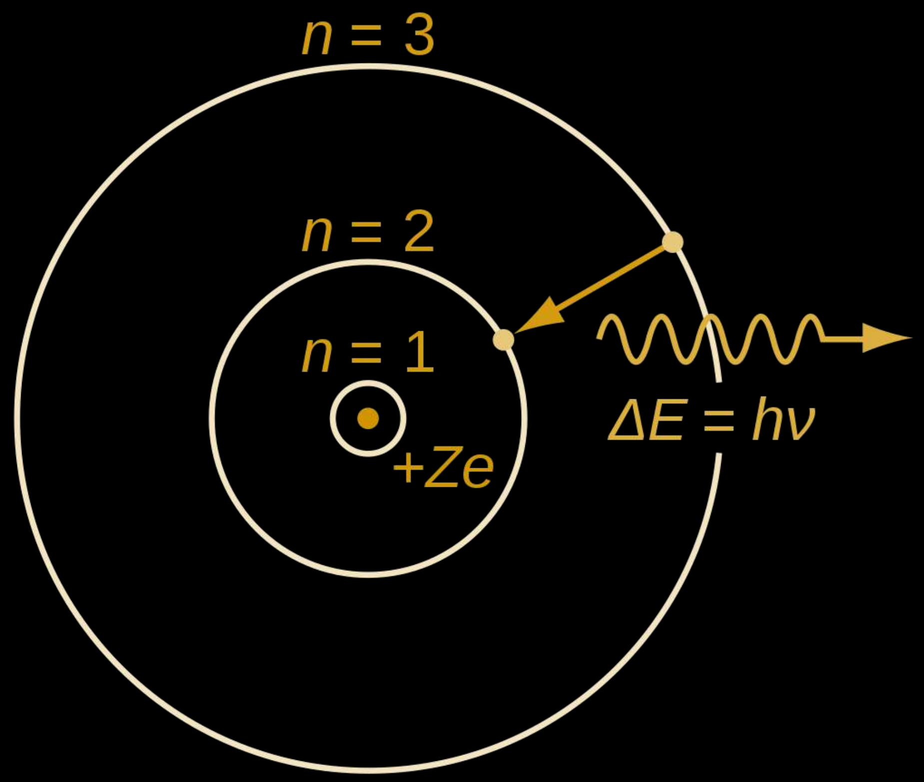
Quantum physics

Quantum Mechanics

History of the word "quantum":

Niels Bohr's 1913 quantum model of the atom, which incorporated an explanation of Johannes Rydberg's 1888 formula, Max Planck's 1900 quantum hypothesis, i.e. that atomic energy radiators have discrete energy values ($\varepsilon = h\nu$), J. J. Thomson's 1904 plum pudding model, Albert Einstein's 1905 light quanta postulate, and Ernest Rutherford's 1907 discovery of the atomic nucleus. Note that the electron does not travel along the black line when emitting a photon. It jumps, disappearing from the outer orbit and appearing in the inner one and cannot exist in the space between orbits 2 and 3.

Source: Wikipedia.org



Quantum Mechanics:

The Heisenberg's uncertainty principle:

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

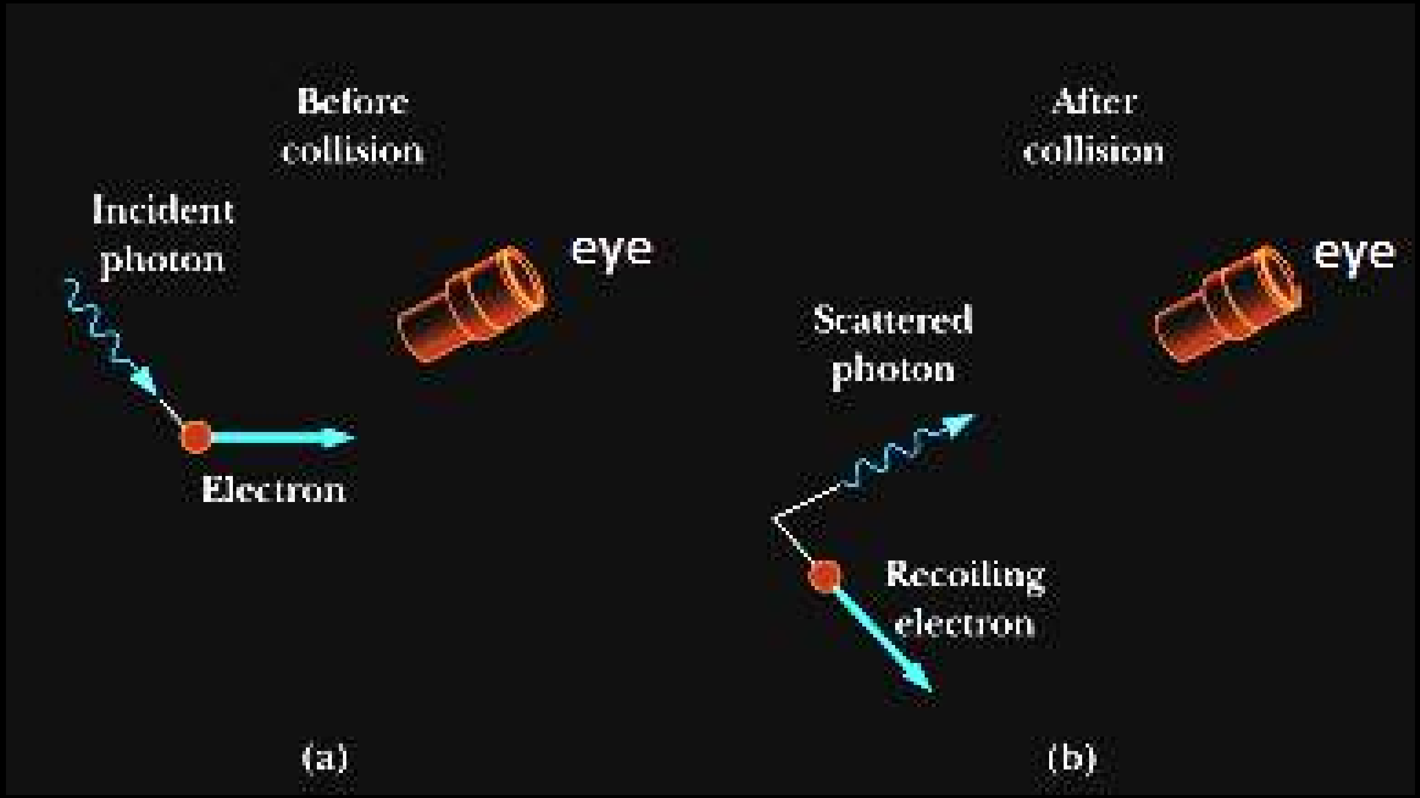
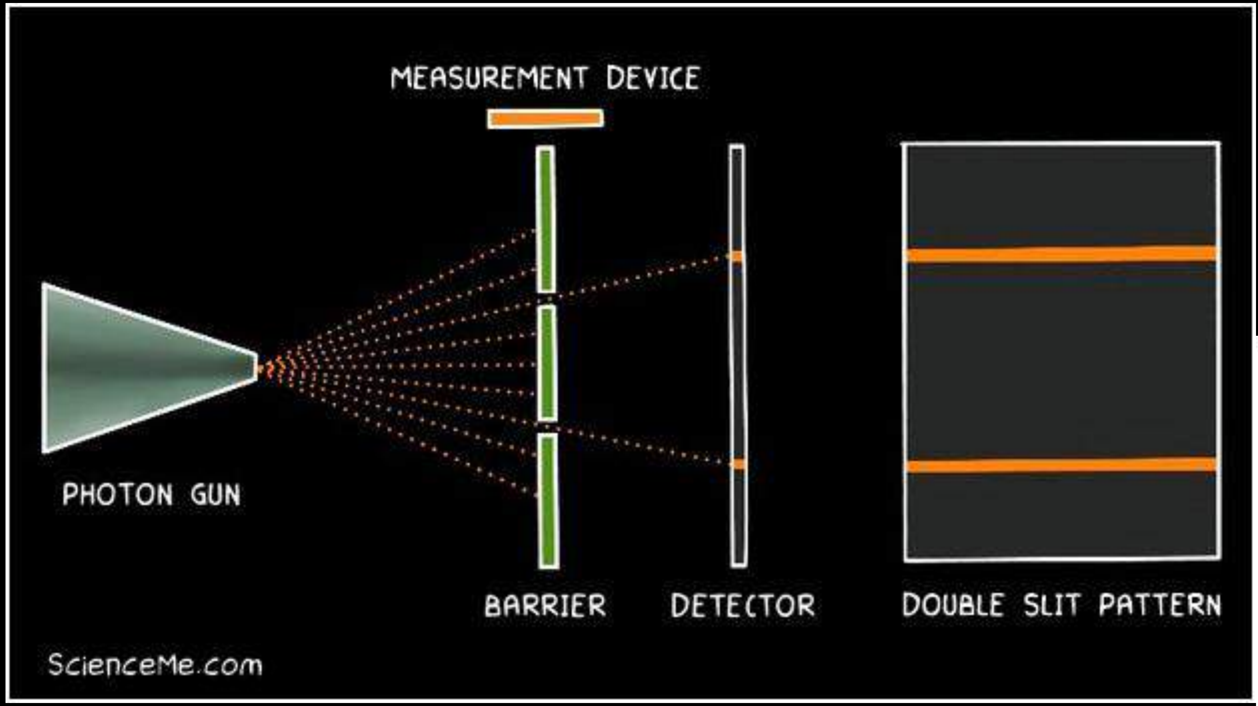


Image credit: https://physicscatalyst.com/graduation/heisenberg-uncertainty-principle

Quantum Mechanics: The Double Slit Experiment



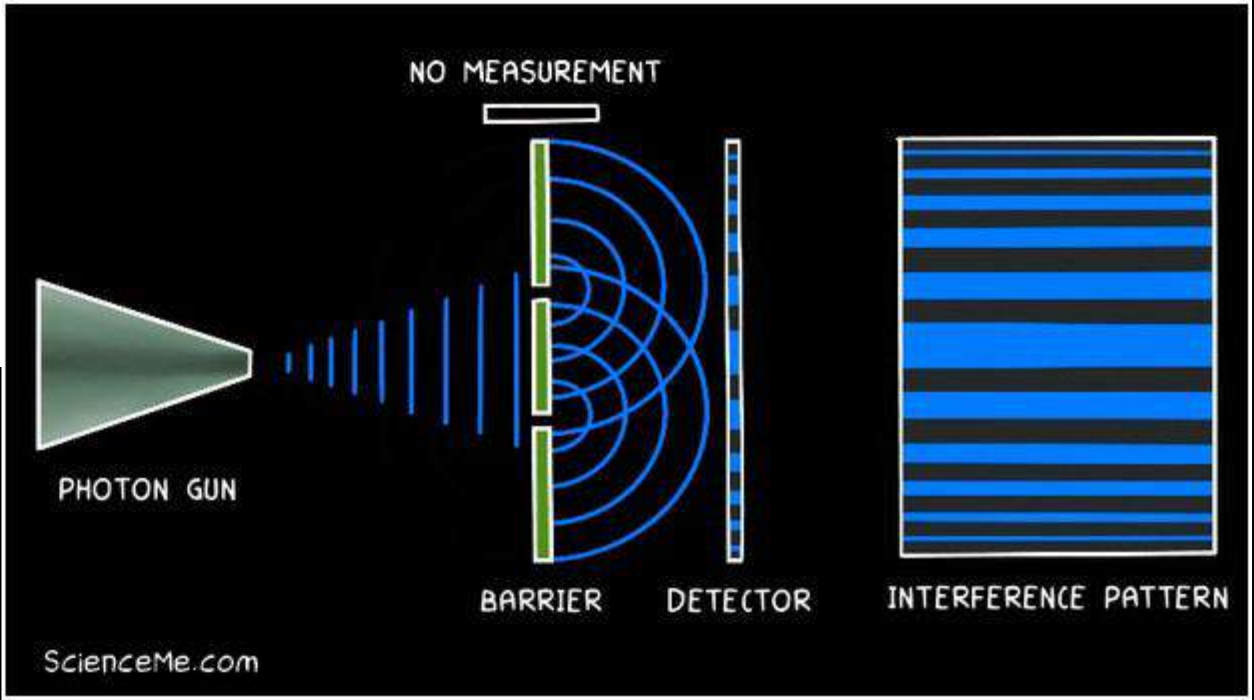
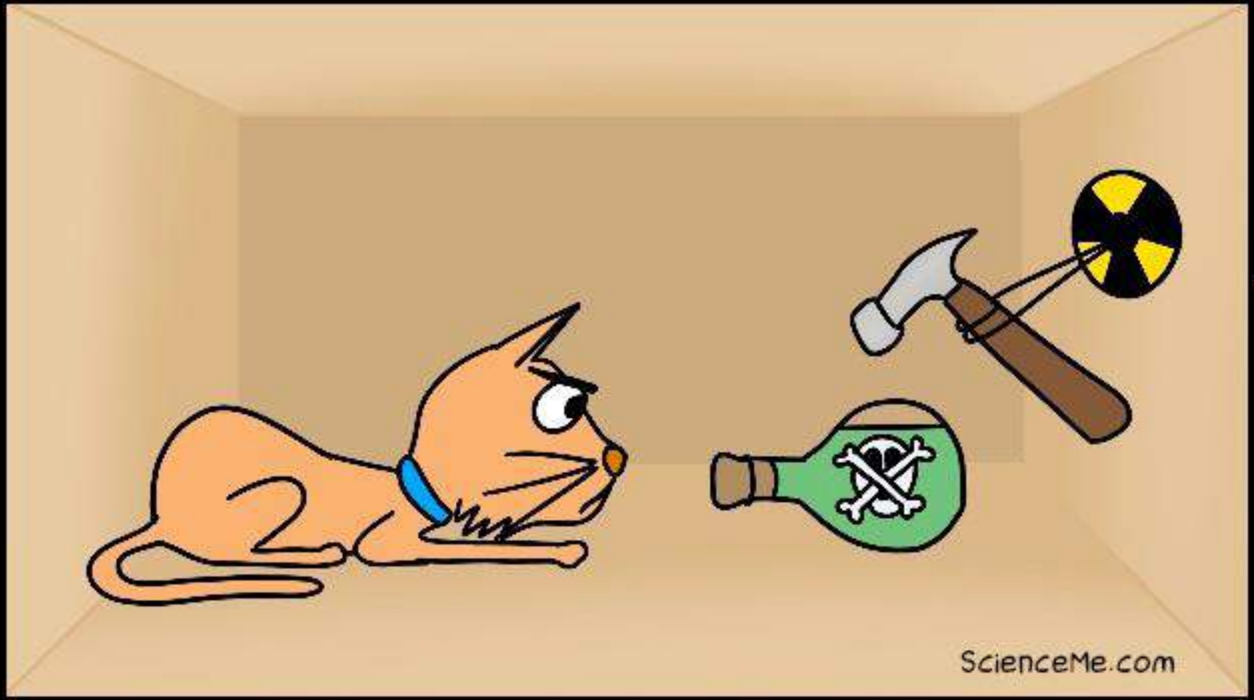


Image Credit: ScienceMe.com

Quantum Mechanics: Schrödinger’s Cat



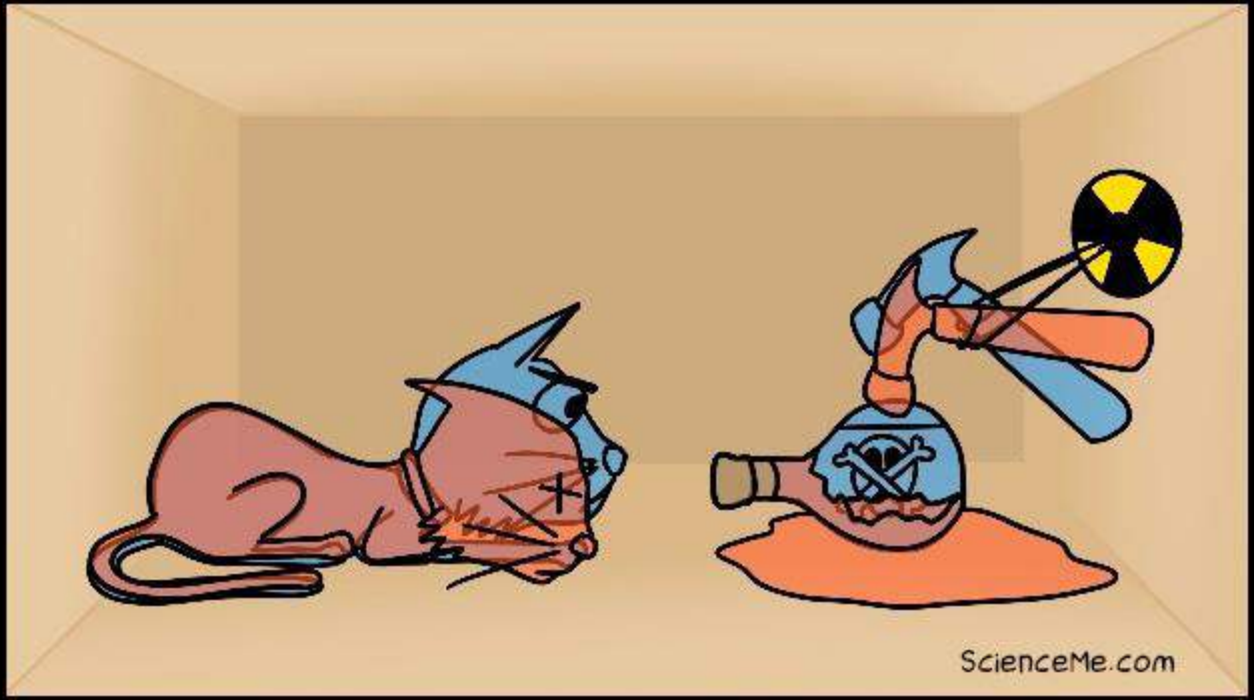


Image Credit: ScienceMe.com

Quantum Mechanics

Wave Function **collapses** when it is **observed**.

(Copenhagen Interpretation of Quantum Mechanics)

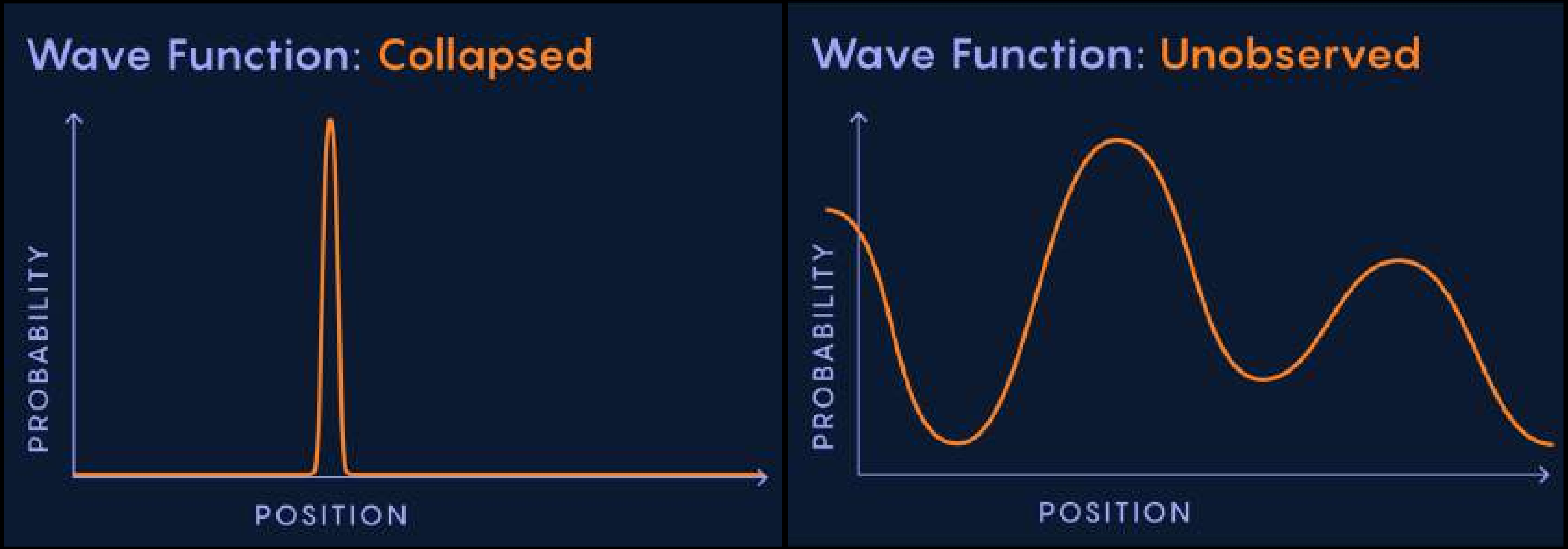


Image credit: https://www.quantamagazine.org

Quantum Computer: Technologies

	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.

Image credit:

https://science.sciencemag.org/content/354/6316/1090/tab-figures-data

Quantum Computing

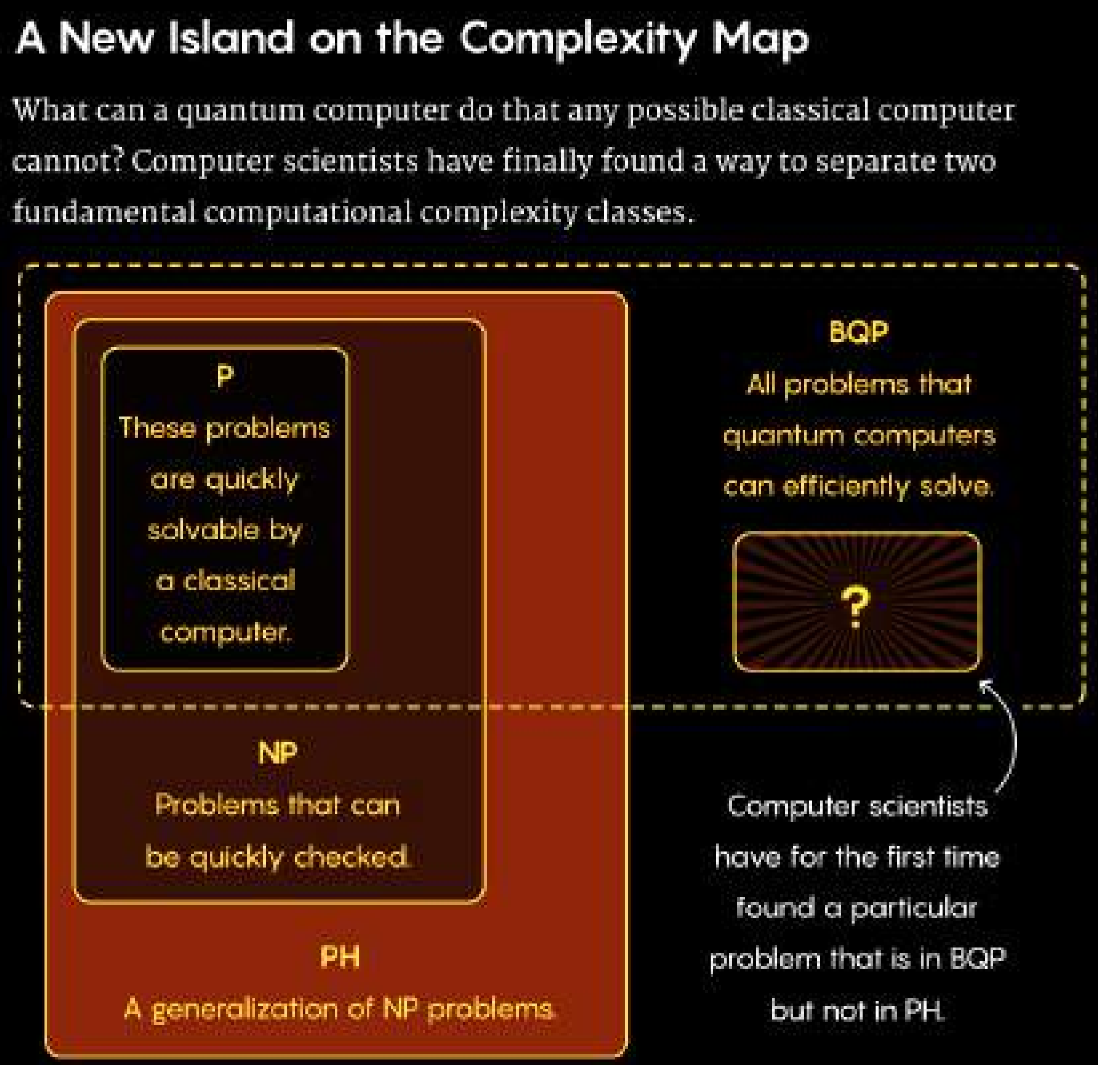
Quantum Complexity Classes

Computer scientists showed strong evidence that quantum computers possess a computing capacity beyond anything classical computers could ever achieve[1, 2].

BQP = “bounded-error quantum polynomial time.”

1. Ran Raz, Avishay Tal, *Oracle Separation of BQP and PH*, Electronic Colloquium on Computational Complexity, Report No. 107 (2018)

2. https://www.quantamagazine.org/finally-a-problem-that-only-quantum-computers-will-ever-be-able-to-solve-20180621



Quantum Computing

Revisit:

Complex Numbers

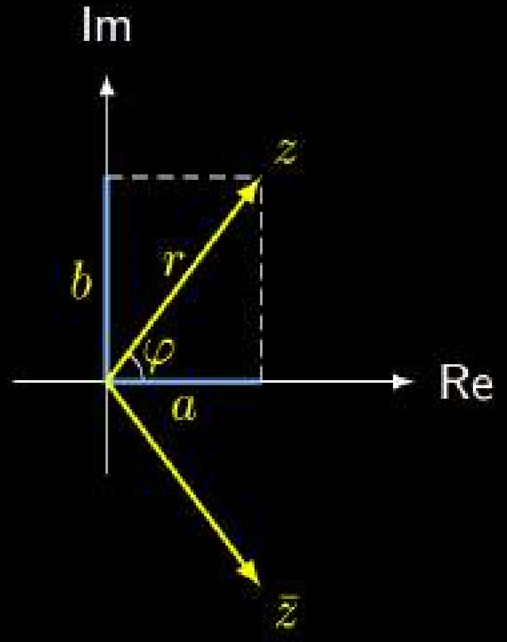
$$i^2 = -1$$

Representations:

- algebraic: $z = a + ib$
- exponential: $z = re^{i\varphi} = r(\cos\varphi + i\sin\varphi)$

Operations:

- addition and subtraction:
  $(a+ib) \pm (c+id) = (a \pm c) + i(b \pm d)$
- multiplication:
  $(a+ib) \cdot (c+id) = (ac - bd) + i(ad + bc)$
  $re^{i\varphi} \cdot r'e^{i\varphi'} = rr'e^{i(\varphi+\varphi')}$
- complex conjugate: $z^* = \bar{z} = a - ib = re^{-i\varphi}$
- absolute value:
  $|z| = \sqrt{a^2 + b^2} = r$, $|z_1 \cdot z_2| = |z_1| \cdot |z_2|$
- absolute value squared: $|z|^2 = a^2 + b^2 = r^2$
  important: $|z|^2 = z\bar{z}$
- inverse: $1/z = \bar{z}/|z|^2$



Quantum Computing: One Qubit System

Qubit (Quantum Bit) is a vector in **Hilbert vector space** with standard basis:

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \text{and} \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

A generic qubit is in a **superposition** quantum state:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where α and β are **complex numbers**, such that

$$|\alpha|^2 + |\beta|^2 = 1$$

where $\alpha, \beta \in \mathbb{C}$ are known as **amplitudes**.

Quantum Computing: One Qubit System

Qubit State:

Bloch Sphere

Any qubit state can be written as

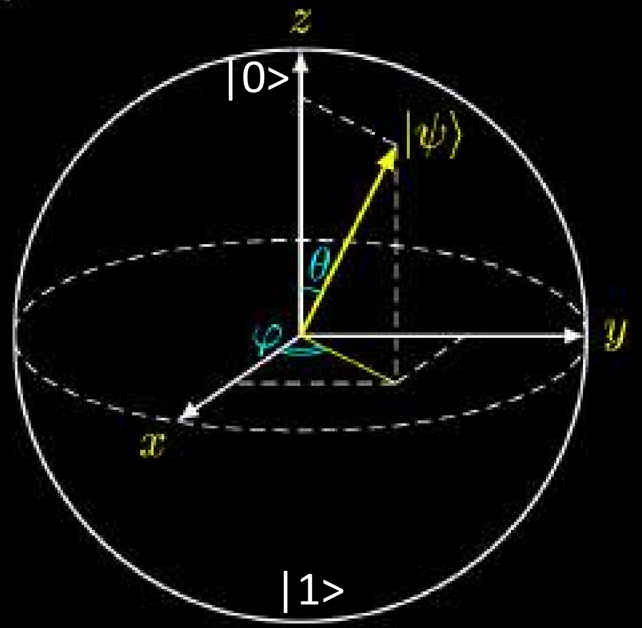
$$|\psi\rangle = \underbrace{\cos\tfrac{\theta}{2}}_{\alpha}|0\rangle + \underbrace{e^{i\varphi}\sin\tfrac{\theta}{2}}_{\beta}|1\rangle$$

for some angles $\theta \in [0, \pi]$ and $\varphi \in [0, 2\pi)$.

There is a one-to-one correspondence between qubit states and points on a unit sphere (also called Bloch sphere):

Bloch vector of $|\psi\rangle$ in spherical coordinates:

$$\begin{cases} x = \sin\theta\cos\varphi \\ y = \sin\theta\sin\varphi \\ z = \cos\theta \end{cases}$$



Measurement probabilities:

$$|\alpha|^2 = (\cos\tfrac{\theta}{2})^2 = \tfrac{1}{2} + \tfrac{1}{2}\cos\theta$$

$$|\beta|^2 = (\sin\tfrac{\theta}{2})^2 = \tfrac{1}{2} - \tfrac{1}{2}\cos\theta$$

Quantum Computing: One Qubit System

Phase:

Phase

If $re^{i\varphi}$ is a complex number, $e^{i\varphi}$ is called phase.

Global phase

The following states differ only by a global phase:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad e^{i\varphi}|\psi\rangle = e^{i\varphi}\alpha|0\rangle + e^{i\varphi}\beta|1\rangle$$

These states are indistinguishable! Why? Because $|\alpha|^2 = |e^{i\varphi}\alpha|^2$ and $|\beta|^2 = |e^{i\varphi}\beta|^2$ so it makes no difference during measurements.

Relative phase

These states differ by a relative phase:

$$|+\rangle := \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad |-\rangle := \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

Are they also indistinguishable? No! (Measure in a *different basis*.)

Quantum Computing: One Qubit System

Measurement:

- The result of the measurement is random, with some probabilities
- When we measure, we only obtain one (classical) bit of information

If we measure a qubit with quantum state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, we get

- 0 with probability $|\alpha|^2$, and the new state will be $|\psi\rangle = |0\rangle$
- 1 with probability $|\beta|^2$, and the new state will be $|\psi\rangle = |1\rangle$

It is known as **collapse of the wave function**.

Quantum Computing: Two-Qubit System

Each of the qubits can be in state $|0\rangle$ or in state $|1\rangle$
So for two qubits we have four possibilities:

$$|0\rangle \otimes |0\rangle, |0\rangle \otimes |1\rangle, |1\rangle \otimes |0\rangle, |1\rangle \otimes |1\rangle$$

that we also denote

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

or

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

Of course, we can have superpositions so a generic state is

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

where α_{xy} are complex numbers such that

$$\sum_{x,y=0}^{1} |\alpha_{xy}|^2 = 1$$

Suppose we have a state

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

If we measure both qubits, we will obtain:

- 00 with probability $|\alpha_{00}|^2$ and the new state will be $|00\rangle$
- 01 with probability $|\alpha_{01}|^2$ and the new state will be $|01\rangle$
- 10 with probability $|\alpha_{10}|^2$ and the new state will be $|10\rangle$
- 11 with probability $|\alpha_{11}|^2$ and the new state will be $|11\rangle$

It is an analogous situation to what we had with one qubit, but now with four possibilities

Quantum Computing: Two-Qubit System

Measurement of just **one qubit** in a **two-qubit system**:

If we have a state

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

We can also measure just one qubit.
If we measure the first qubit (the second one is analogous):

- We will get 0 with probability $|\alpha_{00}|^2 + |\alpha_{01}|^2$
- In that case, the new state of $|\psi\rangle$ will be

$$\frac{\alpha_{00}|00\rangle + \alpha_{01}|01\rangle}{\sqrt{|\alpha_{00}|^2 + |\alpha_{01}|^2}}$$

- We will get 1 with probability $|\alpha_{10}|^2 + |\alpha_{11}|^2$
- In that case, the new state of $|\psi\rangle$ will be

$$\frac{\alpha_{10}|10\rangle + \alpha_{11}|11\rangle}{\sqrt{|\alpha_{10}|^2 + |\alpha_{11}|^2}}$$

Quantum Computing: *n*-Qubit System

There are 2^n terms:

$$|\psi\rangle = \alpha_{0\ldots00}|0\ldots00\rangle + \alpha_{0\ldots01}|0..01\rangle + \alpha_{0\ldots10}|0..10\rangle + \cdots + \alpha_{1\ldots11}|1..11\rangle$$

$$|\psi\rangle = \alpha_0|0\ldots00\rangle + \alpha_1|0..01\rangle + \alpha_2|0..10\rangle + \cdots + \alpha_{2^n-1}|1..11\rangle$$

1-qubit → 2 terms

2-qubit → 4 terms

3-qubit → 8 terms

32-qubit → 4294967296 terms

64-qubit → 18446744073709551616 terms (beyond simulations)

128-qubit → 340282366920938463463374607431768211456 terms (beyond simulations)

Quantum Computing: Quantum Gates

Quantum mechanics tells us that the evolution of an isolated state is given by the Schrödinger equation:

$$H(t)|\psi(t)\rangle = i\frac{h}{2\pi}\frac{\partial}{\partial t}|\psi(t)\rangle$$

For quantum circuits, this implies that the operations that can be carried out are given by unitary matrices:

$$UU^{\dagger} = U^{\dagger}U = I$$

where $U^{\dagger}$ is the **conjugate transpose** of U.

As a consequence, every operation has an inverse: **reversible computing**

Quantum Computing: Quantum Gates

The X gate is defined by the (unitary) matrix

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

Its action (in quantum circuit notation) is

$$|0\rangle \;-\!\boxed{X}\!-\; |1\rangle$$

$$|1\rangle \;-\!\boxed{X}\!-\; |0\rangle$$

that is, it acts like the classical *NOT* gate

On a general qubit its action is

$$\alpha\,|0\rangle + \beta\,|1\rangle \;-\!\boxed{X}\!-\; \beta\,|0\rangle + \alpha\,|1\rangle$$

The Z gate is defined by the (unitary) matrix

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Its action is

$$|0\rangle \;-\!\boxed{Z}\!-\; |0\rangle$$

$$|1\rangle \;-\!\boxed{Z}\!-\; -|1\rangle$$

Y gate

$$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

X, *Y*, *Z* gates also known as Pauli matrices: σ_X , σ_Y, σ_Z.

Quantum Computing: Quantum Gates

The H or Hadamard gate is defined by the (unitary) matrix

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

Its action is

$$|0\rangle \; -\boxed{H}- \; \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

$$|1\rangle \; -\boxed{H}- \; \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

We usually denote

$$|+\rangle := \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

and

$$|-\rangle := \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$