Quantum Computing in Finance

Alonso Peña, PhD, CQF
European Investment Bank

European Investment Bank (EIB)

European Investment Bank (EIB)

"The EU bank“

Its mission is to fund infrastructure projects in Europe

Located in Luxembourg

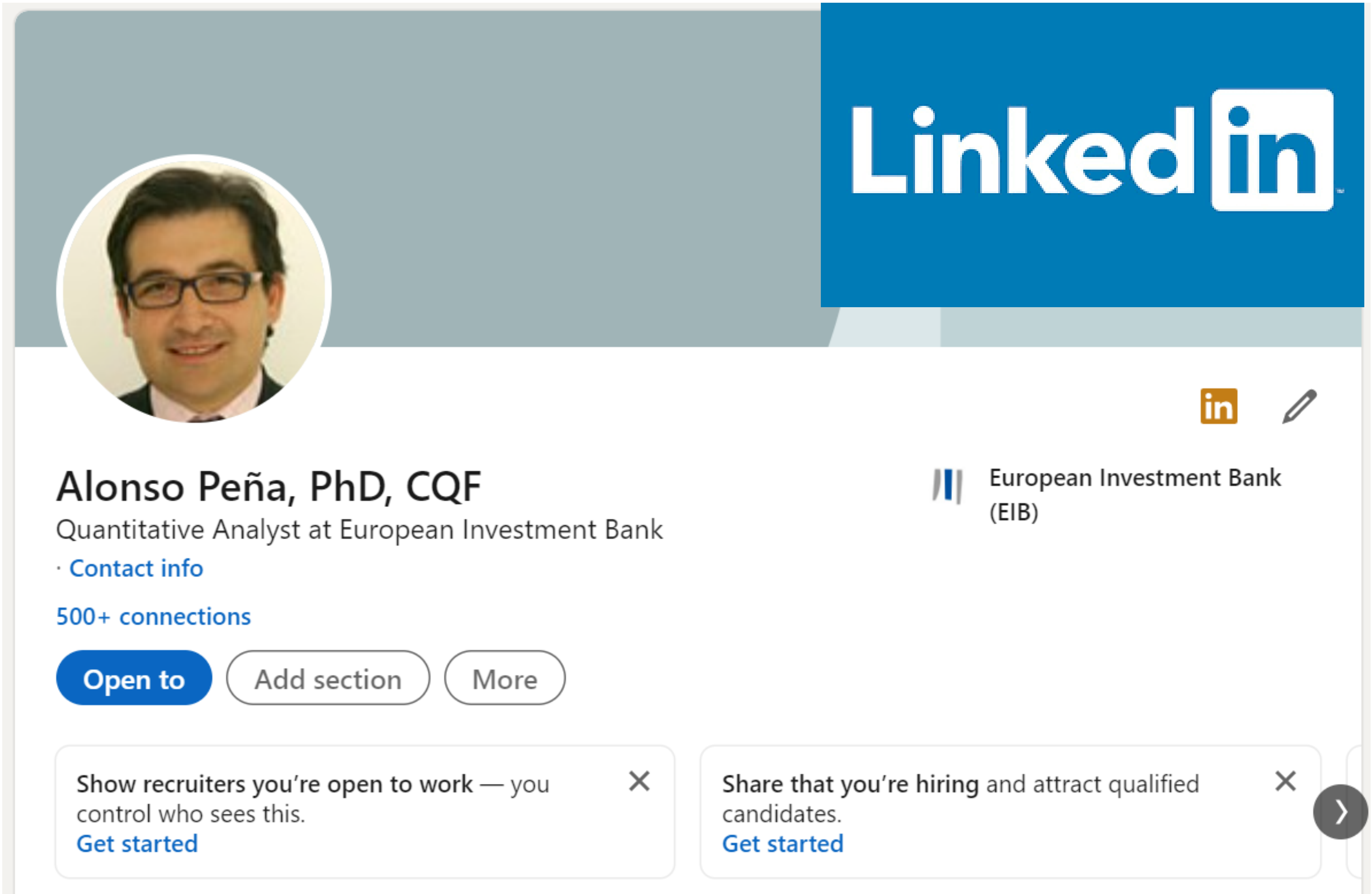
Shareholders are the EU member states

Established in 1958 under the Treaty of Rome

The world's largest international public lending institution

Disclaimer

I confirm that I act in a private capacity and not as a representative of the EIB and that the opinions expressed are personal and may not necessarily reflect the EIB position.

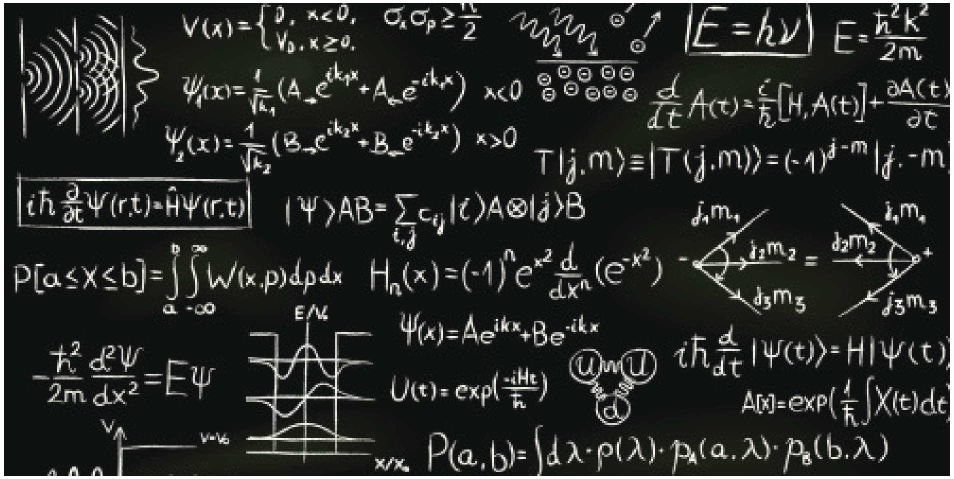


https://www.linkedin.com/in/alonso-pe%C3%B1a-phd-cqf-80bb97a/

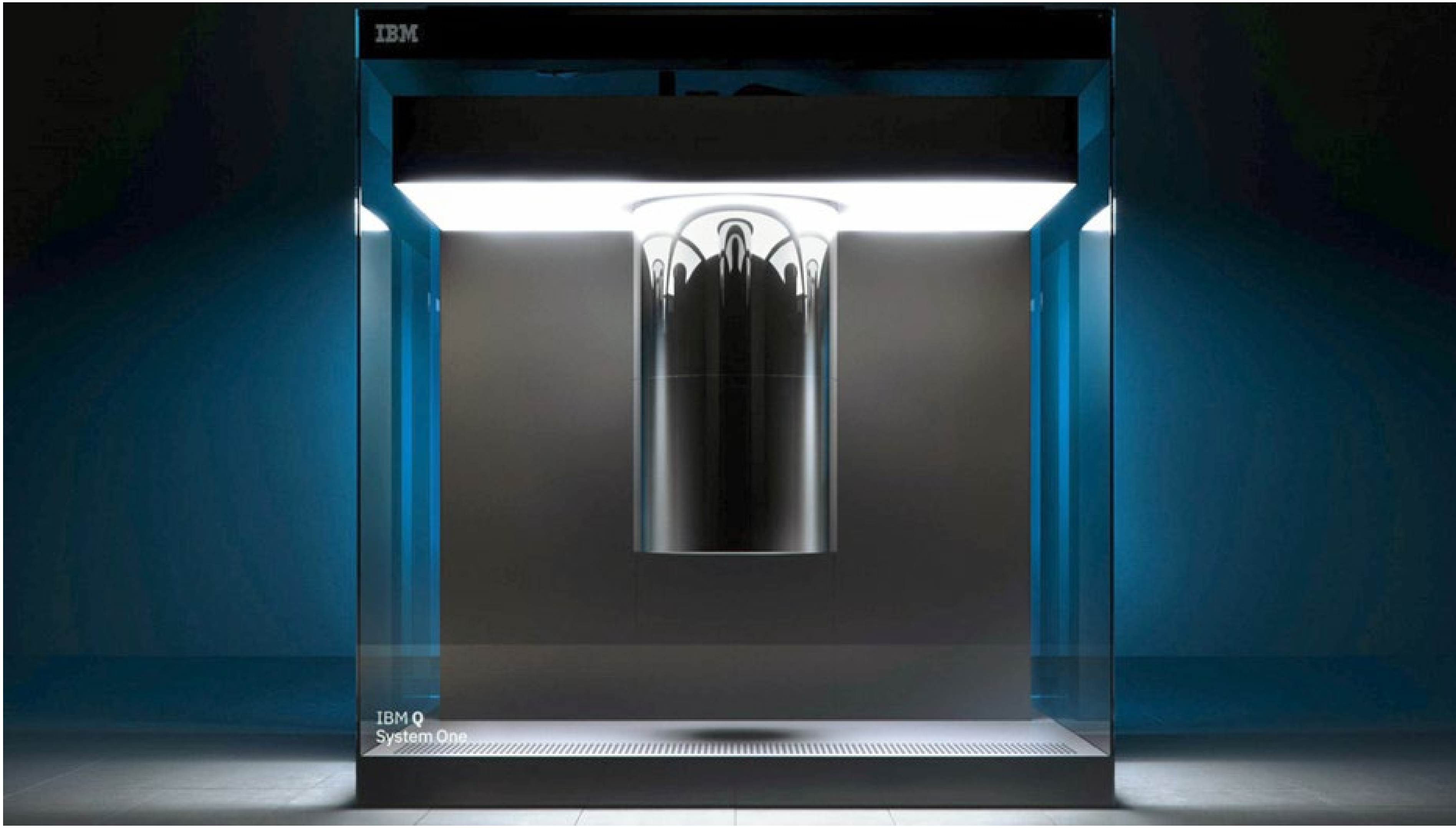
Quantum Computing

Quantum

Computing



???



IBM System One: the first commercial quantum computer, 2019

Lecture:

A Crash Introduction
to Quamtum Computing

In this lecture we will:

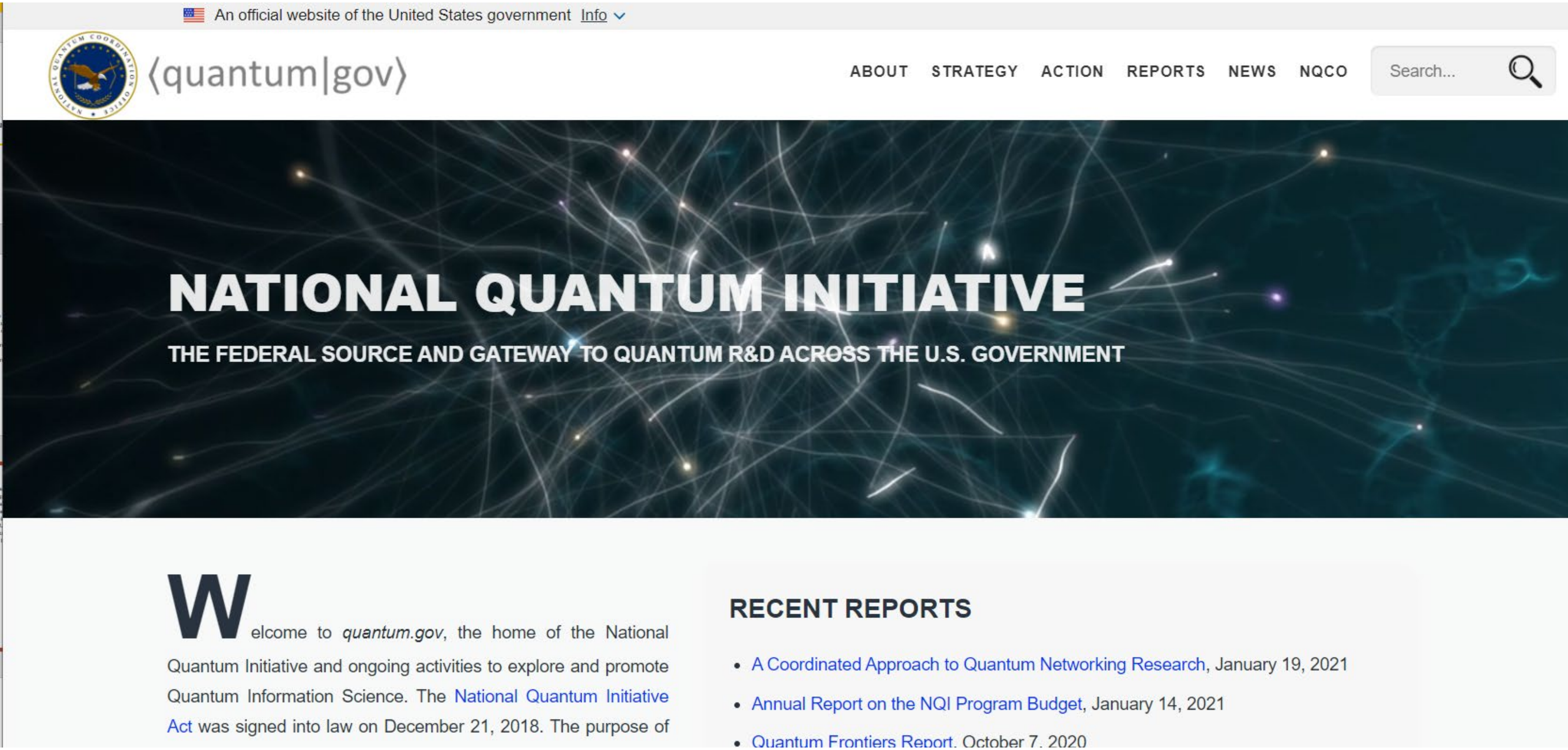
- **review** the fundamentals of quantum computing, and its three key ingredients: qubits, quantum gates and quantum circuits
- **enumerate** some of the applications of quantum computing in various fields
- **construct** a simple quantum circuit online using the IBM Quantum Experience
- write your **first quantum program** using the Python module Qiskit

The quantum computing revolution is here!

*We hear every day that quantum computers are becoming a reality, offering **high-speed solutions to problems in cryptography, medicine, logistics, meteorology, drug design…***

*Public and private institutions around the world announce **new initiatives** to fund research and development in this field. Books and articles are published. Courses are taught…*

President Trump poses with the signed National Quantum Initiative Act. Behind him are, from left, White House Deputy Chief of Staff for Policy Coordination Christopher Liddell, Deputy U.S. Chief Technology Officer Michael Kratsios, and the president's daughter and adviser Ivanka Trump, who has been involved with STEM education policy issues.



https://www.quantum.gov/

⟨quantum|gov⟩

ABOUT STRATEGY ACTION REPORTS NEWS NQCO

Search...

AGENCIES

https://www.quantum.gov/

From Academia to Industry

The story of quantum computing starts in a precise place and a precise date...

1981

May 6, 1981. Boston, Massachusetts, USA. One of the most famous physicist in the world, Professor Richard Feynman from Caltech, is ***about to give a keynote speech in a conference at the Massachusetts Institute of technology (MIT).*** The conference is entitled “Physics of Computation”. During his talk, the Nobel laureate will present a novel idea about building a revolutionary new type computer, a “quantum computer". This idea will change the world.

Physics of Computation Conference Endicott House MIT May 6-8, 1981

1 Freeman Dyson
2 Gregory Chaitin
3 James Crutchfield
4 Norman Packard
5 Panos Ligomenides
6 Jerome Rothstein
7 Carl Hewitt
8 Norman Hardy
9 Edward Fredkin
10 Tom Toffoli
11 Rolf Landauer
12 John Wheeler

13 Frederick Kantor
14 David Leinweber
15 Konrad Zuse
16 Bernard Zeigler
17 Carl Adam Petri
18 Anatol Holt
19 Roland Vollmar
20 Hans Bremerman
21 Donald Greenspan
22 Markus Buettiker
23 Otto Floberth
24 Robert Lewis

25 Robert Suaya
26 Stan Kugell
27 Bill Gosper
28 Lutz Priese
39 Madhu Gupta
30 Paul Benioff
31 Hans Moravec
32 Ian Richards
33 Marian Pour-El
34 Danny Hillis
35 Arthur Burks
36 John Cocke

37 George Michaels
38 Richard Feynman
39 Laurie Lingham
40 Thiagarajan
41 ?
42 Gerard Vichniac
43 Leonid Levin
44 Lev Levitin
45 Peter Gacs
46 Dan Greenberger

Feynman's idea was to move away from the binary representation of information, used in all computers until then.

He argued that the basic building block of information ought to be the individual subatomic particles, such as electrons and photons, where the laws of quantum mechanics apply.

So **not only zeros and ones as binary computers do, but a unit of information infinitely more dense. In fact, the unit of information used by nature**.

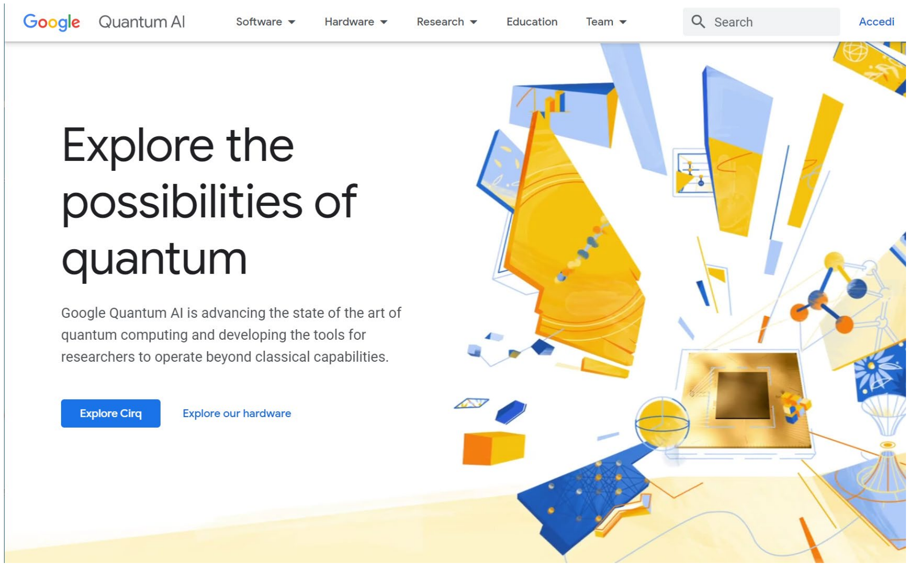
2019

January 8, 2019. Yorktown Heights, New York, USA. The company International Business Machines (IBM) presents ***the first commercial quantum computer in the world.*** A 20-qubit quantum computer. It is a powerful sleek device inside a heavy-duty borosilicate glass enclosure of about 3 meters by 3 meters in size. It looks more like a museum display than a computer. In fact, it has been designed by Goppion, manufacturer of high-end museum display cases with headquarters in Milan.

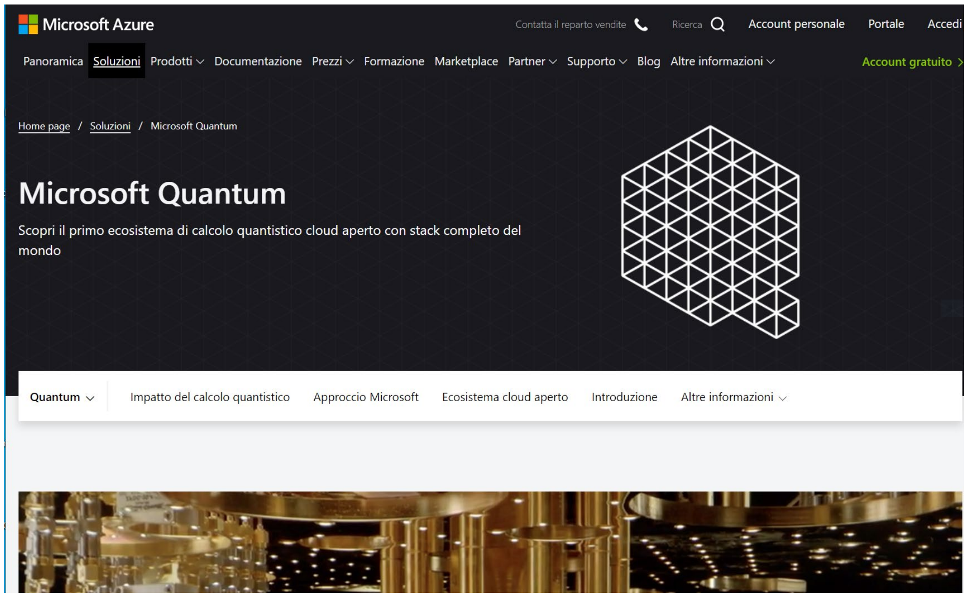
IBM: https://quantum-computing.ibm.com


IBM Q
System One

It is not only IBM who is making Feynman's quantum computing dream a reality. **Google Research** is making tremendous contributions as well. In a recent paper published in the science journal *Nature*, scientists at its research lab in California managed to have their quantum system perform a mathematical calculation in 200 seconds that today's most powerful supercomputers would need more than 10,000 years to complete. [https://www.nature.com/articles/s41586-019-1666-5]. The company has a particular interest in applying quantum computing to artificial intelligence and machine learning.



Google: https://research.google/teams/applied-science/quantum/

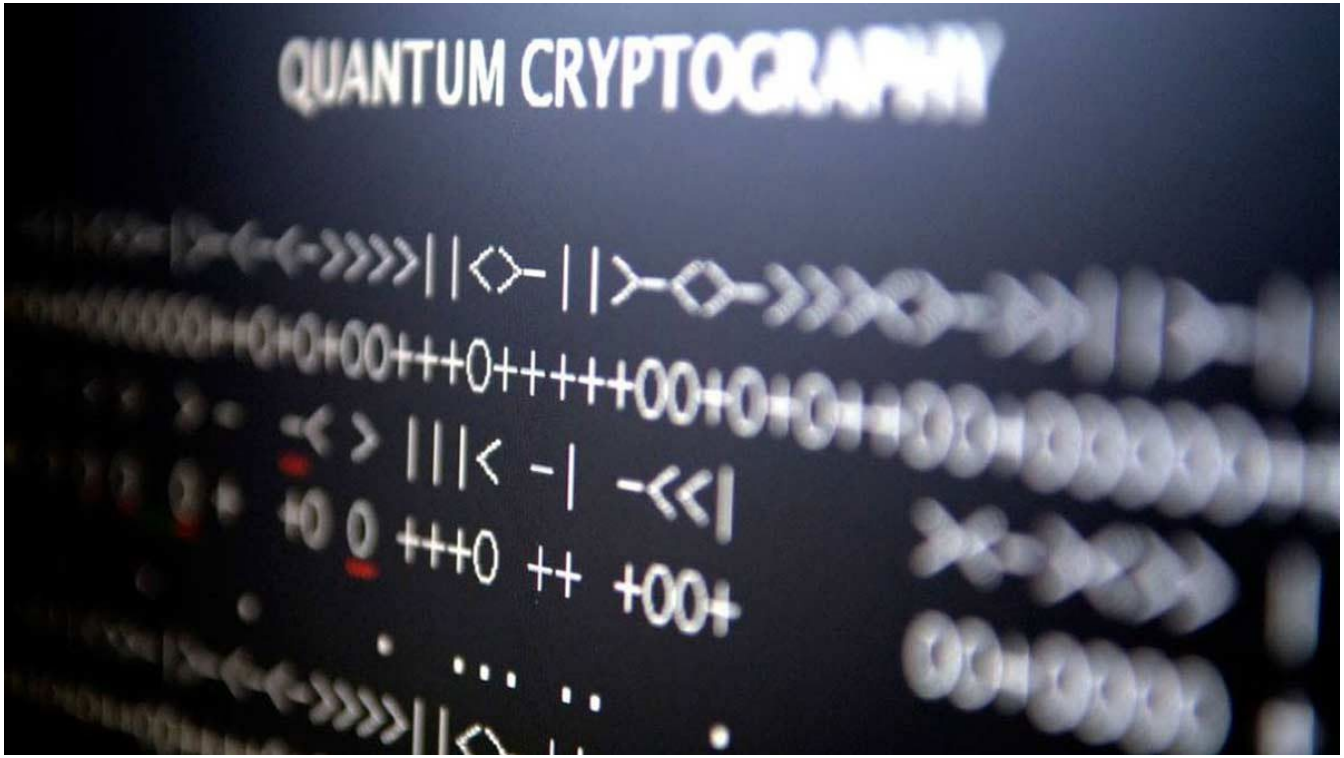


Microsoft Corporation is also very much into the Quantum Computing race. They have created the Microsoft Quantum Network as a community of interested parties collaborating with Microsoft to learn about, research, and launch quantum computing applications. The company has also developed Q# , which is a programming language used for expressing quantum algorithms. It was initially released to the public by Microsoft as part of the Quantum Development Kit.

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

Industrial applications

Quantum Computing has been mentioned to have many applications. The most quoted application of quantum computing is **cryptography**. Here, quantum computers would be able to send super secure messages using security protocols that would be unbreakable, making messages incredibly safe for current standards.



An area where quantum computers could also really bring an edge is **in drug design**. To simulate in a computer the behavior of the structure of molecules would be prohibitively slow. The amount of individual atoms and their interactions that would need to be modelled will very quickly overcome classical computers. Current simulations are restricted to toy versions of the molecules required for real drugs. With quantum computers of say 200 qubits could handle the molecules and simulate the behavior of new drugs.

A similar problem is faced by **airplane design**. Current computers cannot handle simulation the behavior of the solid-fluid interactions in large surfaces, such as wings. Instead, a significant effort in terms of time and money is dedicated to physically build components and test them in wind tunnels under a variety of conditions. This is an expensive and complex task. Instead, quantum computers are expected to offer powerful algorithms to conduct full computer simulations in a short time. The company Airbus launched the Airbus Quantum Computing Challenge 2019 to explore this issue.

Another example of how quantum computing might accelerate the leap from the drawing board to commercial applications is in **battery technologies**, such as the lithium-sulfur (Li-S) battery. Mercedes-Benz R&D North America is currently exploring how this complex chemical design could be conducted with the help of quantum computers in alliance with IBM.

Government Initiatives

United States. The US government has recently created the National Quantum Initiative following the National Quantum Initiative Act (signed into law on December 21, 2018 by President Trump). The purpose of this Act is to help in the promotion of quantum information science and its technology applications. This is backed by significant investments in this field.

China. The Chinese government via the Chinese Academy of Science has been are the forefront of efforts in the field of quantum computation. Recently, Chinese scientists have created the world's first light-based quantum computer, called Jiuzhang, that can reliably demonstrate "quantum computational advantage".

European Union. The EU launched a investment program for Quantum Computation in October 2018, called the Quantum Technologies Flagship. Its aim is to support the work of hundreds of quantum researchers in Europe over ten years, with an expected budget of EUR 1 billion. It brings together research institutions, industry and public funders.

USA: www.quantum.gov

China: https://english.cas.cn

European Union: https://qt.eu

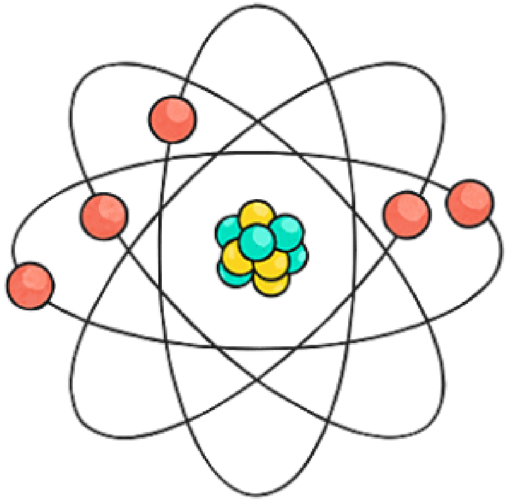
Quantum Computing

quantum computing is about the applications of the principles of quantum mechanics to information technology.

quantum comput... is about the applications o... ...nciples of quantum ...nics to information technolog...

so what !!!

2.8179 × E −15 m

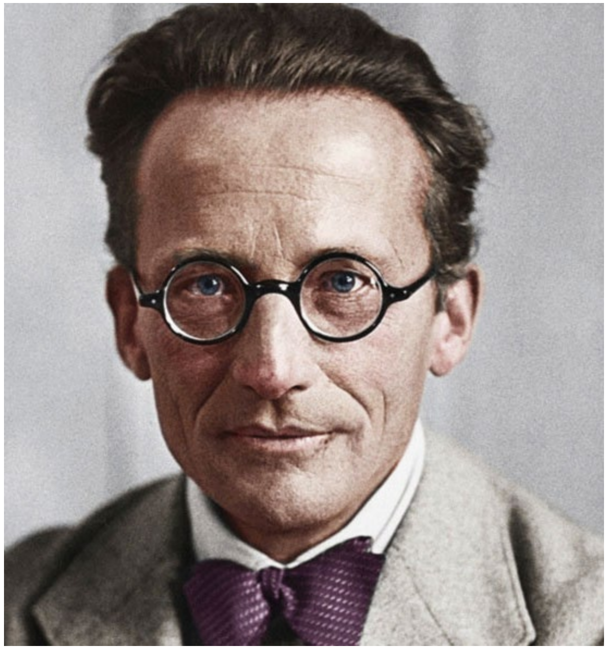


6.3781 × E +6 m

MICROSCOPIC WORLD

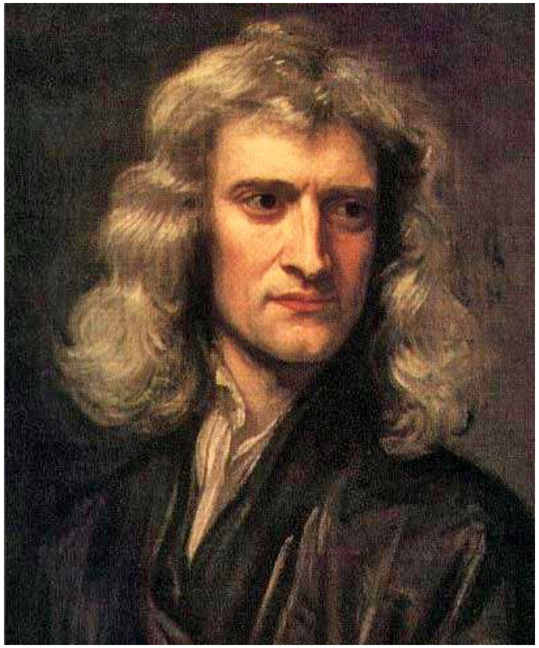
MACROSCOPIC WORLD

Schroedinger



MICROSCOPIC WORLD

Newton



MACROSCOPIC WORLD

Schroedinger

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

MICROSCOPIC WORLD

Newton

$$F = G\frac{m_1 m_2}{r^2}$$

MACROSCOPIC WORLD

The laws of physics are different depending on the scale (size)

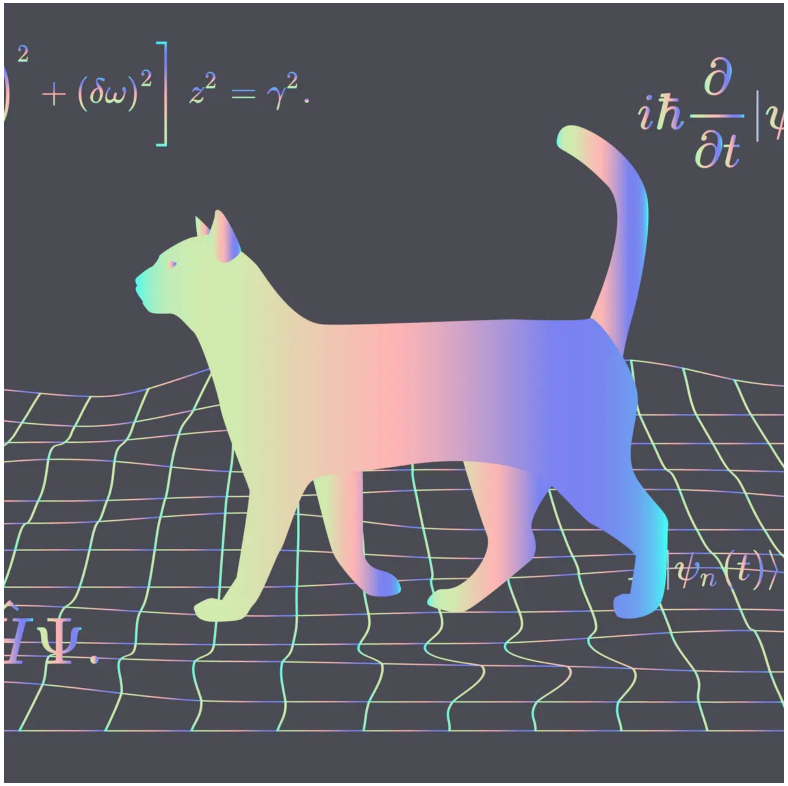
Quantum mechanics ought to be distinguished from classical physics …

One is that while **classical physics applies to the <u>macroscopic</u> world, quantum mechanics applies to the <u>microscopic</u>** world.

Another is that quantum mechanics is based on probabilistic laws rather than deterministic laws.

A crucial difference is that objects in the quantum world behave according to **two principles that are unique to the microscopic world**: **Superposition and Entanglement**.

Quantum computers are going to allow us to use these principles to our advantage, by **manipulating individual atoms (electrons and photons) that behave according to these laws.**



Superposition

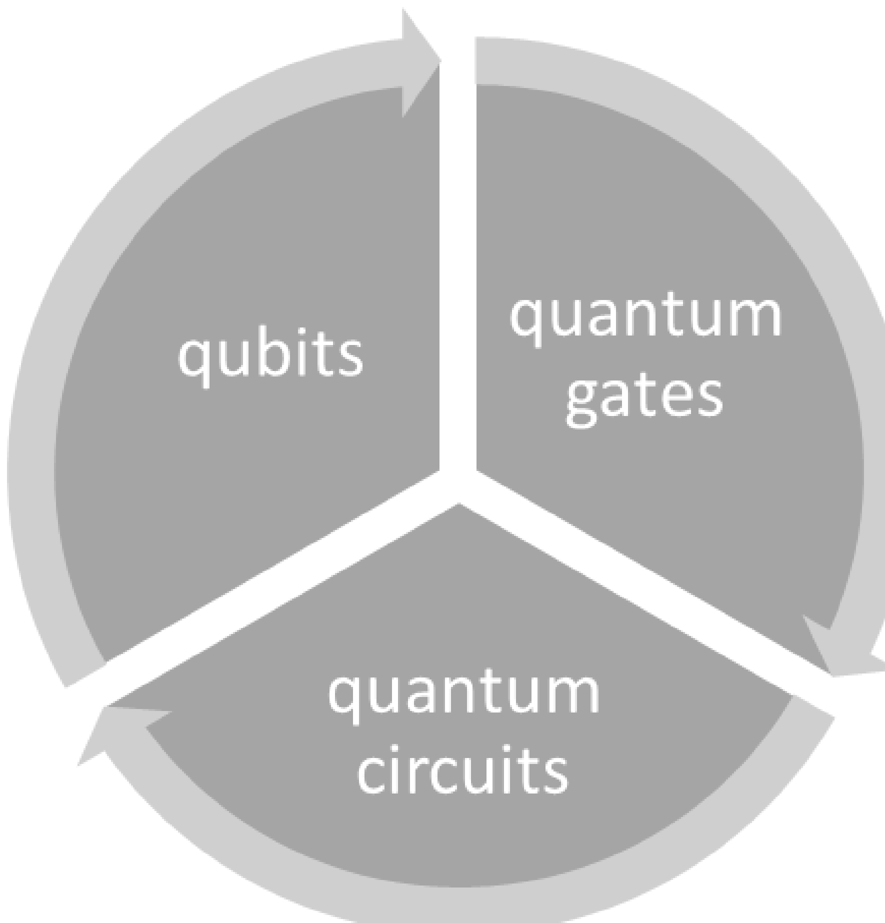
the act of putting something on or above something else

Entanglement

the act of becoming caught or twisted in something; the state of being caught or twisted in something

The Three Ingredients

The Three Ingredients of QC



Ingredient 1: Qubits

qubit = quantum bit

Ingredient 1: Qubits

The first ingredient are qubits. In classical computers, a bit can take only two possible values: either 0 or 1. In quantum computing, the values 0 and 1 are substituted by more general objects, i.e. the vectors $|0\rangle$ and $|1\rangle$. This can be understood as a transformation from scalars into vectors.

This special notation is called the **Dirac notation** and is commonly used in quantum mechanics. In contrast to classical bits, a quantum denoted $|\psi\rangle$can also be a linear combination of vectors $|0\rangle$and $|1\rangle$, therefore we can write it as:

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

Imagine the following. If computers were ***photographs*** made up of dots (pixels). Classical computers use pixels than can be only black or white. Quantum computers allow each pixel to have any color in the spectrum. Imagine what images!

bits = black/white

qubits = color

bits = black/white

qubits = color

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

where a and b are complex numbers. The vector is said to be a superposition of the vectors $|0\rangle$ and $|1\rangle$, with probabilities (or amplitudes) a and b. Therefore $|\psi\rangle$ can be regarded as a vector in a two dimensional complex vector space, where $|0\rangle$and $|1\rangle$forms its orthonormal basis, called the computational basis.

We can also have a matrix representations of the vectors $|0\rangle$ and $|1\rangle$ as

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

There exists a very important geometrical representation of the qubit using the Bloch sphere (Marquezino et al, 2019). In order to understand this representation, we can write the amplitudes as

$$\boldsymbol{a} = |\boldsymbol{a}|\boldsymbol{e}^{\boldsymbol{i\gamma}}$$
$$\boldsymbol{b} = |\boldsymbol{b}|\boldsymbol{e}^{\boldsymbol{i(\gamma+\varphi)}}$$

and if we define

$$cos\left(\frac{\theta}{2}\right) = |a|$$

$$sin\left(\frac{\theta}{2}\right) = |b|$$

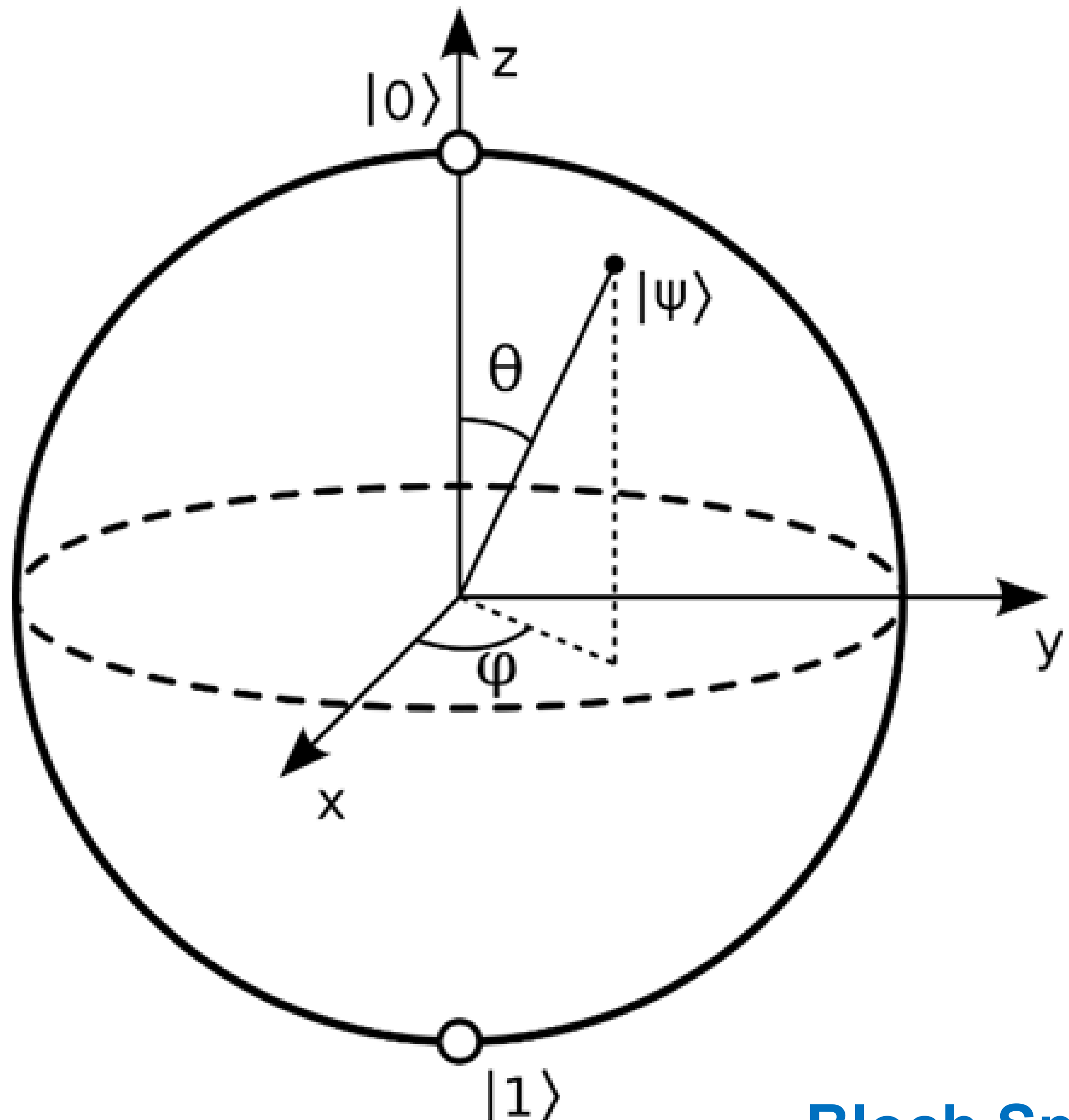
then it is possible to prove that we can write the qubit as:

$$|\psi\rangle = e^{i\gamma}\left(cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\, sin\left(\frac{\theta}{2}\right)|1\rangle\right)$$

For purposes of visualization, the factor $e^{i\gamma}$ outside parenthesis, known as global phase factor, can be ignored, because it has no observable effect on the state of the qubit. Therefore, we can represent any qubit as a point on the surface of a sphere, called the Bloch sphere, and limit ourselves to the two angles φ and θ.

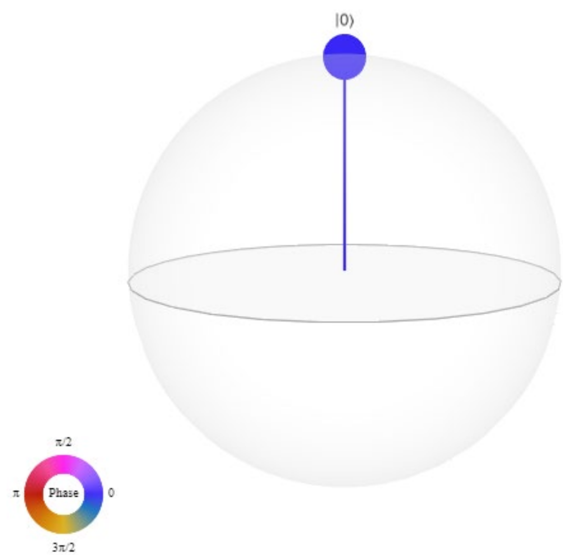
$$|\psi\rangle = cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\, sin\left(\frac{\theta}{2}\right)|1\rangle$$

And using these two angles would allow us to represent any qubit as a point in the surface of the Bloch sphere as in the following image.



Bloch Sphere

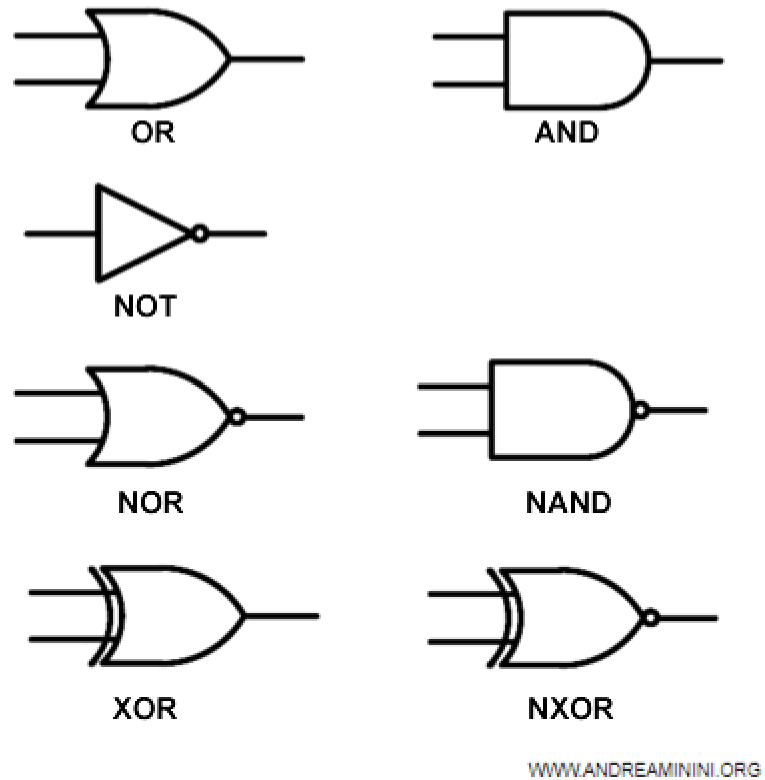
A qubit in the base state $|\mathbf{0}\rangle$ will be represented by an arrow pointing up (North Pole) in the Bloch sphere, as illustrated in the following figure.



Bloch sphere with a qubit at the $|\mathbf{0}\rangle$ state.

Ingredient 2: Quantum Gates

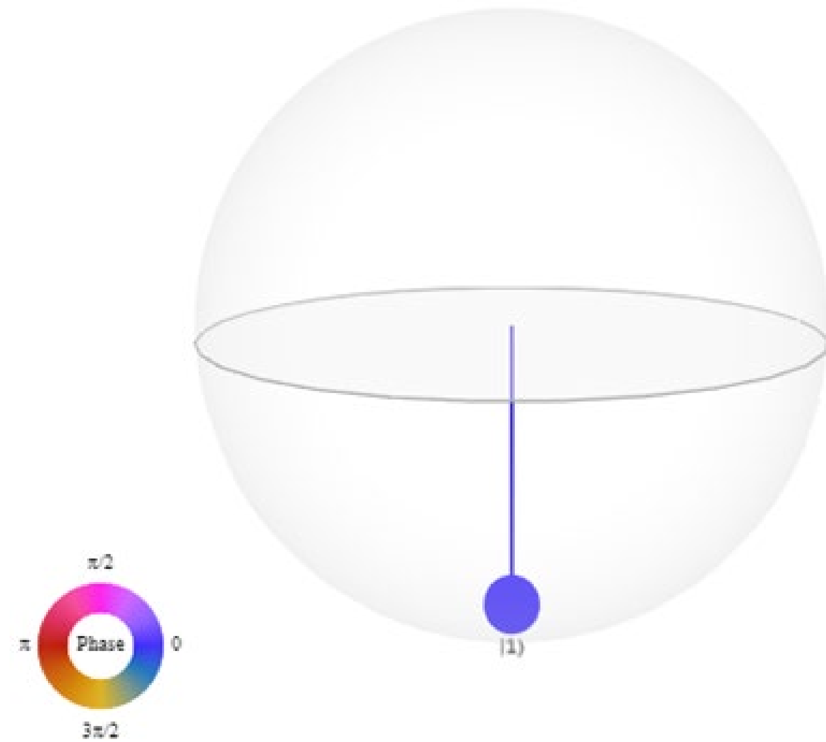
The second ingredient will be quantum gates. That is, the transformation of certain inputs in certain outputs according to some rules. These logic gates, such as NOT, AND, OR, , are well known in classical computer science using bits. But if we change from bits to qubits, how would they look like?



X Quantum Gate. This is the equivalent of the classical NOT. Its effect is to invert the state if the qubit. Thus if the qubit is in state $|0\rangle$the application of the X gate will change it to state and$|1\rangle$. If the qubit is in state $|1\rangle$ the X gate will change it $|0\rangle$. Quantum gates can be represented as matrix operations on qubits. The X gate is thus represented by the matrix:

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

If an X gate is applied to a qubit in state $|0\rangle$, the result of the operation can be represented by an arrow pointing down (South Pole) in the Bloch sphere.



Bloch sphere with a qubit at the $|1\rangle$ state.

Y and Z gates. The X gate is part of a family known as Pauli gates. In addition to the X gate, this family includes the Y gate, defined as

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

and the Z gate, defined by

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

These gates have the effect of rotation the qubit vector around x and y axis respectively.

H Gate. The Hadamard gate is another important one-qubit gate. Its operation is defined by the matrix:

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

where we can see that after applying it to qubits in states $|0\rangle$and $|1\rangle$we obtain

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

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

The H gate is important because it creates a **superposition of** states with equal amplitudes or probabilities. With this gate information becomes like Schrodinger's Cat which exists in two states at the same time. For us, this will mean that **we can represent information in a much more flexible way, a probabilistic way**, rather than having to rely only on a binary representation (like 0's and 1's) as in classical computers.

There are many more gates, but in this introduction, we focus only on these.

Ingredient 3: Quantum Circuit

The third ingredient is quantum circuits. That is, the set of operations that will transform some quantum information into another quantum information. In other words, we give qubits as inputs to a series of gates and, after doing the respective operations, we obtain some outputs. This **can be thought of as a set of matrix operations applied to a quantum system**.

And because the **elements of quantum circuits obey the laws of quantum mechanics, a quantum computer capable of efficiently running these circuits would be capable of using the powerful principles of the microscopic world (such as superposition and entanglement)** to solve problems in the macroscopic world. Conceptually what we describe above is an algorithm. When we want to implement this concept into a practical quantum computer it's better to think about it in terms of a quantum circuit, indicating the network of connections between qubits and quantum gates.

EXAMPLE if we wanted to do a simple operation such as flipping or inverting the value of a qubit from 0 to 1, what would be its quantum circuit representation?

Using the qubits and the quantum gates as described above, we can represent it as an input, some process and then an output. In particular, we could think about it in three steps:

STEP 1: INPUT

$$|\psi_0\rangle = |0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

STEP 2: PROCESSING

$$X\,\psi_0 = \psi_1$$

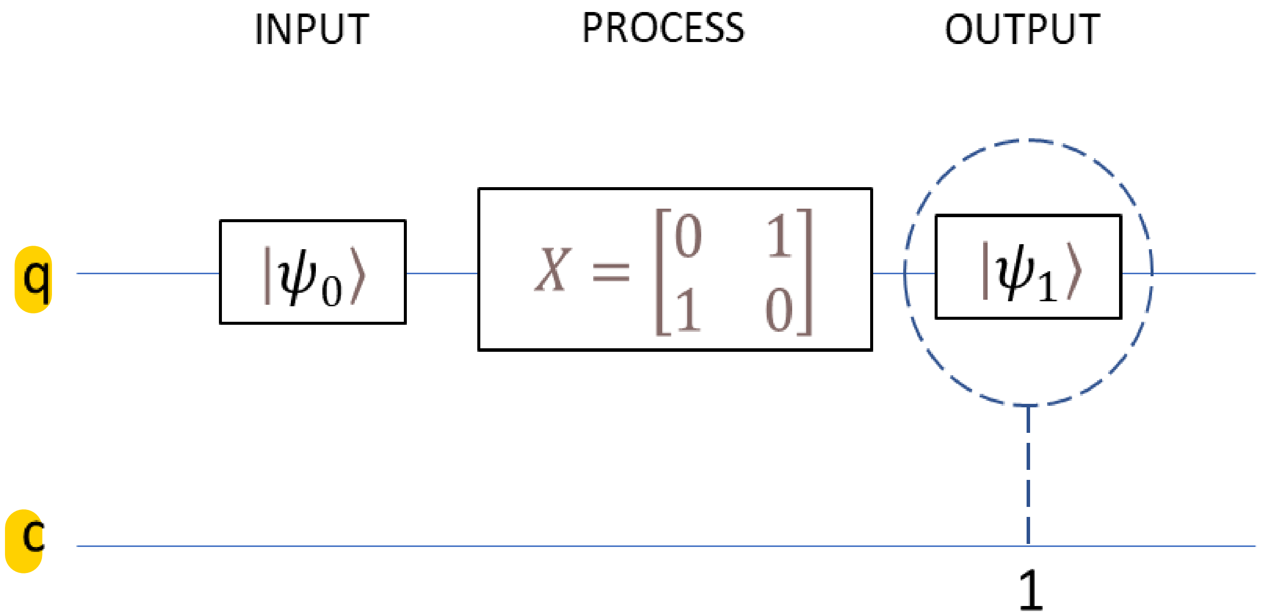
$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

STEP 3: OUTPUT

$$\text{Measure}(\psi_1) = 1$$

algorithm for flipping a quibit.

In graphical terms one might represent the above algorithm in terms of a circuit as follows:

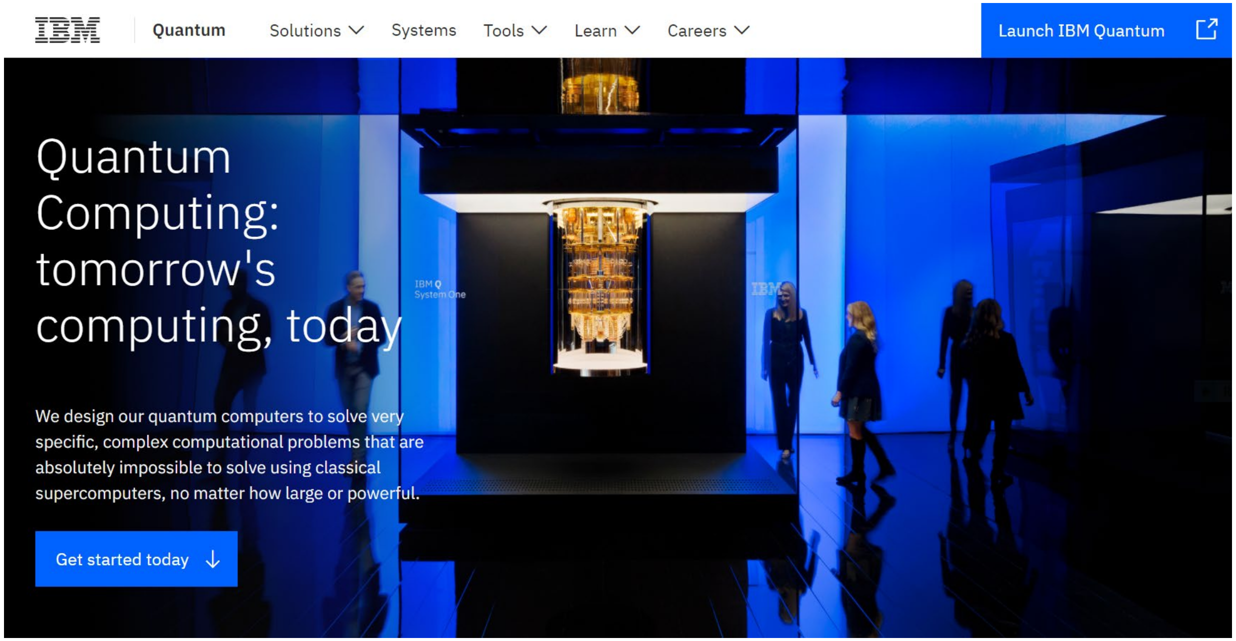


quantum circuit for flipping a quibit.

Where in **STEP 1** we define the input for the circuit, in this case a qubit in state $|\psi_0\rangle = |0\rangle$. We then apply a quantum NOT gate to it via a matrix multiplication in **STEP 2**. The result is now in another qubit $|\psi_1\rangle = |1\rangle$. In the final **STEP 3**, we ought to observe the result and measure it. From the theory of quantum mechanics we know that the act of measurement will make the qubit to collapse to a classical bit, in this case with a value of 1.

IBM Quantum

IBM Quantum is a web-based platform dedicated to the use of quantum computing for the public. It is the best place to start to learn about quantum computing in practice.



https://www.ibm.com/quantum-computing/

The IBM Quantum platform is composed of six parts.

[1] The *Dashboard,* which contains information about your personal profile and an overview of the recent circuits that you have worked with, as well as the jobs (runs) that these have been executed and the hardware systems that you have used. It’s the homepage of the platform.

[2] The *Quantum Services* contains detailed information about the quantum computers that are made available to you by IBM.

[3] *Jobs* gives information about the programs that you have executed, including the ones pending and those completed.

[4] The *Quantum Composer* is the place where you can construct graphically quantum circuits by drag-and-drop their basic components (e.g. gates) into a blank page. From here you can also see qubits in the Bloch Sphere and see an histogram to assess their probabilities. The circuits represented in terms of a simplified assembly language type of code, called QASM, that can also bee seen here. You have the possibility to setup how you want to run your code, either in a simulator or in a areal quantum computer. You can send jobs to be executed with a button on this page.

[5] The *Quantum Lab* is where you can develop and run your quantum programs using Python and the Qiskit module developed by IBM. You can see a series of tutorials to explore various aspects of quantum computing. This page allows you to run these tutorials and/or your own programs interactively as Jupyter Notebooks.

[6] The next section *User Guides*, contains a wide variety of information about quantum computing in general and documentation about the various aspects of this platform in particular.