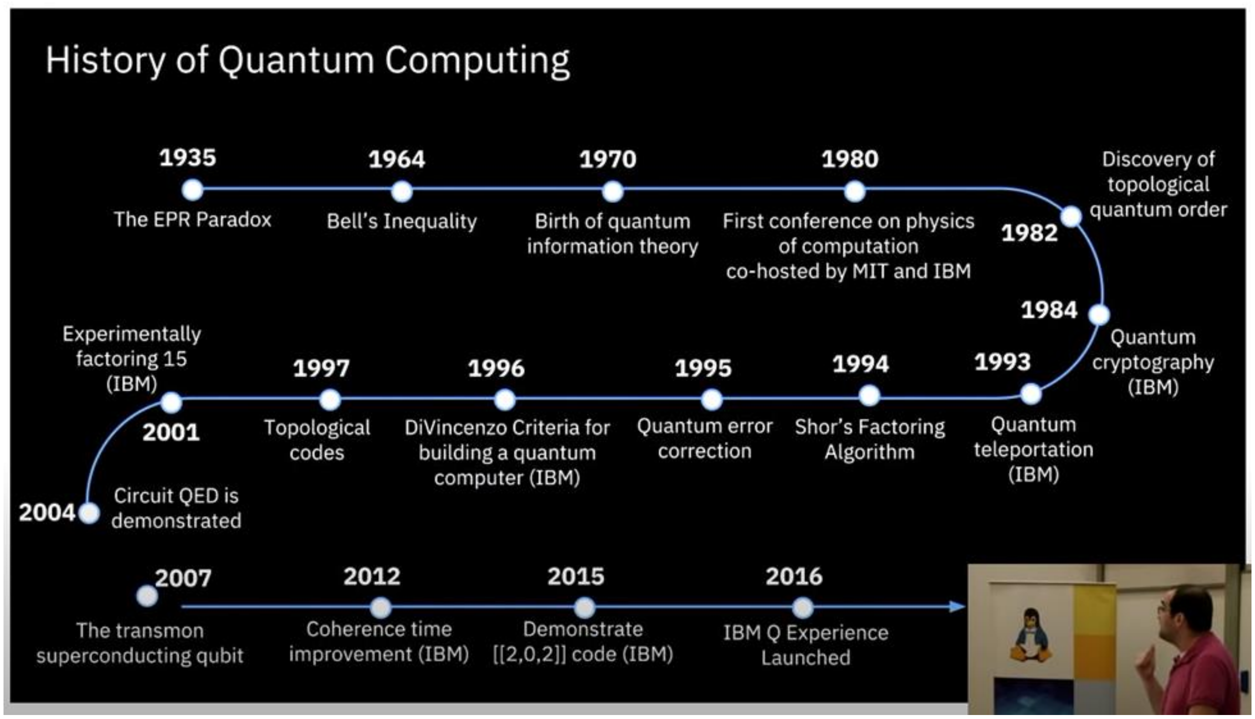
Introduction

A new kind of computing

We experience the benefits of classical computing every day. However, there are challenges that today's systems will never be able to solve. For problems above a certain size and complexity, we don't have enough computational power on Earth to tackle them.

To stand a chance at solving some of these problems, we need a new kind of computing. Universal quantum computers leverage the quantum mechanical phenomena of superposition and entanglement to create states that scale exponentially with number of qubits, or quantum bits.



Definition of Quantum Computing

Quantum computing is an area of study focused on the development of computer based technologies centered around the principles of quantum theory. Quantum theory explains the nature and behavior of energy and matter on the quantum (atomic and subatomic) level. Quantum computing uses a combination of bits to perform specific computational tasks. All at a much higher efficiency than their classical counterparts. Development of quantum computers mark a leap forward in computing capability, with massive performance gains for specific use cases. For example, quantum computing excels at like simulations.

The quantum computer gains much of its processing power through the ability for bits to be in multiple states at one time. They can perform tasks using a combination of 1's, 0's and both a 1 and 0 simultaneously. Current research centers in quantum computing include MIT, IBM, Oxford University, and the Los Alamos National Laboratory. In addition, developers have begun gaining access to quantum computers through cloud services.

Quantum computing began with finding its essential elements. In 1981, Paul Benioff at Argonne National Labs came up with the idea of a computer that operated with quantum mechanical principles. It is generally accepted that David Deutsch of Oxford University provided the critical idea behind quantum computing research. In 1984, he began to wonder about the possibility of designing a computer that was based exclusively on quantum rules, publishing a breakthrough paper a few months later.

Quantum Theory

Quantum theory's development began in 1900 with a presentation by Max Planck. The presentation was to the German Physical Society, in which Planck introduced the idea that energy and matter exists in individual units. Further developments by a number of scientists over the following thirty years led to the modern understanding of quantum theory.

Fig: The IBM Q System One was introduced in January 2019 and was the first quantum computing system for scientific and commercial use.

The Essential Elements of Quantum Theory:

- Energy, like matter, consists of discrete units; as opposed to a continuous wave.
- Elementary particles of energy and matter, depending on the conditions, may behave like particles or waves.
- The movement of elementary particles is inherently random, and, thus, unpredictable.
- The simultaneous measurement of two complementary values -- such as the position and momentum of a particle -- is flawed. The more precisely one value is measured, the more flawed the measurement of the other value will be.

Further Developments of Quantum Theory

Niels Bohr proposed the Copenhagen interpretation of quantum theory. This theory asserts that a particle is whatever it is measured to be, but that it cannot be assumed to have specific properties, or even to exist, until it is measured. This relates to a principle called superposition. Superposition claims when we do not know what the state of a given object is, it is actually in all possible states simultaneously -- as long as we don't look to check. To illustrate this theory, we can use the famous analogy of Schrodinger's Cat. First, we have a living cat and place it in a lead box. At this stage, there is no question that the cat is alive. Then throw in a vial of cyanide and seal the box. We do not know if the cat is alive or if it has broken the cyanide capsule and died. Since we do not know, the cat is both alive and dead, according to quantum law -- in a superposition of states. It is only when we break open the box and see what condition the cat is in that the superposition is lost, and the cat must be either alive or dead. The principle that, in some way, one particle can exist in numerous states opens up profound implications for computing.

A Comparison of Classical and Quantum Computing

Classical computing relies on principles expressed by Boolean algebra; usually Operating with a 3 or 7-mode logic gate principle. Data must be processed in an exclusive binary state at any point in time; either 0 (off / false) or 1 (on / true). These values are binary digits, or bits. The millions of transistors and capacitors at the heart of computers can only be in one state at any point. In addition, there is still a limit as to how quickly these devices can be made to switch states. As we progress to smaller and faster circuits, we begin to reach the physical limits of materials and the threshold for classical laws of physics to apply. The quantum computer operates with a two-mode logic gate: XOR and a mode called QO1 (the ability to change 0 into a superposition of 0 and 1). In a quantum computer, a number of elemental particles such as electrons or photons can be used. Each particle is given a charge, or polarization, acting as a representation of 0 and/or 1. Each particle is called a quantum bit, or qubit. The nature and behavior of these particles form the basis of quantum computing and quantum supremacy. The two most relevant aspects of quantum physics are the principles of superposition and entanglement.

Quantum Properties

Quantum computing properties are:

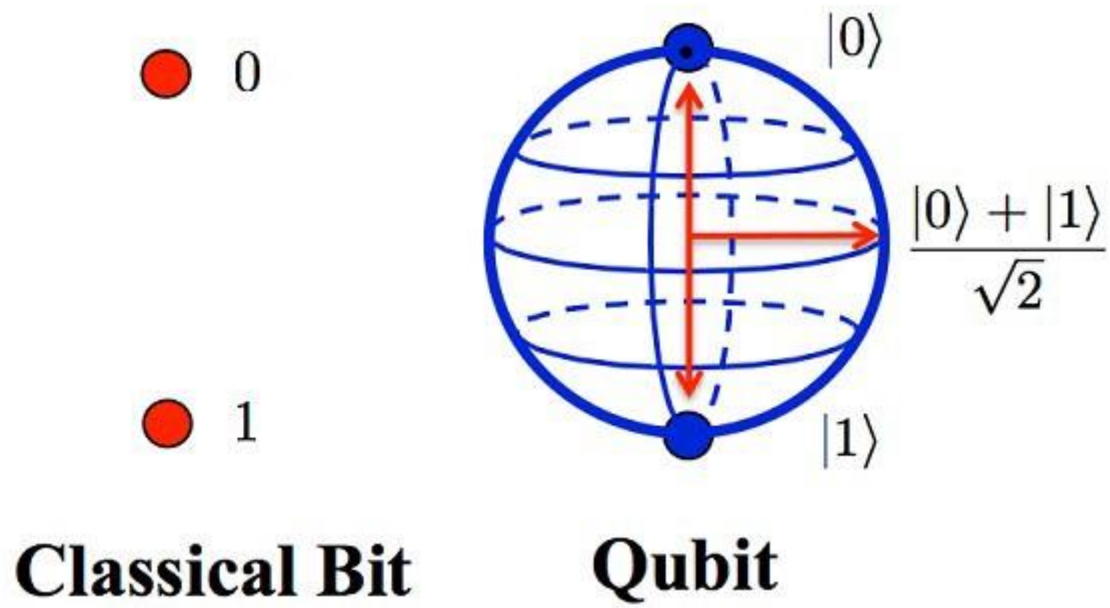
Superposition

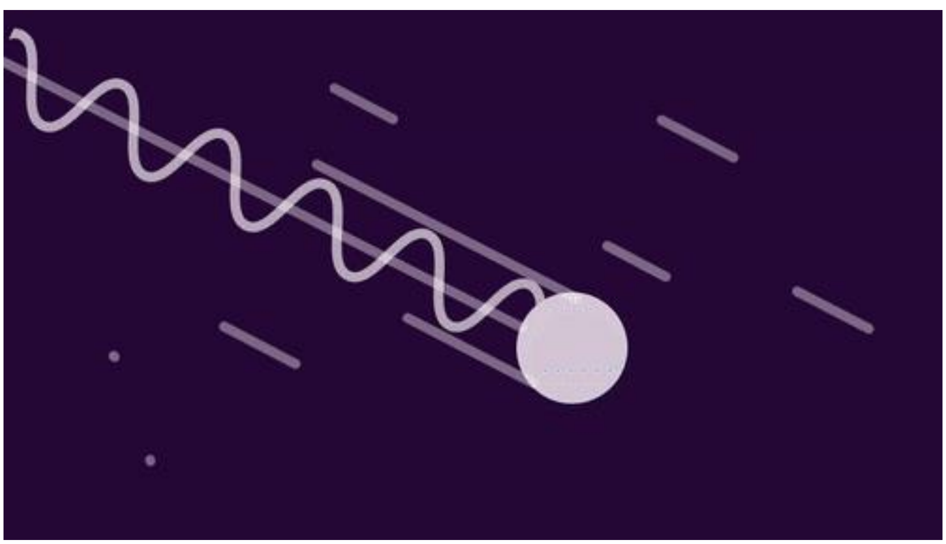
A classical computer uses ‘bits’ as the fundamental unit to store data. These ‘bits’ can only ever take one of two values — 0 or 1.

On the quantum side of things, we refer to these ‘quantum bits’ as ‘qubits’. The cool fact about qubits however is that they can take a value of 0 or 1, or — wait for it — BOTH 0 and 1 at the same time! We call this intermediate state as Quantum Superposition.

In fact, this is the state every qubit is in, until we decide to measure it. Yes, I say until we try to measure it, because the very act of measuring the value of the qubit makes it 'collapse' into one of the two values 0 or 1. We can never see a qubit in its superposition state

Here's a little illustration to highlight the difference between a classical bit and a qubit, and another to give you a visual of what superposition is like:





The symbols |0⟩ and |1⟩ in the qubit are nothing but the notations we use to represent the value of a qubit, and are known as Bra-Ket notations. (|0⟩ +|1⟩)/√2 represents the 'intermediate' or superposition value of the qubit, which is a combination of the |0⟩ and |1⟩ state.

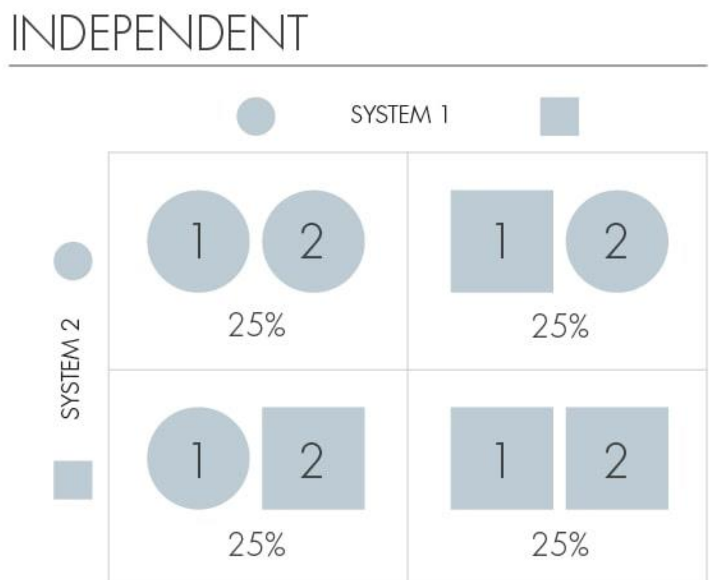
Entanglement

Quantum entanglement is a quantum mechanical phenomenon in which the quantum states of two or more objects have to be described with reference to each other, even though the individual objects may be spatially separated.

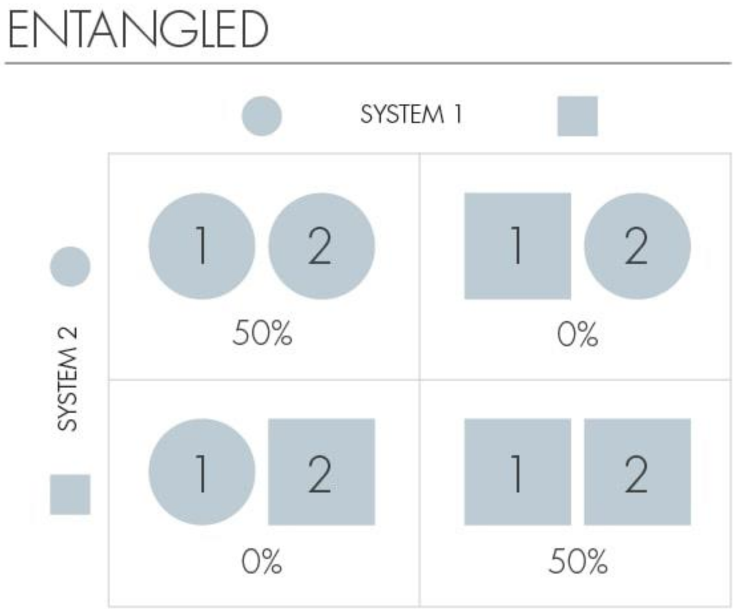
Let's take one example to get this concept crystal clear —

Let's our systems can have two objects that we'll call c-ons. The "c" is meant to suggest "classical," but if you'd prefer to have something specific and pleasant in mind, you can think of our c-ons as cakes. Our c-ons come in two shapes, square or circular, which we identify as their possible states. Then the four possible joint states, for two c-ons, are (square, square), (square, circle), (circle, square), (circle, circle). The following tables show two examples of what the probabilities could be for finding the system in each of those four states.

We say that the c-ons are "Independent" if knowledge of the state of one of them does not give useful information about the state of the other. Our first table has this property. If the first c-on (or cake) is square, we're still in the dark about the shape of the second. Similarly, the shape of the second does not reveal anything useful about the shape of the first.



On the other hand, we say our two c-ons are Entangled when information about one improves our knowledge of the other. Our second table demonstrates extreme entanglement. In that case, whenever the first c-on is circular, we know the second is circular too. And when the first c-on is square, so is the second. Knowing the shape of one, we can infer the shape of the other with certainty.



Code for making an entangled qubit

```
# Import libraries
from qiskit import ClassicalRegister, QuantumRegister, QuantumCircuit
from qiskit import execute
from qiskit import BasicAer


# import basic plot tools
from qiskit.tools.visualization import plot_histogram, circuit_drawer
In [2]:
#Selecting the qasm simulator as backend for executing the circuit using BasicAer
backend = BasicAer.get_backend('qasm_simulator')
In [3]:
q = QuantumRegister(2)     # A qauntum register of size 2 qubits
c = ClassicalRegister(2)   # A classical register of size 2 bits to measure the probability
```

```
qc = QuantumCircuit(q, c)  # Making a quantum circuit

# Add a Hadamard Gate at q0 bit
qc.h(q[0])

# Add a controlled-NOT Gate with control bit at q0 and target bit at q1
qc.cx(q[0], q[1])

# Measure the circuit
qc.measure(q, c)

#Execute the circuit
job_exp = execute(qc, backend=backend, shots=1024)
```

In [4]:

```
# plot the graph to visualize the probabilities of 00 and 11 states
plot_histogram(job_exp.result().get_counts(qc))
```

Out[4]:

In [5]:

```
print('You have made entanglement!')
```

You have made entanglement!

In [6]:

```
#Representing the circuit
qc.draw()
```

Out[6]:

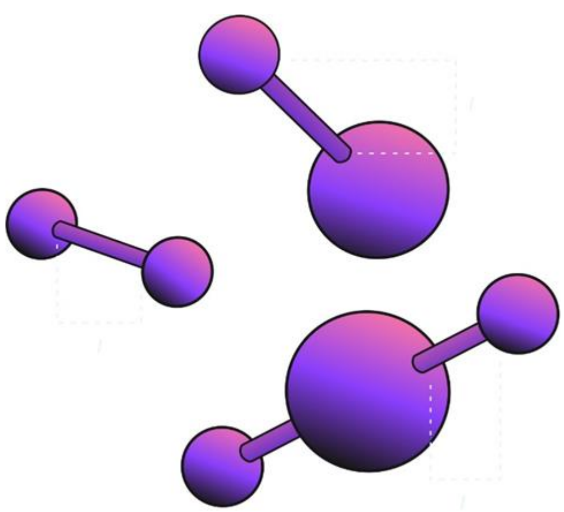
```
         ┌───┐      ┌─┐
q0_0: |0>┤ H ├──■───────┤M├
         └───┘ ┌─┴─┐ ┌─┐ └╥┘
```

```
q0_1: |0>──────┤ X ├┤M├─╫─
         └─────┘ └╥┘ ║
c0_0: 0 ══════════════╬═══╩═
              ║
c0_1: 0 ══════════════╩═════
```

In [ ]:

Quantum Computation

There are a few different ways quantum systems use quantum properties to compute. Let's investigate one type of algorithm designed for current quantum hardware, which uses quantum computing to find the "best" solution among many possible solutions. This algorithm can be used to simulate a molecule by determining the lowest energy state among various molecular bond lengths. For each possible bond length, parts of the energy state are represented on a quantum processor. Then, aspects of the quantum state are measured and related back to an energy in the molecule, for the given electronic configuration. Repeating this process for different inter-atomic spacings eventually leads to the bond length with the lowest energy state, which represents the equilibrium molecular configuration.



In addition to algorithms for near-term quantum computing systems, researchers have designed algorithms for future quantum systems, often referred to as fault-tolerant quantum computers. These systems will need to perform many sequential quantum operations and run for long periods of time.