Introduction to Quantum Computing

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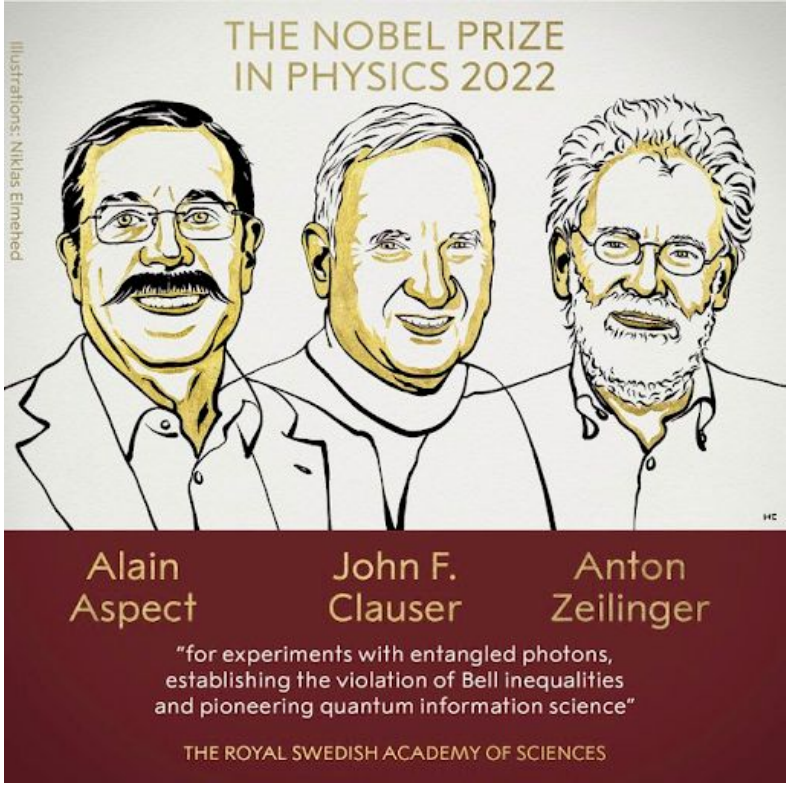
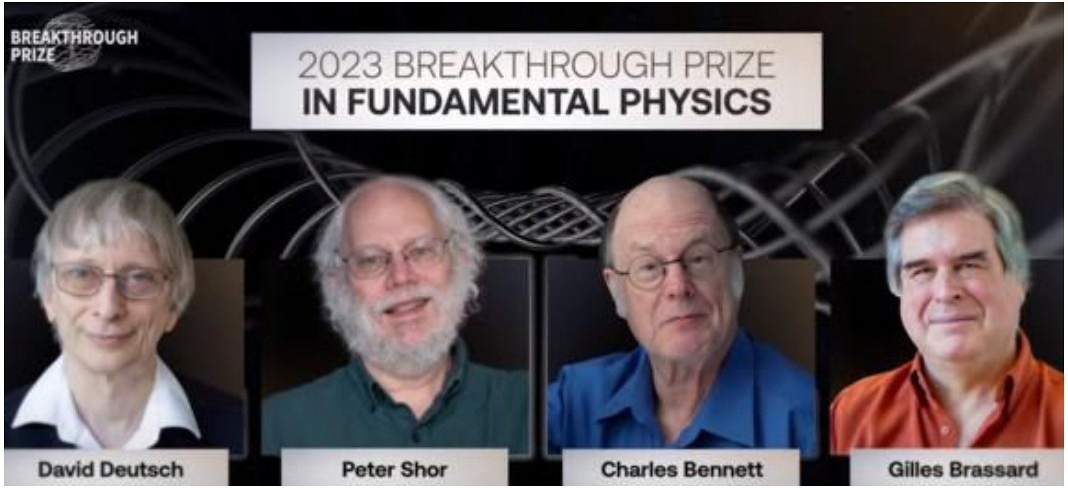
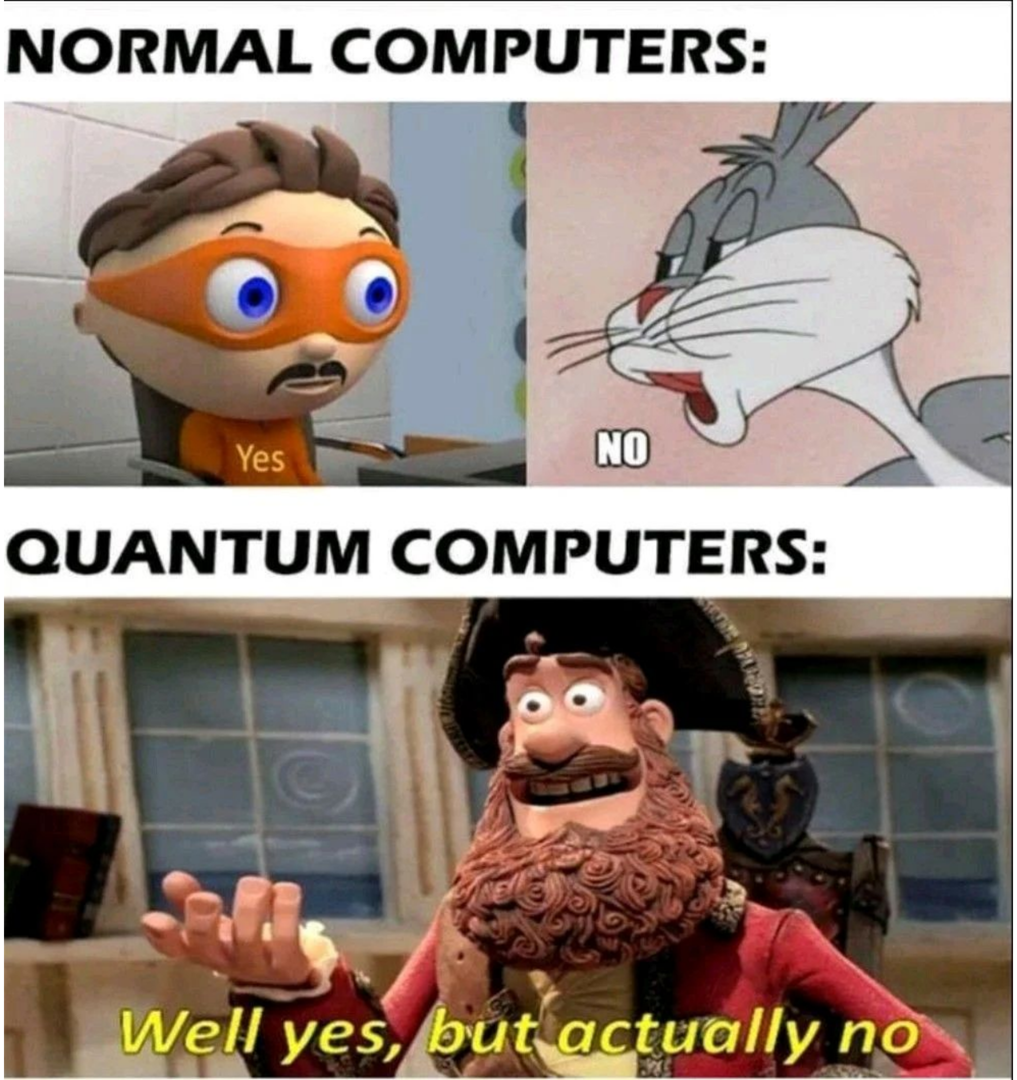
How to Quantum Compute? Winter School on Quantum Computing

December 12 - December 15, 2022, IISER Kolkata, Mohanpur


THE NOBEL PRIZE
IN PHYSICS 2022
Illustrations: Niklas Elmehed
Alain
Aspect
John F.
Clauser
Anton
Zeilinger
"for experiments with entangled photons,
establishing the violation of Bell inequalities
and pioneering quantum information science"
THE ROYAL SWEDISH ACADEMY OF SCIENCES


BREAKTHROUGH
PRIZE
2023 BREAKTHROUGH PRIZE
IN FUNDAMENTAL PHYSICS
David Deutsch
Peter Shor
Charles Bennett
Gilles Brassard

Classical computers can do a lot of things!



But there are few things, that it can’t solve!

Why do we need quantum computing?

Combinatorial optimization problems involve finding an optimal object out of a finite set of objects.

For example: **Max-Cut problem**

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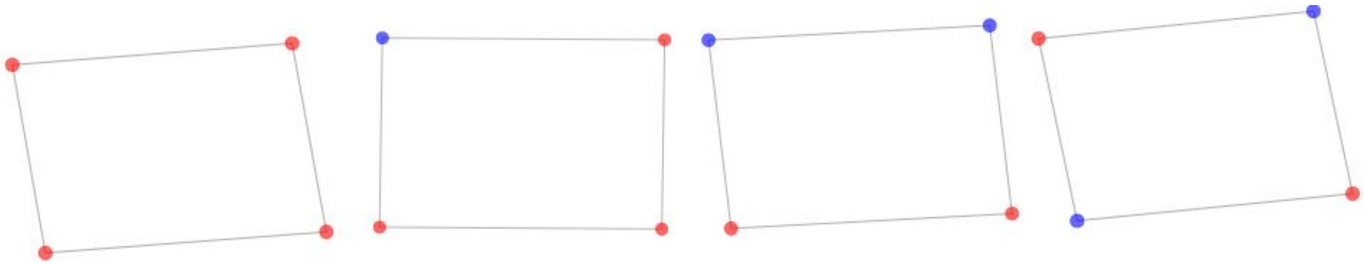
Partitions nodes of a graph into two sets, such that the number of edges between the sets is maximum.

Example: Graph with **four** nodes , partitioned into two sets, **"red" and "blue"** is shown.



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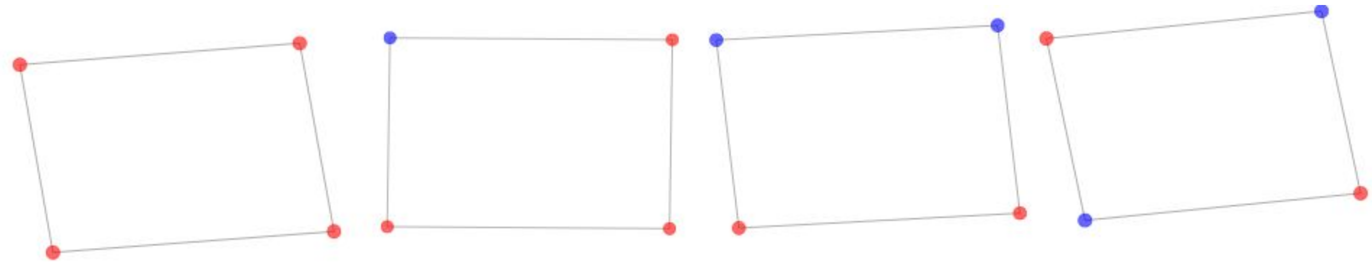

For 4 nodes, 2^4=16 possible assignments.

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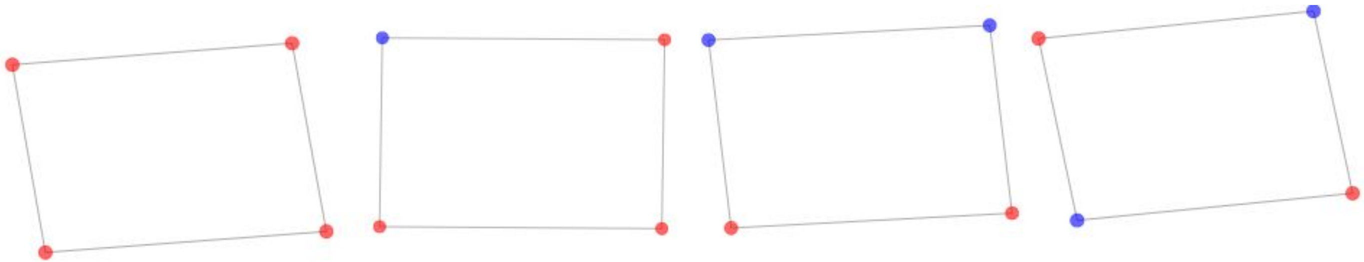

For 4 nodes, 2^4=16 possible assignments.
For 10 nodes, 2^{10}=1024 possible assignments.
For 30 nodes, 2^{30} = about 100 crores!

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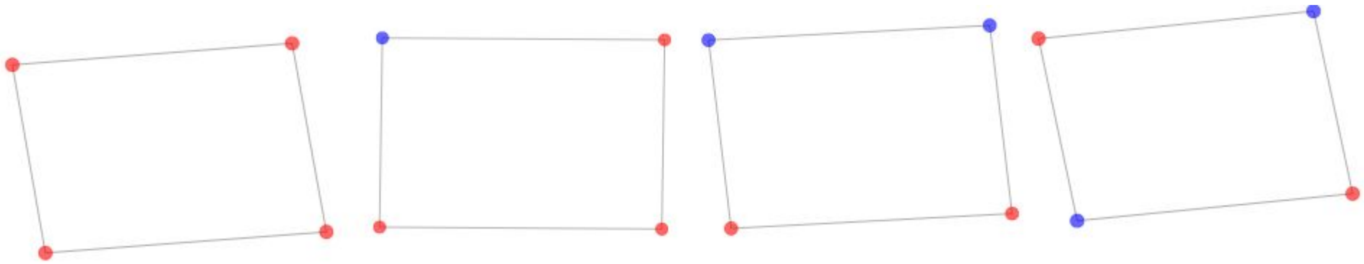

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As the number of nodes in the graph increases, the number of possible assignments that you have to examine to find the solution increases exponentially.

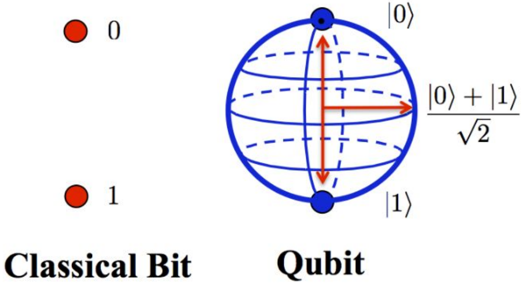
Classical Physics vs Quantum Physics

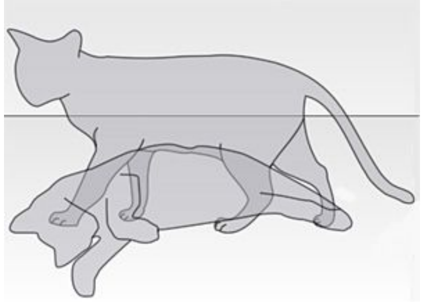
Physics:

- Classical or Newtonian mechanics
- Thermodynamics
- Statistical mechanics
- Electromagnetism

Quantum Mechanics: tackles the physical properties of nature on an atomic scale, where the same principles of physics which govern our daily lives *no longer apply*.

From bits to qubits

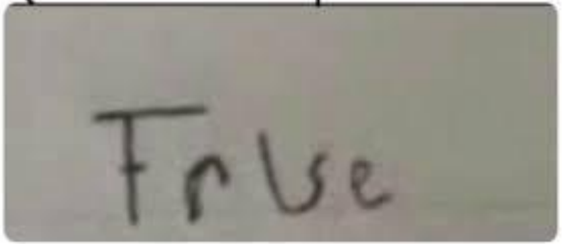




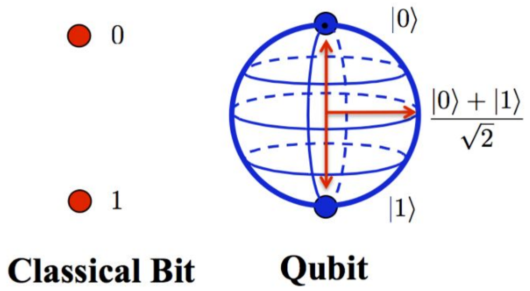
In the Schrodinger’s cat paradox, a cat is both dead and alive until someone opens the box to find out.

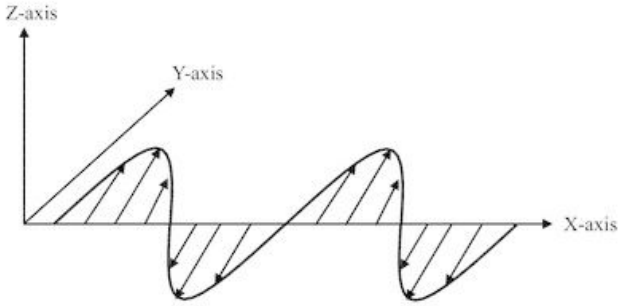
boolean: exists

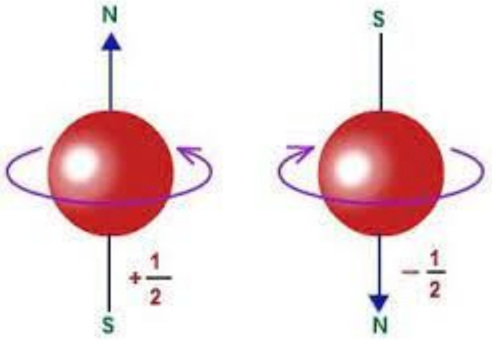
Quantum computer:

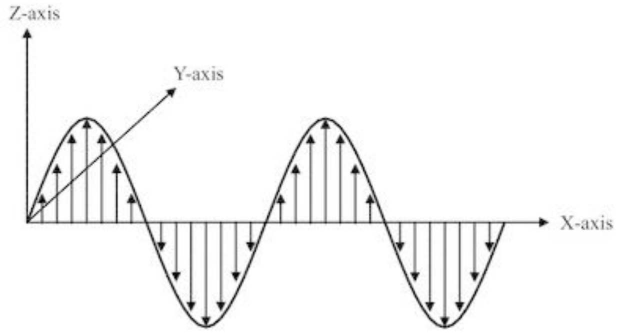


From bits to qubits: Concept and BRA-KET notation









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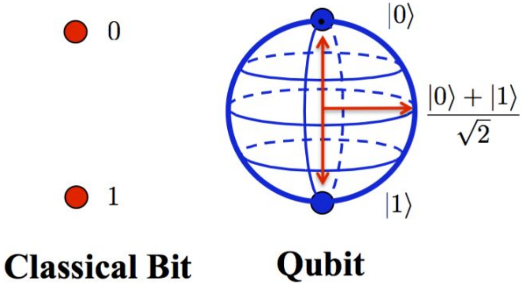

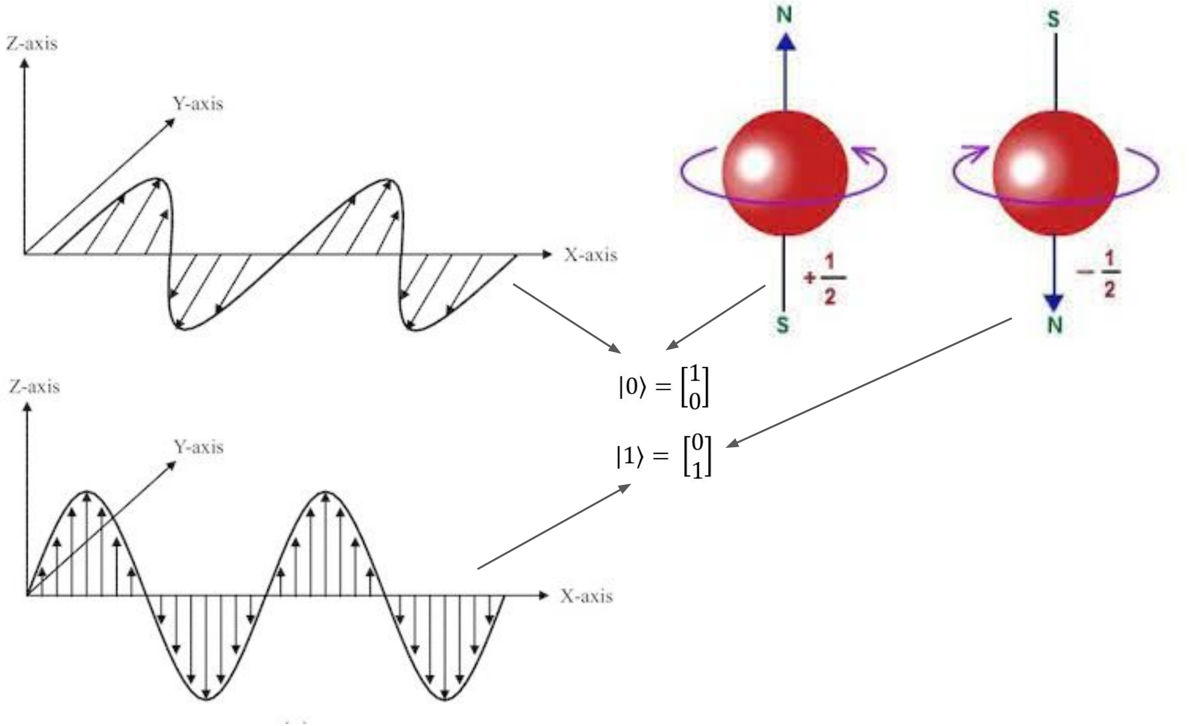

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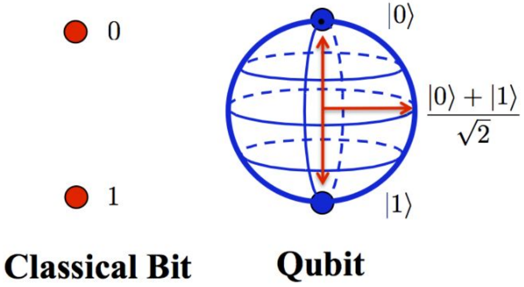
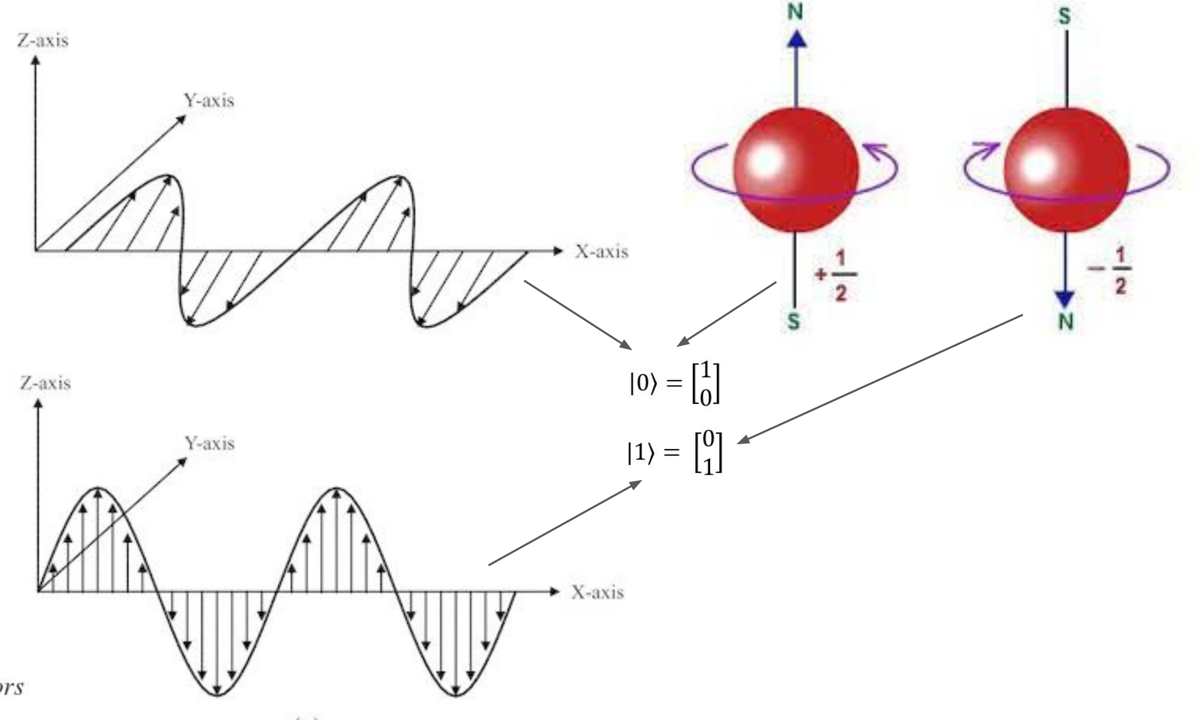




Unit vector in hilbert space

Ket - Column Vector

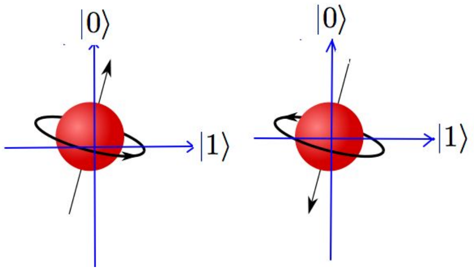
Bra - Row Vector

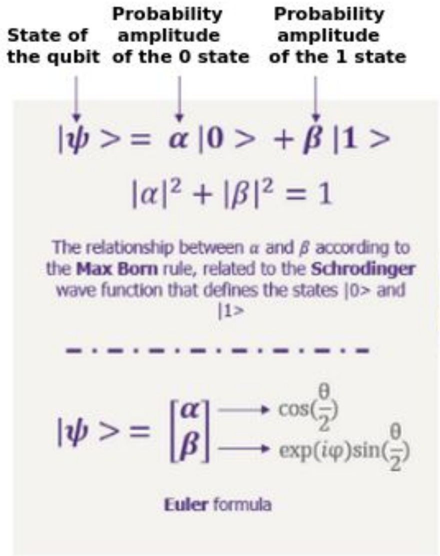
$|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$ *or* $\begin{bmatrix}1\\0\end{bmatrix}$; $|1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$ *or* $\begin{bmatrix}0\\1\end{bmatrix}$ $\rightarrow$ *Column Vectors*

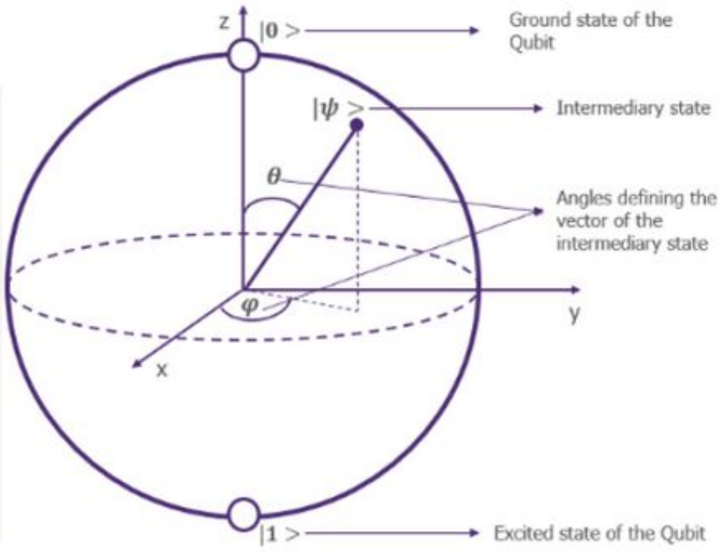
$\langle 0| = [1\ 0]$; $\langle 1| = [0\ 1]$ $\rightarrow$ *Row Vectors*

$\langle\psi|\psi\rangle$ - *Inner Product Notation*

Superposition







Source: https://teksands.ai/blog/introduction-to-quantum-computing-for-ml

Quantum Gates

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

- Gates are unitary operator
- Conjugate transpose is equal to its inverse $UU^{\dagger} = I$

Quantum Gates

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

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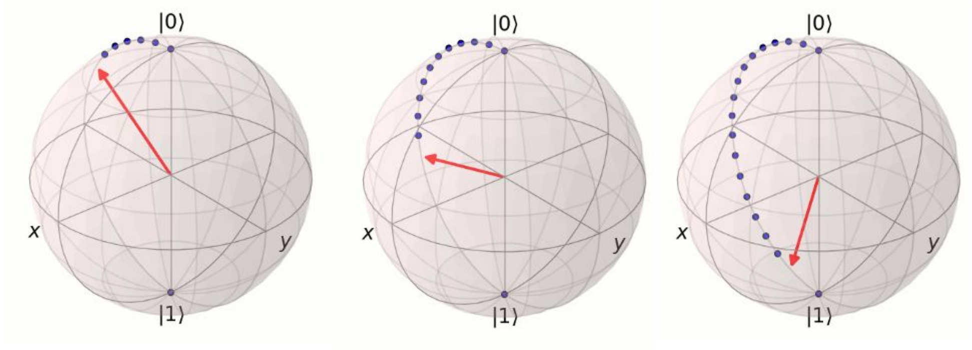
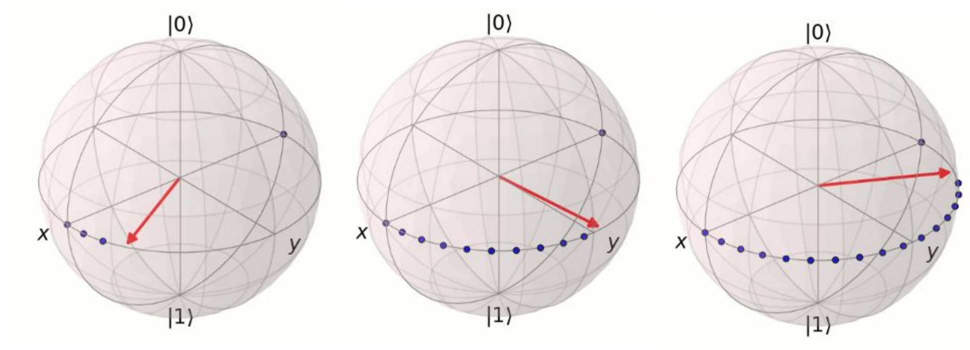


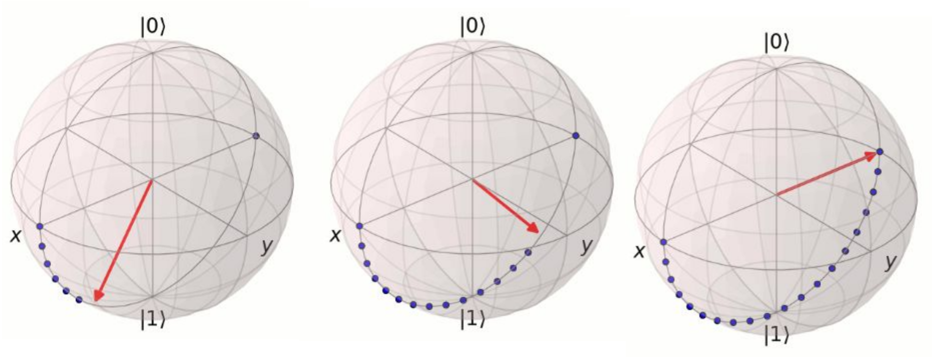
Quantum Gates

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



Quantum Gates

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$



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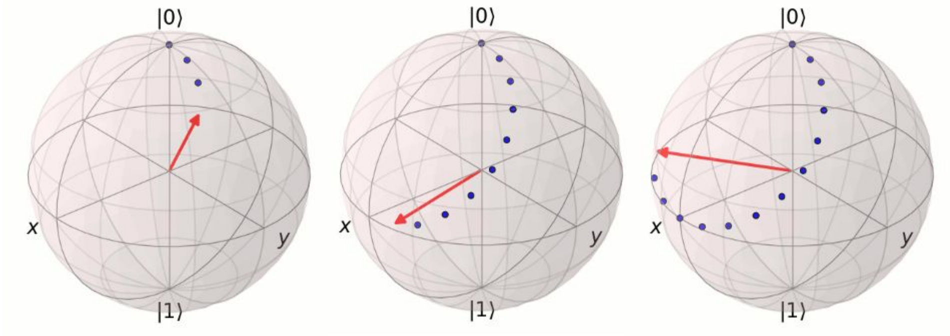

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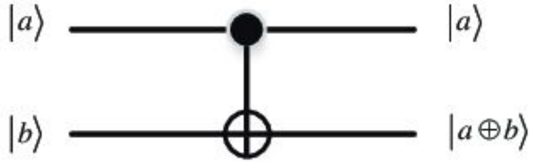
$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



Before		After	
Control bit	Target bit	Control bit	Target bit
$\lvert 0\rangle$	$\lvert 0\rangle$	$\lvert 0\rangle$	$\lvert 0\rangle$
$\lvert 0\rangle$	$\lvert 1\rangle$	$\lvert 0\rangle$	$\lvert 1\rangle$
$\lvert 1\rangle$	$\lvert 0\rangle$	$\lvert 1\rangle$	$\lvert 1\rangle$
$\lvert 1\rangle$	$\lvert 1\rangle$	$\lvert 1\rangle$	$\lvert 0\rangle$

Parametrized gates

$$Rx = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

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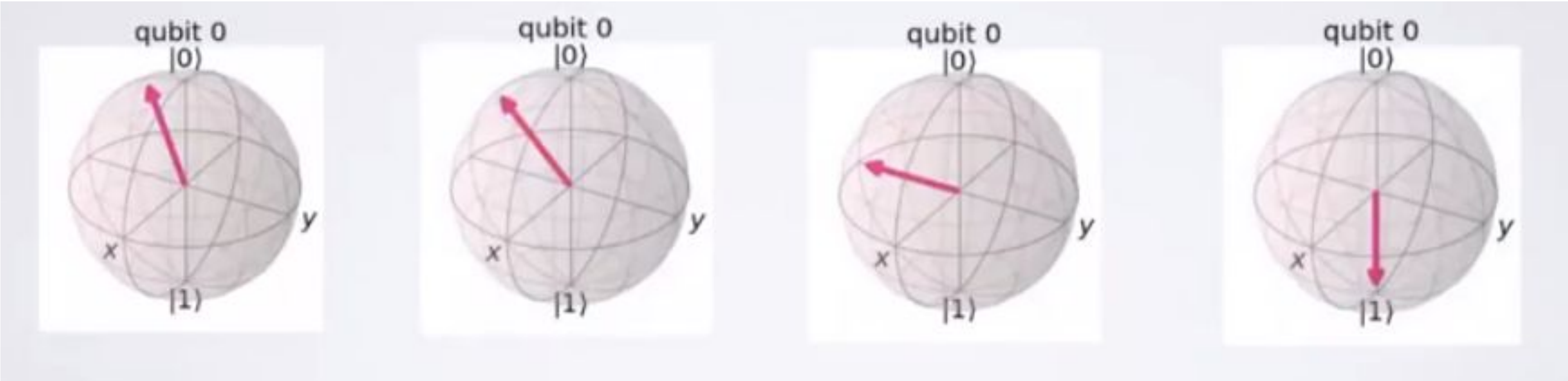
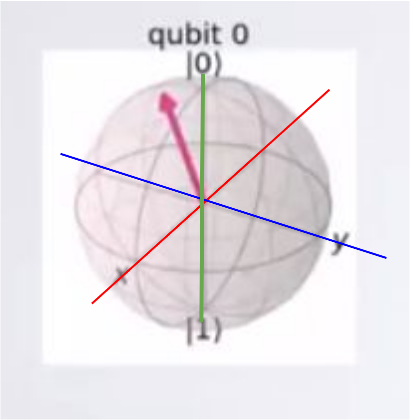
Rotation along X axis



Parametrized gates

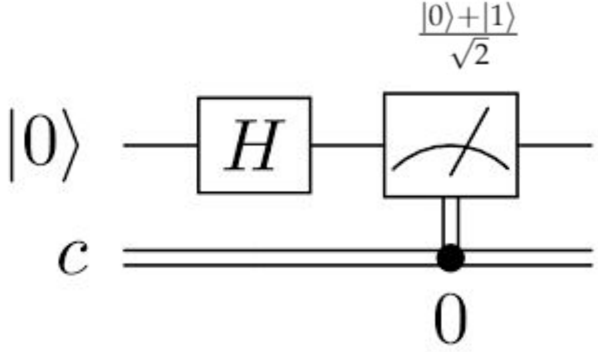
$$Rx = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix} \qquad Ry = \begin{bmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix} \qquad Rz = \begin{bmatrix} e^{-i\frac{\varphi}{2}} & 0 \\ 0 & e^{i\frac{\varphi}{2}} \end{bmatrix}$$



Measurement (the weirdest part)

“Measuring” a quantum particle collapses down its superposition into a single state (to a basis)

- Measurement is always associated with a basis state
- Default is the Z basis (or {<0|,<1|} basis)



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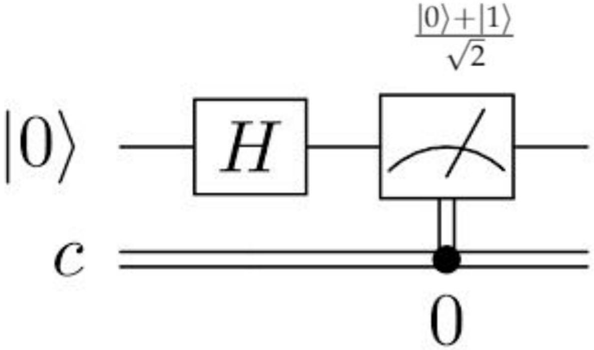

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

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

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

Also known as
Phase flip

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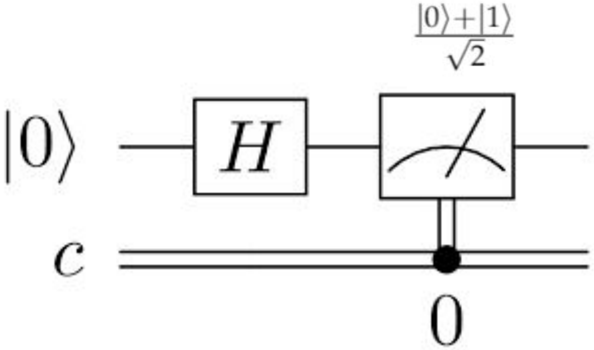

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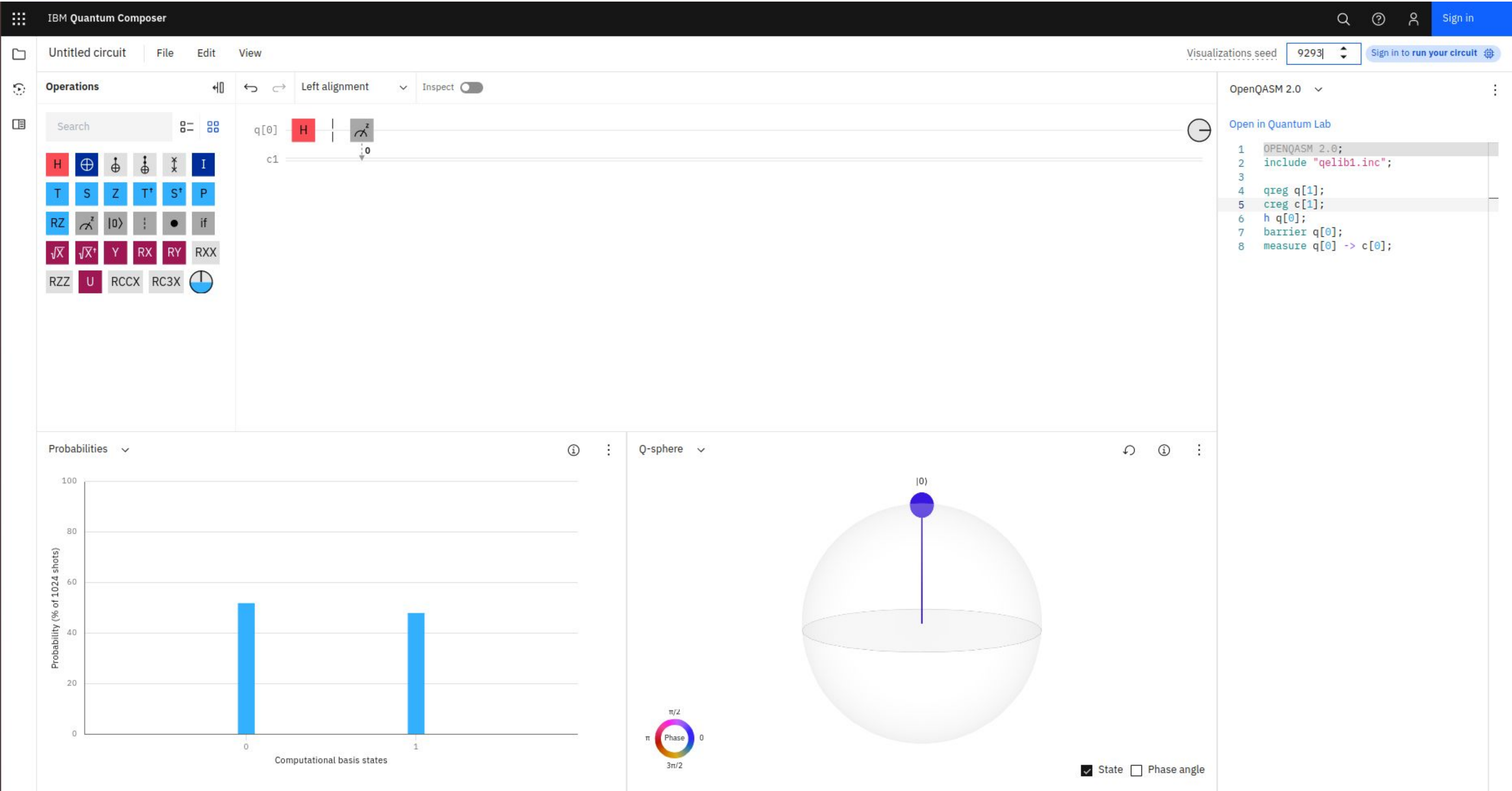
Eigen value	Eigen vector
+1	$\lvert 0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$
-1	$\lvert 1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

Also known as
Phase flip


IBM Quantum Composer
Sign in
Untitled circuit
File
Edit
View
Visualizations seed
9293
Sign in to run your circuit
Operations
Left alignment
Inspect
Search
H
I
T
S
Z
T†
S†
P
RZ
|0⟩
if
√X
√X†
Y
RX
RY
RXX
RZZ
U
RCCX
RC3X
q[0]
c1
0
OpenQASM 2.0
Open in Quantum Lab
OPENQASM 2.0;
include "qelib1.inc";
qreg q[1];
creg c[1];
h q[0];
barrier q[0];
measure q[0] -> c[0];
Probabilities
Probability (% of 1024 shots)
Computational basis states
Q-sphere
|0⟩
Phase
π/2
π
0
3π/2
State
Phase angle

Born Rule

If a qubit |ψ> is measured in a basis {|b>}, the probability of getting outcome as |b> is :

$$P(|b\rangle) = |\langle b|\psi\rangle|^2$$

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

$$Z = \{|0\rangle, |1\rangle\}$$

$$P(|0\rangle) = |\langle 0|\psi\rangle|^2$$

$$= \left|\langle 0|\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right|^2$$

$$= \frac{1}{2}|\langle 0|0\rangle + \langle 0|1\rangle|^2$$

$$= \frac{1}{2}$$

$$P(|0\rangle) = |\langle 1|\psi\rangle|^2 = \frac{1}{2}|\langle 0|0\rangle - \langle 0|1\rangle|^2$$

$$= \frac{1}{2}$$

Normalization of qubit

If the state is $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$

Then $|\alpha|^2+|\beta|^{2=}1$

Measuring in other basis

If the state is $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$

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

Eigen values	Eigen Vectors
+1	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} = \vert + > = \frac{1}{\sqrt{2}}(\vert 0 > + \vert 1 >)$
-1	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix} = \vert - > = \frac{1}{\sqrt{2}}(\vert 0 > - \vert 1 >)$

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	Eigen values	Eigen Vectors
	+1	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} = \|+> = \frac{1}{\sqrt{2}}(\|0> + \|1>)$
	-1	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix} = \|-> = \frac{1}{\sqrt{2}}(\|0> - \|1>)$

Don't get confused with the Hadamard gate H|0> = |+> and H|1> = |->

Measuring in other basis

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

$$X|0\rangle = |1\rangle$$

$$P|\langle +|1\rangle|^2 = \frac{1}{2}|\langle 0|1\rangle + \langle 1|1\rangle|^2 = \frac{1}{2}$$

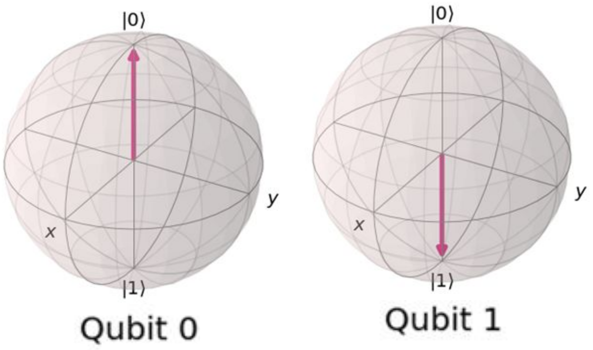
$$P|\langle -|1\rangle|^2 = \frac{1}{2}|\langle 0|1\rangle - \langle 1|1\rangle|^2 = \frac{1}{2}$$

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

$$P|\langle 0|\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)|^2 = \frac{1}{2}|\langle 0|0\rangle - \langle 0|1\rangle|^2 = \frac{1}{2}$$

$$P|\langle 1|\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)|^2 = \frac{1}{2}|\langle 1|0\rangle - \langle 1|1\rangle|^2 = \frac{1}{2}$$

Representing Multi-Qubit States



Composite system of |q0> and |q1>

$$|q_0\rangle \otimes |q_1\rangle$$

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

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

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

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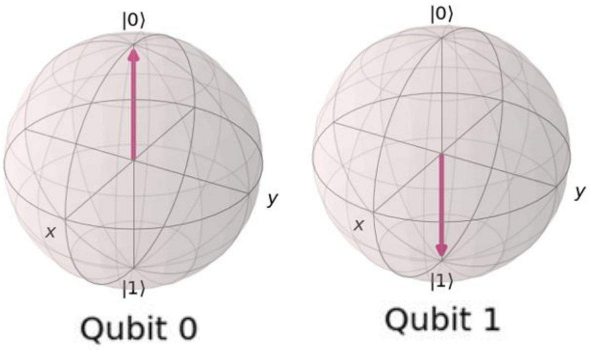

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$$= \begin{bmatrix} 1 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \\ 0 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

2 qubit $\rightarrow$ dim 4

3 qubit $\rightarrow$ dim 8

$\vdots$

n qubit $\rightarrow$ dim 2^n

Representing Multi-Qubit States

$$|\psi\rangle = \frac{\sqrt{3}}{2\sqrt{2}}|00\rangle - \frac{\sqrt{3}}{2\sqrt{2}}|01\rangle + \frac{1}{2\sqrt{2}}|10\rangle - \frac{1}{2\sqrt{2}}|11\rangle$$

Measuring both the qubits	Measuring the first qubit
$P(\|00\rangle) = \left(\frac{\sqrt{3}}{2\sqrt{2}}\right)^2 = \frac{3}{8}$	
$P(\|01\rangle) = \frac{3}{8}$	
$P(\|10\rangle) = \left(\frac{1}{2\sqrt{2}}\right)^2 = \frac{1}{8}$	
$P(\|11\rangle) = \frac{1}{8}$	

Representing Multi-Qubit States

$$|\psi\rangle = \frac{\sqrt{3}}{2\sqrt{2}}|00\rangle - \frac{\sqrt{3}}{2\sqrt{2}}|01\rangle + \frac{1}{2\sqrt{2}}|10\rangle - \frac{1}{2\sqrt{2}}|11\rangle$$

Measuring both the qubits	**Measuring the first qubit**
$P(\lvert 00\rangle) = \left(\frac{\sqrt{3}}{2\sqrt{2}}\right)^2 = \frac{3}{8}$ $P(\lvert 01\rangle) = \frac{3}{8}$ $P(\lvert 10\rangle) = \left(\frac{1}{2\sqrt{2}}\right)^2 = \frac{1}{8}$ $P(\lvert 11\rangle) = \frac{1}{8}$	$\lvert\psi\rangle = \frac{\sqrt{3}}{2}\lvert 0\rangle\left(\frac{1}{\sqrt{2}}\lvert 0\rangle - \frac{1}{\sqrt{2}}\lvert 1\rangle\right) + \frac{1}{2}\lvert 1\rangle\left(\frac{1}{\sqrt{2}}\lvert 0\rangle - \frac{1}{\sqrt{2}}\lvert 1\rangle\right)$ $= \left(\frac{\sqrt{3}}{2}\lvert 0\rangle + \frac{1}{\sqrt{2}}\lvert 1\rangle\right) \otimes \left(\frac{1}{\sqrt{2}}\lvert 0\rangle - \frac{1}{\sqrt{2}}\lvert 1\rangle\right)$ $P(0) = \frac{3}{4}$ $P(1) = \frac{1}{4}$

Entanglement

What if the multi qubit state is in the below format?

$$|\phi^+\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$$

Can you factorize and separate?

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$$= ac|00\rangle + bc|10\rangle + ad|01\rangle + bd|11\rangle$$

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$$ac = \frac{1}{\sqrt{2}} \quad bc = 0$$

$$bd = \frac{1}{\sqrt{2}} \quad ad = 0$$

$$\Rightarrow \quad b = 0 \qquad c = 0$$

$$\Downarrow \qquad \Downarrow$$

$$bd = 0 \qquad ac = 0$$

NOT POSSIBLE!

Bell State

$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$$|\Phi^-\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$

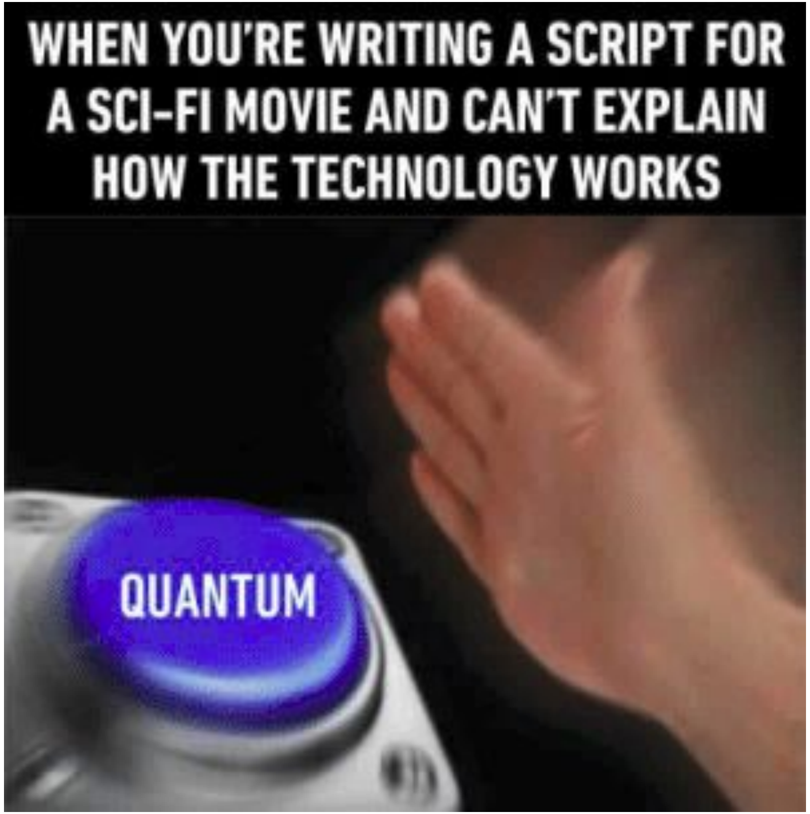
$$|\Psi^+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$|\Psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

Forms an orthonormal basis for 2 qubit states

Applications found in :

1. Superdense coding
2. Quantum teleportation
3. Quantum cryptography etc.


WHEN YOU'RE WRITING A SCRIPT FOR A SCI-FI MOVIE AND CAN'T EXPLAIN HOW THE TECHNOLOGY WORKS
QUANTUM

Measure an entangled state

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Measure qubit 1

$P(|0\rangle) = \left|\frac{1}{\sqrt{2}}\right|^2 = \frac{1}{2}$

$P(|1\rangle) = \frac{1}{2}$

State of qubit 2

Measure an entangled state

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Measure qubit 1	State of qubit 2
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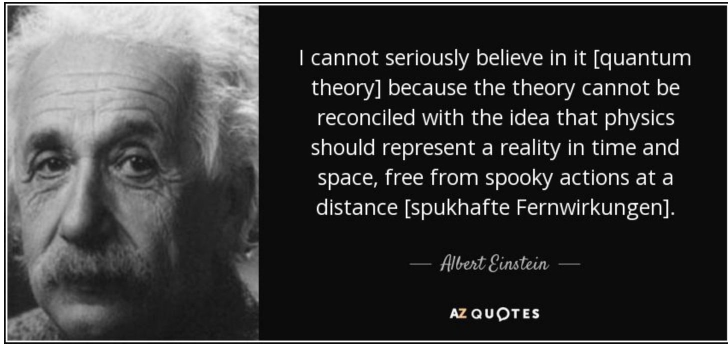

No cloning theorem

$$|\psi\rangle|b\rangle \xrightarrow{C} |\psi\rangle|\psi\rangle$$

$\Downarrow$

CLONER

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$$C\left(|0\rangle|b\rangle\right) = |0\rangle|0\rangle$$

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CLONER

Does there exist an universal cloning machine?

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$\Downarrow$

CLONER

Does there exist an universal cloning machine?

$C\left((\alpha|0\rangle+\beta|1\rangle)\;|b\rangle\right)$

$\xrightarrow{\text{Expectation}} (\alpha|0\rangle+\beta|1\rangle)(\alpha|0\rangle+\beta|1\rangle)$

$C\left(|0\rangle|b\rangle\right)=|0\rangle|0\rangle$

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No cloning theorem

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$$C\big(|0\rangle|b\rangle\big) = |0\rangle|0\rangle$$

$$C\big(|1\rangle|b\rangle\big) = |1\rangle|1\rangle$$

$$\xrightarrow{\text{Reality}} C\big(\alpha|0\rangle|b\rangle+\beta|1\rangle|b\rangle\big)$$

$$= \alpha C|0\rangle|b\rangle + \beta C|1\rangle|b\rangle$$

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

$$\neq (\alpha|0\rangle+\beta|1\rangle)(\alpha|0\rangle+\beta|1\rangle)$$

Quantum circuits (prerequisite for the hands-on)

```
qc = QuantumCircuit(1)
qc.draw()
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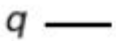


```
qc = QuantumCircuit(1)
qc.x(0)
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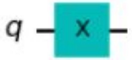
```



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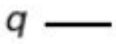


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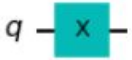
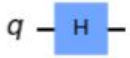
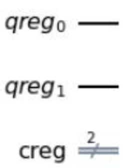



```
qc = QuantumCircuit(1)
qc.h(0)
qc.draw()
```



Quantum Circuits Using Multi-Qubit Gates

```
# initialize a quantum circuit with 2 qubits and 2 cbits
qc = QuantumCircuit()
qr = QuantumRegister(2, 'qreg')
cr = ClassicalRegister(2, 'creg') #labeling qreg creg is optional
qc.add_register(qr)
qc.add_register(cr)
qc.draw()
```



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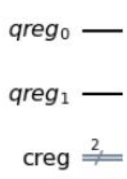
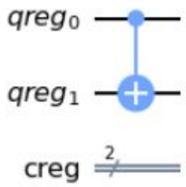



```
qc.cx(qr[0], qr[1])
qc.draw()
```



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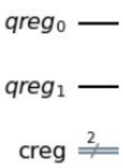


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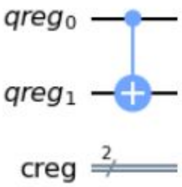
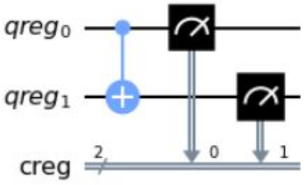
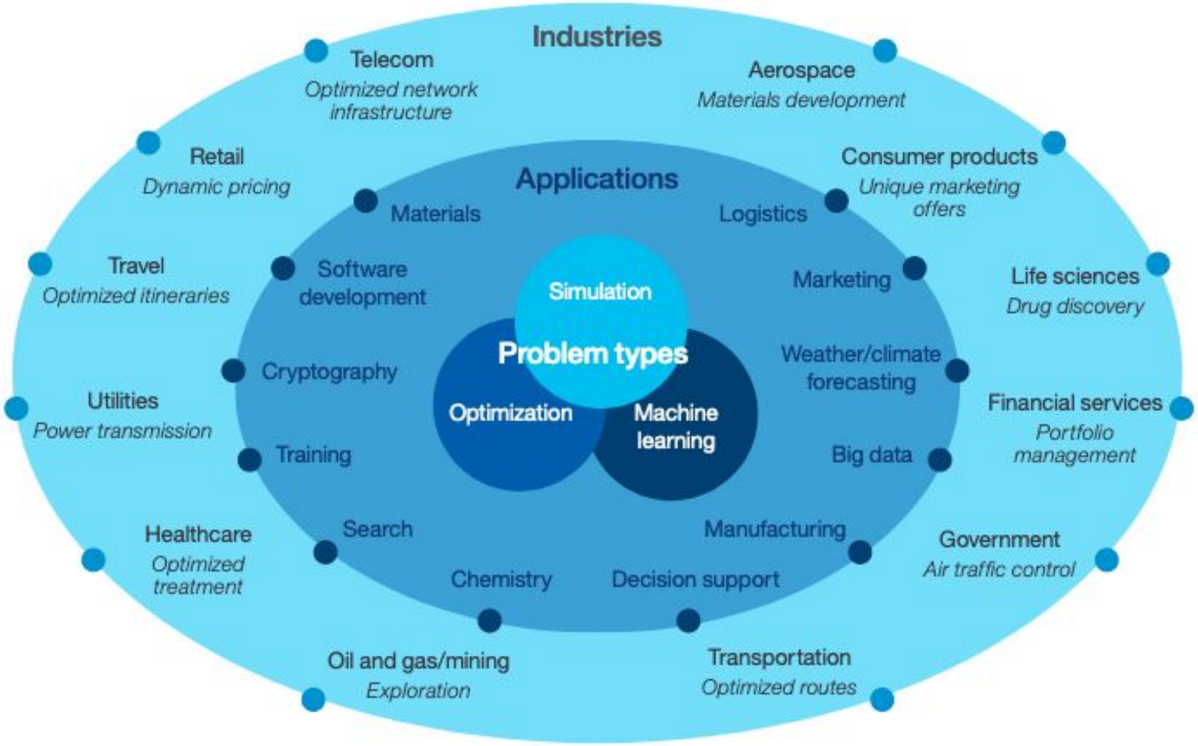



```
qc.measure(qr[0],cr[0])
qc.measure(qr[1],cr[1])

qc.draw()
```



Applications

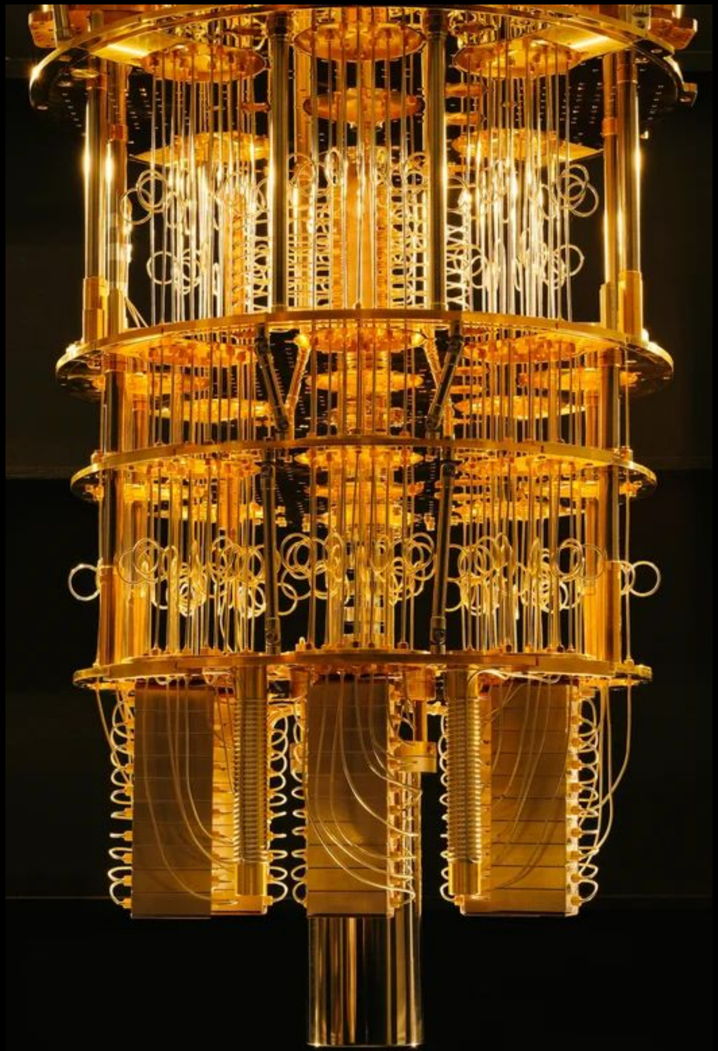


Some useful materials

1. To brush up linear algebra: https://qiskit.org/textbook/ch-appendix/linear_algebra.html#Matrices-and-Matrix-Operations
2. For anything related to qiskit: https://qiskit.org/textbook/preface.html
3. To brush up probability theory : https://www.khanacademy.org/math/statistics-probability/random-variables-stats-library
4. For python : https://www.w3schools.com/python/
5. How to install qiskit to your local machine: https://qiskit.org/documentation/getting_started.html

Thank you!

Questions???



Reach out :
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Gmail: debasmita.ria21@gmail.com