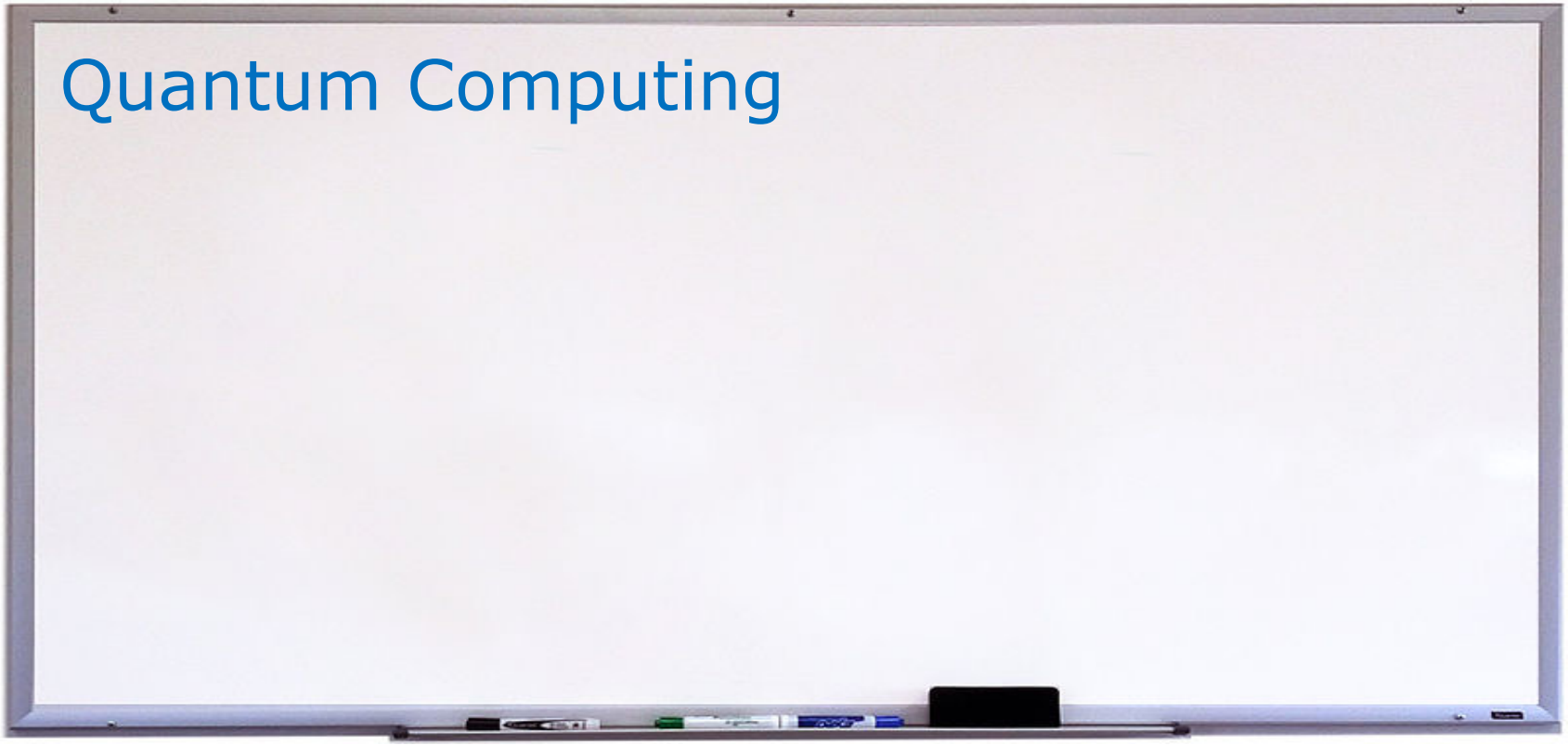
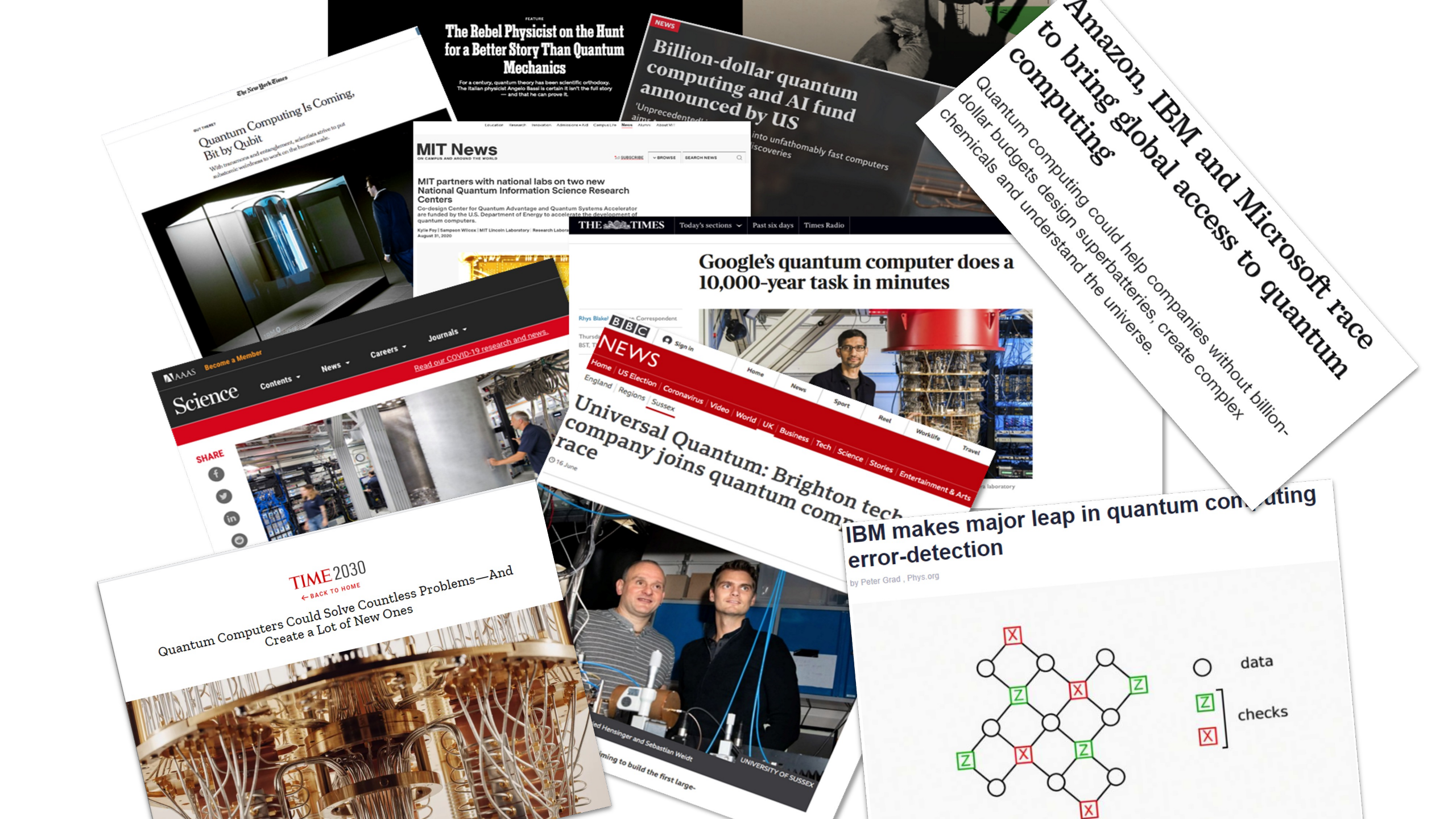
Cloud-based Quantum Computing 101

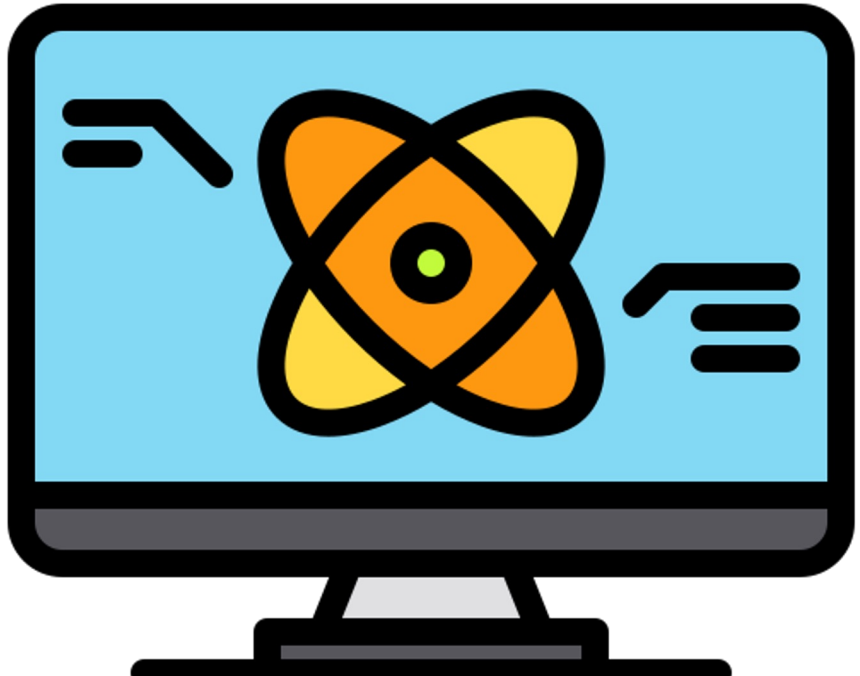
Giuseppe Bisicchia and Antonio Brogi

Department of Computer Science
University of Pisa


Quantum Computing


FEATURE
The Rebel Physicist on the Hunt for a Better Story Than Quantum Mechanics
For a century, quantum theory has been scientific orthodoxy. The Italian physicist Angelo Bassi is certain it isn't the full story — and that he can prove it.
The New York Times
Quantum Computing Is Coming, Bit by Qubit
With tracemous and entanglement, scientists strive to put solutionic weirdness to work on the human scale.
NEWS
Billion-dollar quantum computing and AI fund announced by US
MIT News
ON CAMPUS AND AROUND THE WORLD
MIT partners with national labs on two new National Quantum Information Science Research Centers
Co-design Center for Quantum Advantage and Quantum Systems Accelerator are funded by the U.S. Department of Energy to accelerate the development of quantum computers.
August 31, 2020
THE TIMES
Today's sections
Past six days
Times Radio
Amazon, IBM and Microsoft race to bring global access to quantum computing
Quantum computing could help companies without billion-dollar budgets design superbatteries, create complex chemicals and understand the universe.
AAAS
Become a Member
Science
Contents
News
Careers
Journals
Read our COVID-19 research and news.
SHARE
Google's quantum computer does a 10,000-year task in minutes
BBC
NEWS
Home
US Election
Coronavirus
Video
World
UK
Business
Tech
Science
Stories
Entertainment & Arts
England
Regions
Sussex
Universal Quantum: Brighton tech company joins quantum comp race
16 June
TIME 2030
BACK TO HOME
Quantum Computers Could Solve Countless Problems—And Create a Lot of New Ones
UNIVERSITY OF SUSSEX
IBM makes major leap in quantum computing error-detection
by Peter Grad , Phys.org
data
checks

Quantum Computing Fundamentals

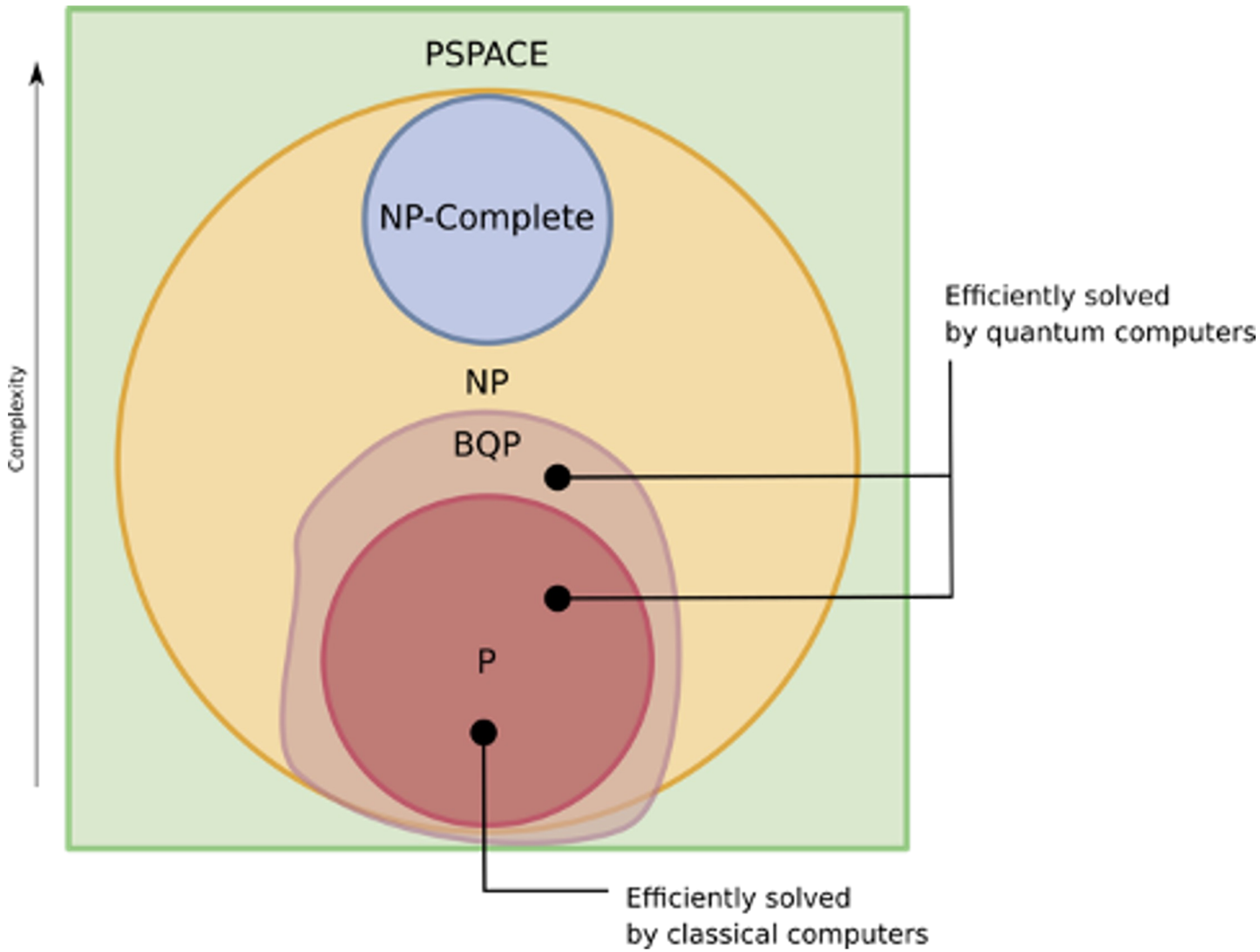


Why should I invest in Quantum Computing?

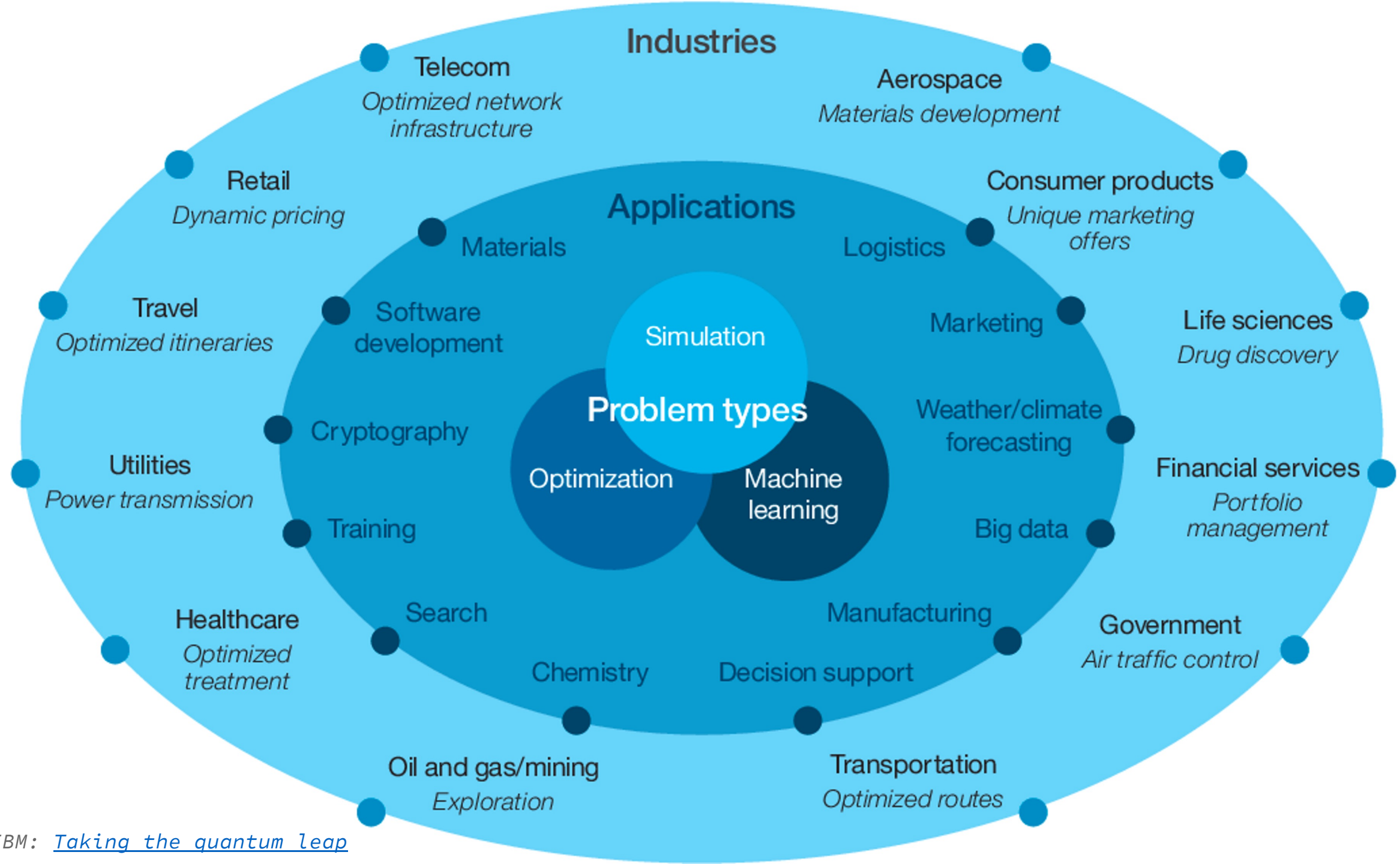
G

Why should I invest in Quantum Computing?

Investing in quantum computing is a strategic move for those with a long-term perspective. Quantum computing has the potential to revolutionize various industries by solving complex problems exponentially faster than classical computers. It promises breakthroughs in fields like cryptography, drug discovery, materials science, and optimization.


PSPACE
NP-Complete
NP
BQP
P
Complexity
Efficiently solved
by quantum computers
Efficiently solved
by classical computers

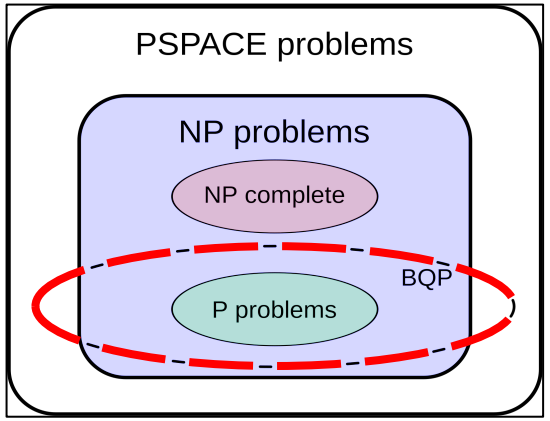
Problems	Explication	Quantum Complexity	Classical Complexity
Factorization (Shor)	Decomposition of a number into a product of smaller integers	O(logN)	$\Theta\left(\exp\left(\left(\frac{32}{9}n\right)^{\frac{1}{3}}(\log n)^{\frac{2}{3}}\right)\right)$
Search (Grover)	Search in an unordered sequence of data	O(√n)	O(n)



by IBM: [Taking the quantum leap]

Quantum Computing

Quantum computers can solve various problems **exponentially faster** than traditional computers



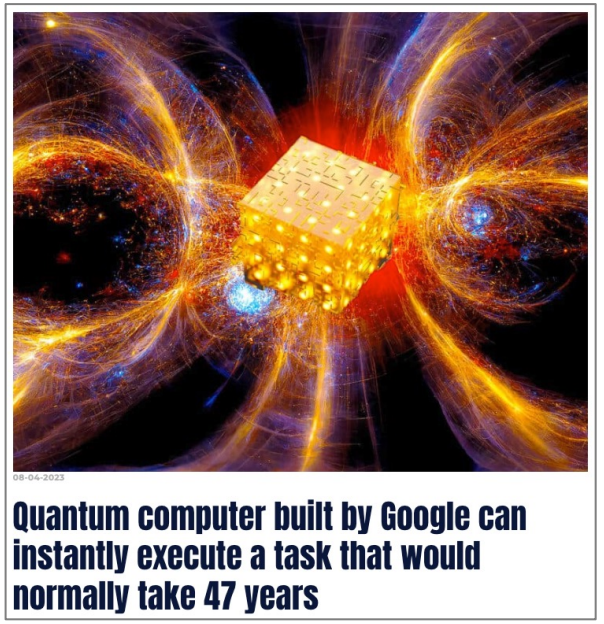
15 Significant Ways Quantum Computing Could Soon Impact Society

Forbes Technology Council

Expert Panel® Forbes Councils Member

Apr 18, 2023,

1. Breaking Current Encryption Schemes
2. Better Securing Sensitive Data
3. 'Breaking' The Blockchain
4. Modeling Chemical Reactions For Drug Development
5. Enhancing Drug Discovery And Personalized Medicine
6. Improving AI Capabilities
7. Optimizing Investment Portfolios
8. Safe Computing Of Encrypted Data
9. Democratizing Generative AI
10. Enabling True Real-Time Reporting
11. Discovering New Materials
12. Improving Weather Forecasting
13. Enabling Hyper-Personalized Shopping Experiences
14. Optimizing Traffic Flows
15. Combating Climate Change



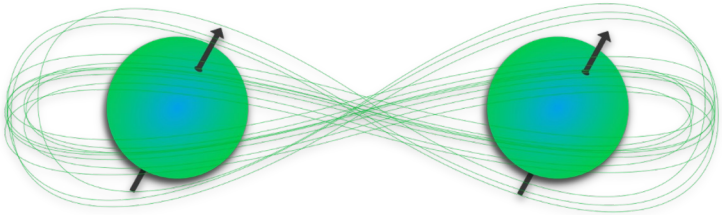
What is a Quantum Computer?

What is a Quantum Computer?

A *Quantum Computer* is a device that leverages

Quantum Mechanics Properties to perform **computations**

Superposition



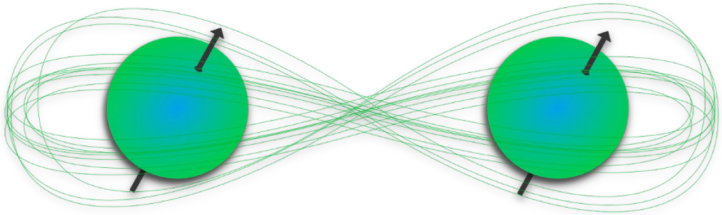
Entanglement

What is a Quantum Computer?

A *Quantum Computer* is a device that leverages

Quantum Mechanics Properties to perform **computations**

Superposition



Entanglement

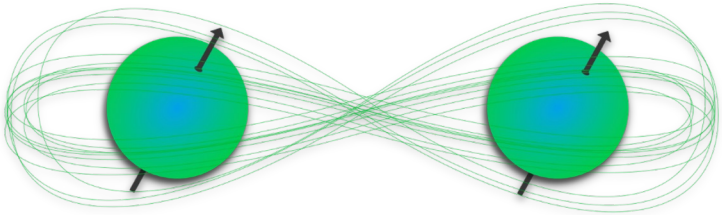
In essence, qubits leverage the principles of **quantum mechanics** to provide a **new way of representing and processing information**, promising **significant advantages** for solving specific problems when compared to classical computing

What is a Quantum Computer?

A *Quantum Computer* is a device that leverages

Quantum Mechanics Properties to perform **computations**

Superposition



Entanglement

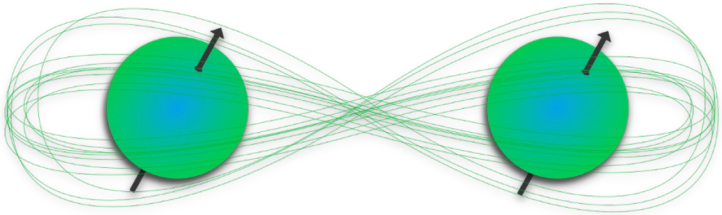
From Bits…

What is a Quantum Computer?

A *Quantum Computer* is a device that leverages

Quantum Mechanics Properties to perform **computations**

Superposition



Entanglement

…to Qubits!

2 Qubits
IBM, Oxford, Berkeley, Stanford & MIT

5 Qubits
Technical University of Munich

7 Qubits
Los Alamos National Laboratory

12 Qubits
Institute for Quantum Computing & MIT

28 Qubits
D-Wave Systems

50 Qubits
IBM

72 Qubits
Google

128 Qubits
Rigetti

32 Qubits
IonQ

127 Qubits
IBM

443 Qubits
IBM

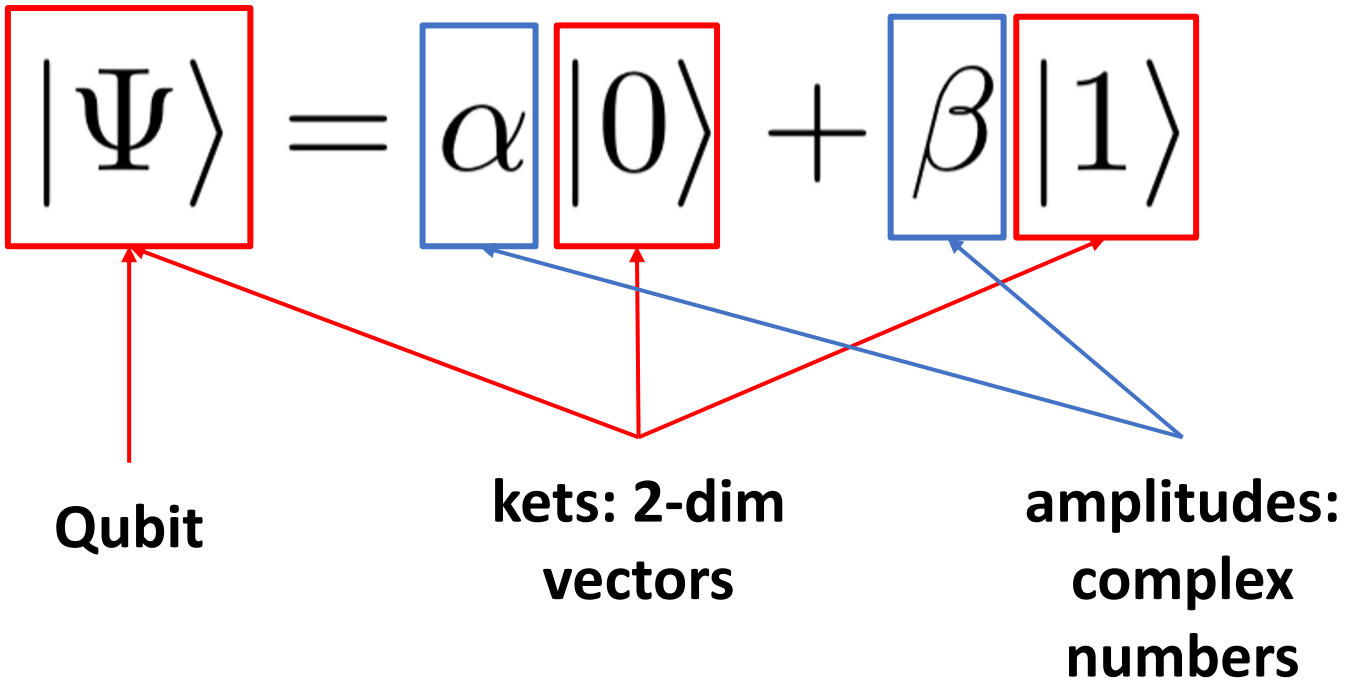
1121 Qubits
IBM

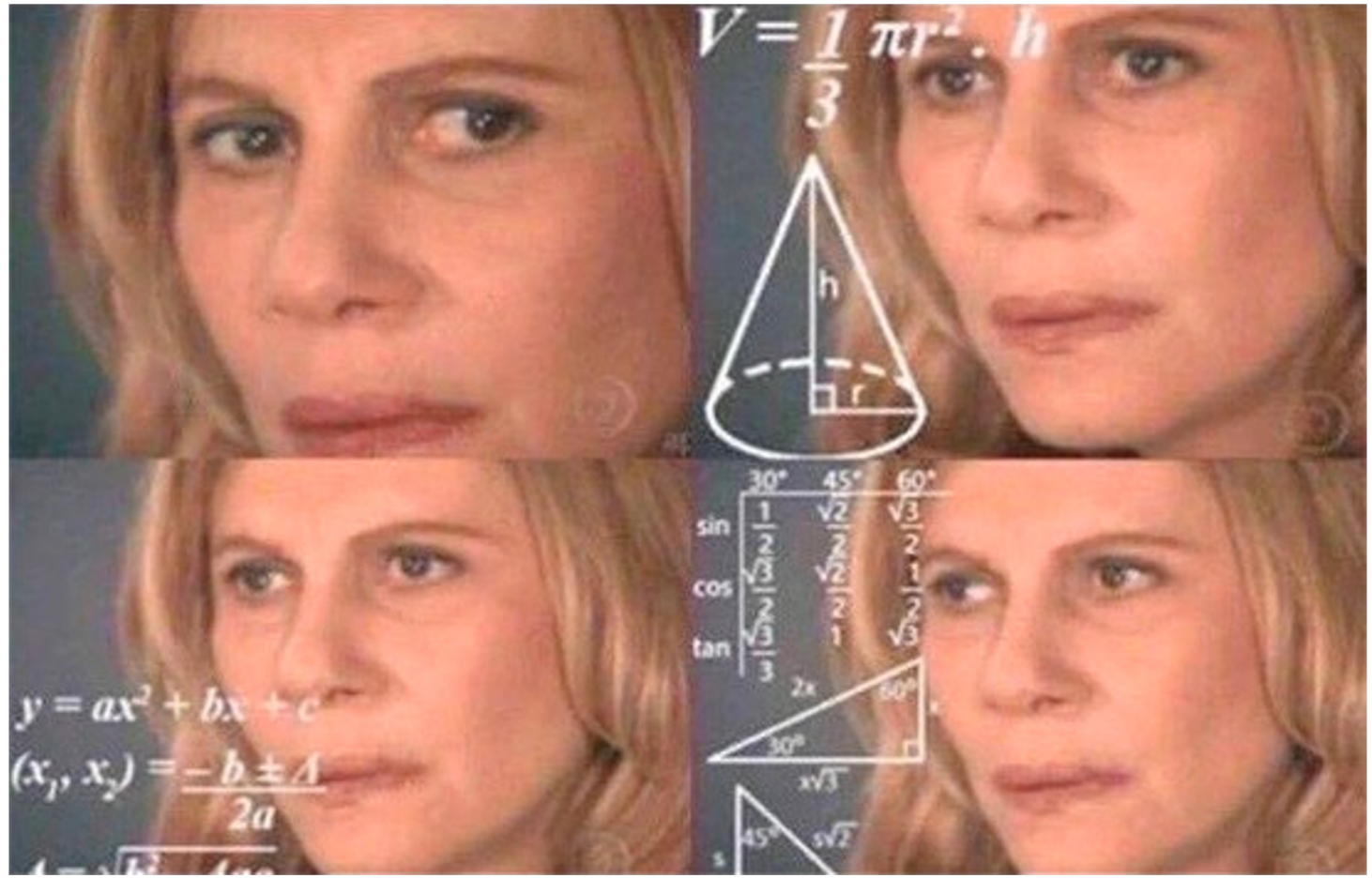
98 00 06 08 16 18 19 21 21 22 23

1990 2000 2010 2020

A Qubit

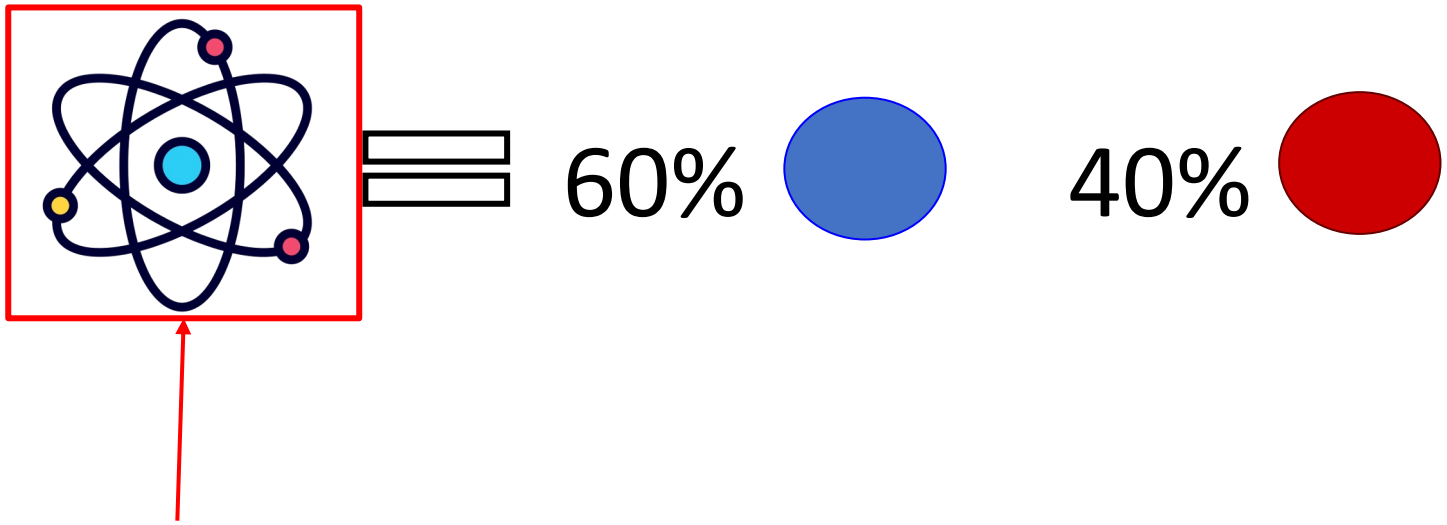
Mathematically, a qubit is a **complex-valued linear combination** of its two possible basis states “0” (the *ground state*) and “1” (the *excited state*).




$V = \frac{1}{3}\pi r^2 \cdot h$
h
r
$y = ax^2 + bx + c$
$(x_1, x_2) = \frac{-b \pm \Delta}{2a}$
30° 45° 60°
sin $\frac{1}{2}$ $\frac{\sqrt{2}}{2}$ $\frac{\sqrt{3}}{2}$
cos $\frac{\sqrt{3}}{2}$ $\frac{\sqrt{2}}{2}$ $\frac{1}{2}$
tan $\frac{\sqrt{3}}{3}$ 1 $\sqrt{3}$
2x
60°
30°
x√3
45°
x√2
x

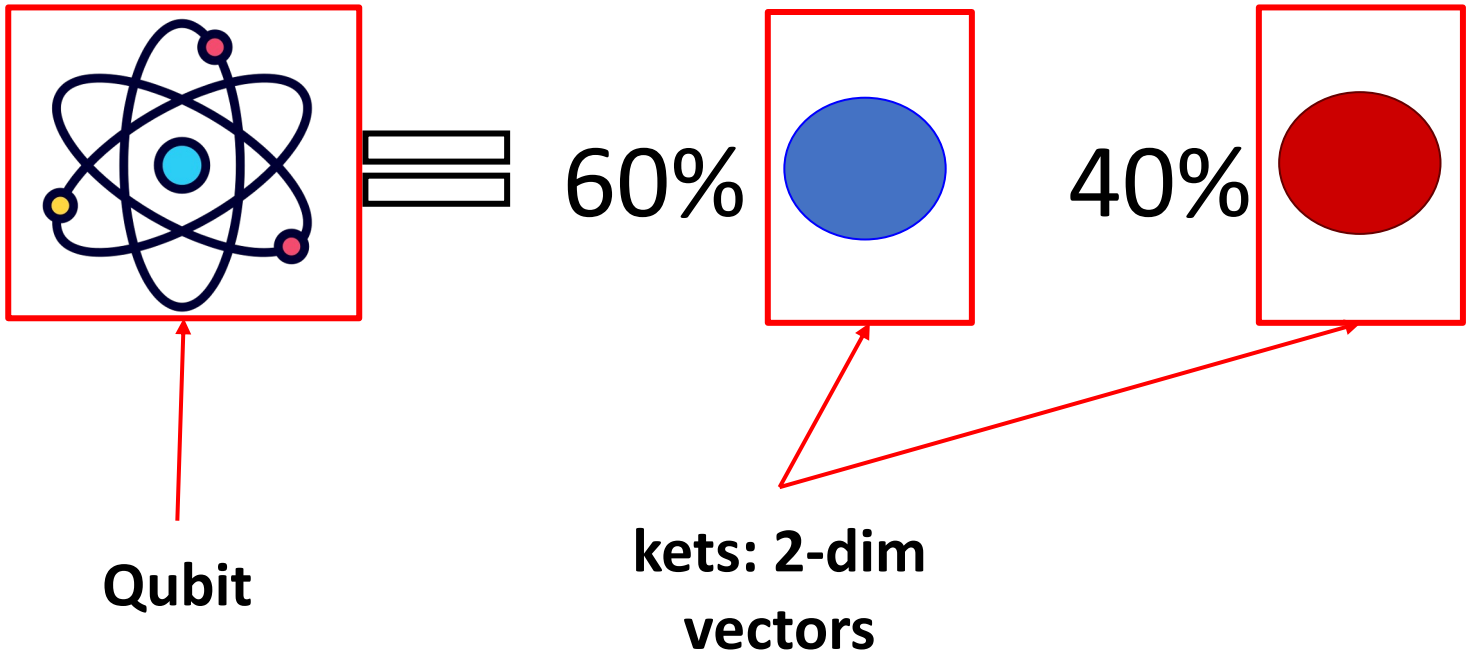
A Qubit

Conceptually, a qubit is the **fundamental unit of quantum information**. Unlike classical the bit, its state can be “0”, “1” or a ***superposition*** (i.e., linear combination) of both. When eventually *observed,* the state of a qubit will *collapse* only to the plain states “0” or “1”, with **different probabilities** according to its superposition



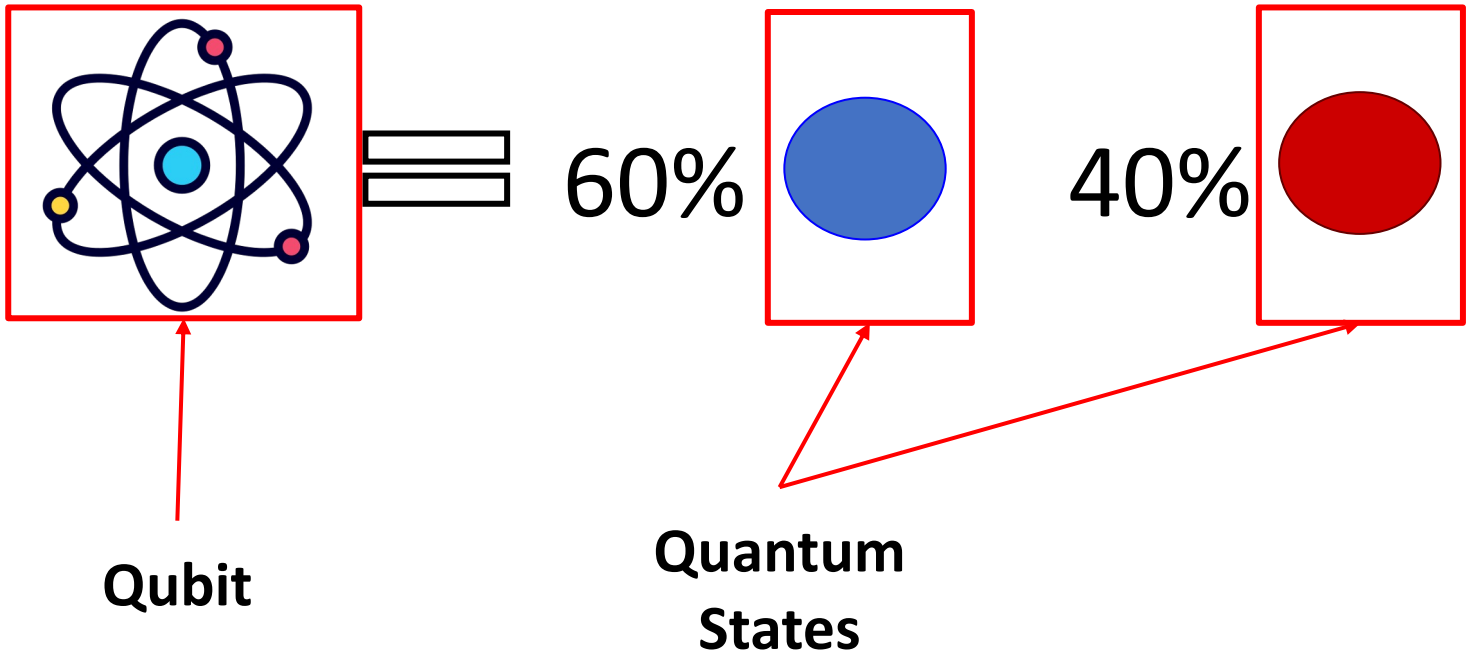
A Qubit

Conceptually, a qubit is the **fundamental unit of quantum information**. Unlike classical the bit, its state can be “0”, “1” or a ***superposition*** (i.e., linear combination) of both. When eventually *observed,* the state of a qubit will *collapse* only to the plain states “0” or “1”, with **different probabilities** according to its superposition



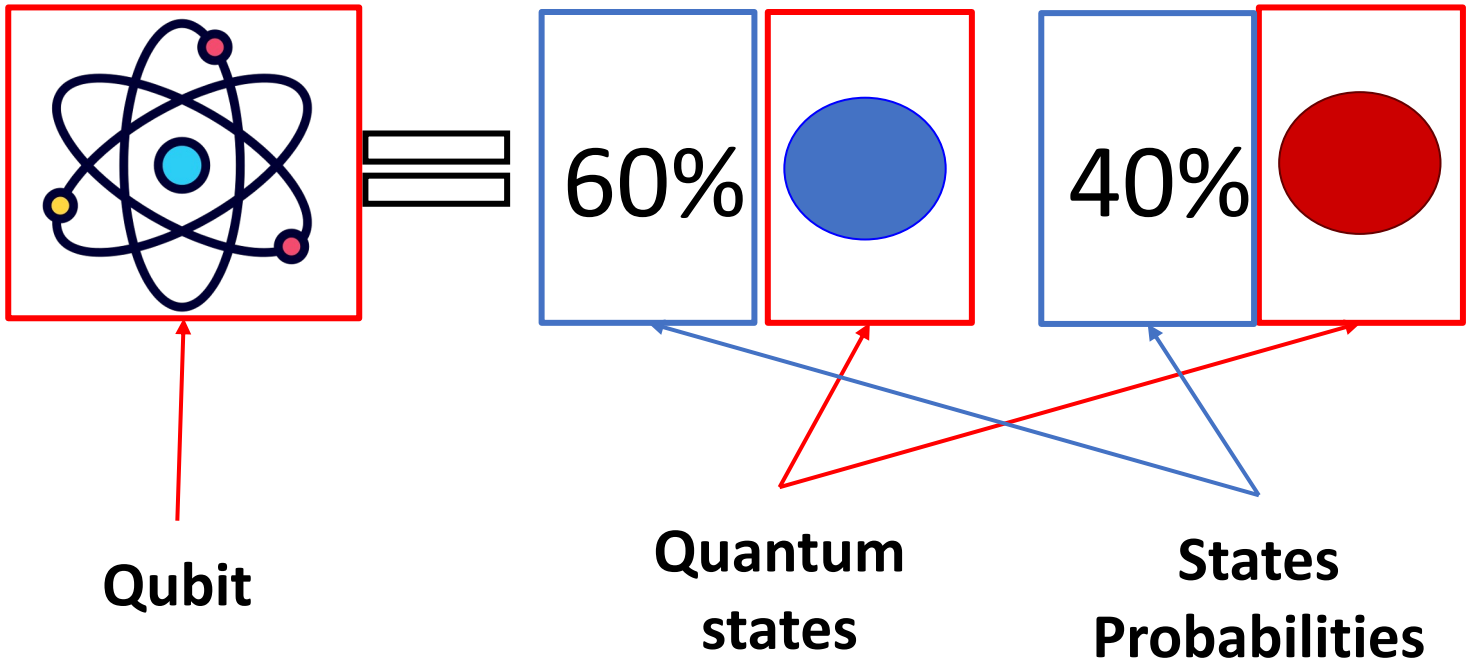
A Qubit

Conceptually, a qubit is the **fundamental unit of quantum information**. Unlike classical the bit, its state can be “0”, “1” or a ***superposition*** (i.e., linear combination) of both. When eventually *observed,* the state of a qubit will *collapse* only to the plain states “0” or “1”, with **different probabilities** according to its superposition



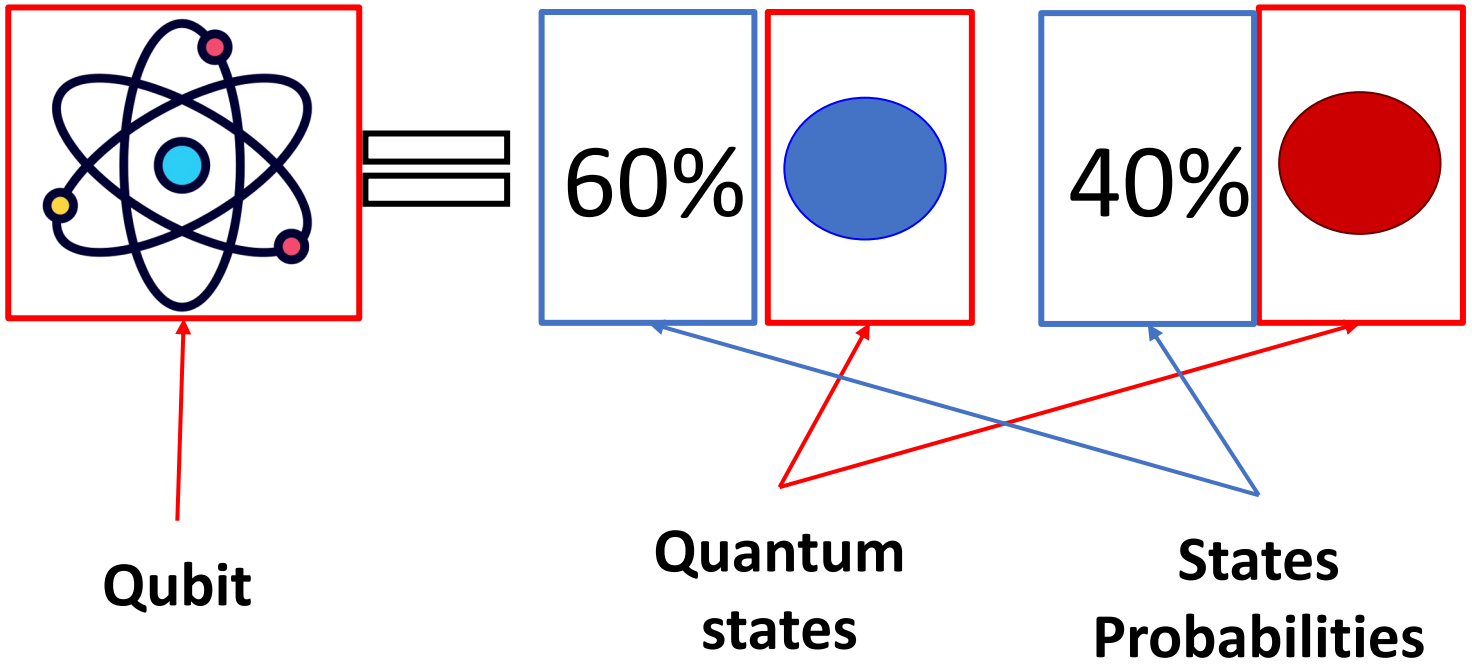
A Qubit

Conceptually, a qubit is the **fundamental unit of quantum information**. Unlike classical the bit, its state can be “0”, “1” or a ***superposition*** (i.e., linear combination) of both. When eventually *observed,* the state of a qubit will *collapse* only to the plain states “0” or “1”, with **different probabilities** according to its superposition



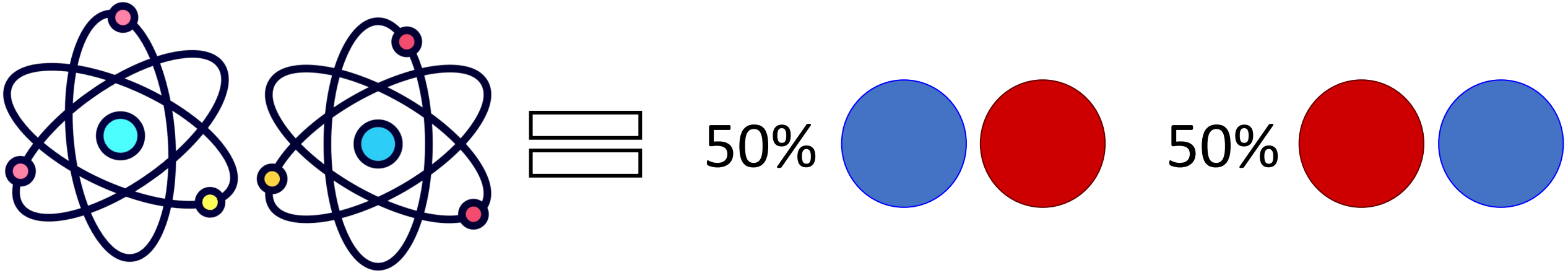
A Qubit

Conceptually, a qubit is the **fundamental unit of quantum information**. Unlike classical the bit, its state can be “0”, “1” or a ***superposition*** (i.e., linear combination) of both. When eventually *observed,* the state of a qubit will *collapse* only to the plain states “0” or “1”, with **different probabilities** according to its superposition



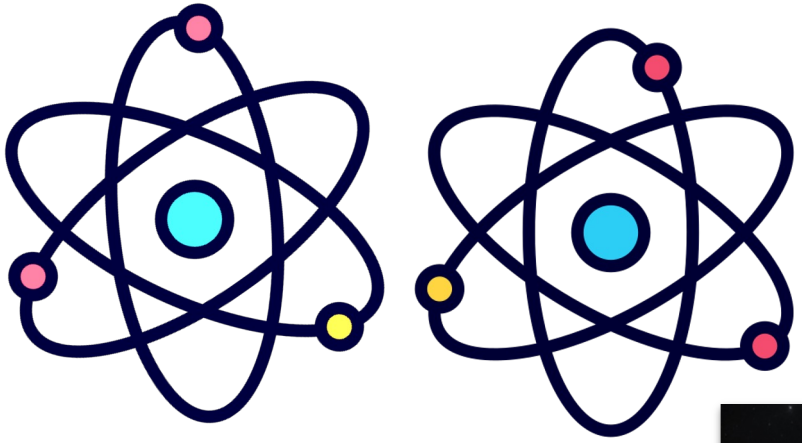
Entanglement

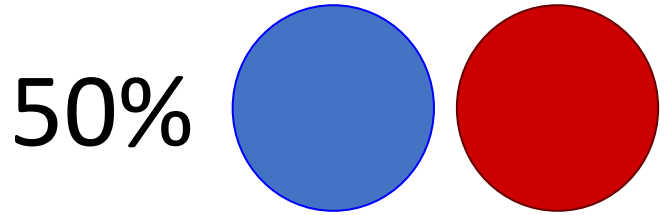
Qubits can be ***entangled***, meaning **the state of one qubit** becomes **directly correlated** to **the state of another**, no matter how far apart they are

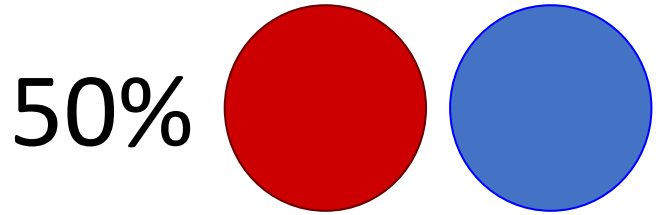


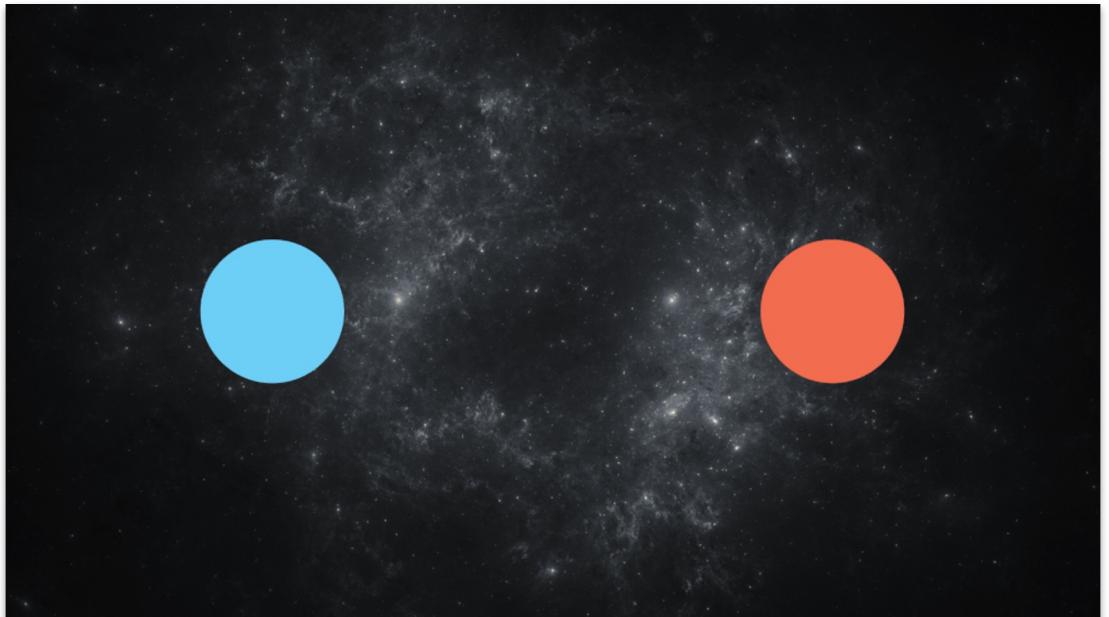
Entanglement

Qubits can be ***entangled***, meaning **the state of one qubit** becomes **directly correlated** to **the state of another**, no matter how far apart they are









Qubit You Choose, Features You Find

Classification	Description	Examples	Qubit lifetime (1)	Gate fidelity (2)	Gate operation time (3)	Connectivity	Scalability	Pros	Cons
Superconducting	Two level system of a superconducting circuit which forms a qubit (a transmon, first developed at Yale)	IBM, Google, Rigetti, Alibaba, Intel, Quantum Circuits	c.50-100μs	c.99.4%	c.10-50ns	Neighbours	Highly scalable (see OQC coaxmon tech)	- Fast gate times - Builds on existing semiconductor industry	- Typically low longevity - Must be kept very cold to work
Ion trap	Single charged ions trapped in magnetic fields. Energy level of its spin comprises the qubits	IonQ; Alpine Quantum Technologies; Honeywell	>1,000s	c.99.9%	c.3-50μs	All-to-all	TBC	- High gate fidelity - Very stable	- Slow operations
Photonics	Qubits made from single particles of light (photons) operating on silicon chips pathways	PsiQuantum, Xanadu	c. 150μs	c. 98.0%	c.1ns	Unknown	Highly scalable (see Psi Quantum)	- Highly scalable - Utilises existing SC industry infrastructure - No temperature requirements	- Nascent technology - Connectivity to be demonstrated
Neutral atoms	Qubits made from individual atoms (rather than ions which have a charge)	Atom Computing, PASQAL, QuEra	Similar to ion trap	c.95%	TBC	TBC	TBC	- Long qubit coherence times	- Must be kept cold - Nascent
Silicon	Artificial atoms made by adding an electron to a small piece of pure silicon and microwaves control the electrons state	Intel, Silicon Quantum Computing	c. 1-10s	c. 99%	c.1-10ns	Neighbours	Expect high scalability	- Stable - Utilises existing semiconductor industry infrastructure	- Must be kept cold - Nascent
Topological qubits	Qubits made from non-Abelian forms of matter	Microsoft (WIP)	Very high	Very high	Unknown	Unknown	Unknown	- Estimated long lifetime and high fidelities	- Existence to be confirmed

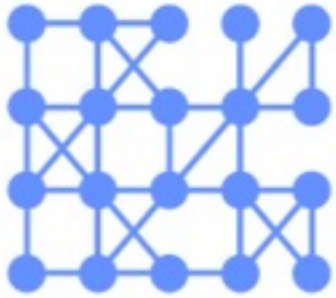
Notes: (1) *Record coherence time for a single qubit position state; (2) Highest reported fidelity for two qubit gate operations; (3) Speed of gate operations*
Sources: Literature review, TQD expert interviews. Special reference to BCG reports, Science Mag and NAE report on quantum computing.

s = seconds
μs = microsecond (10^ -6 seconds)
ns = nanosecond (10^ -9 seconds)

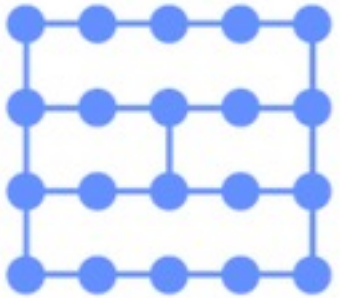
Quantum Topologies

Different qubits should be «physically» connected to be able to perform a multi-qubit operation among such qubits. There are different ways (topologies) we can connect qubits.

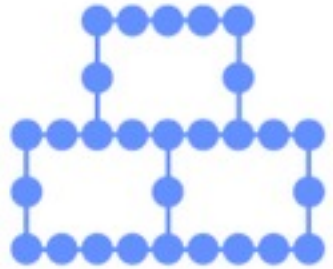
Rueschlikon



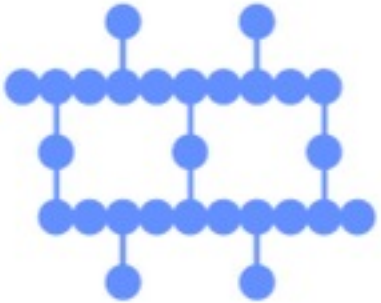
Tokyo



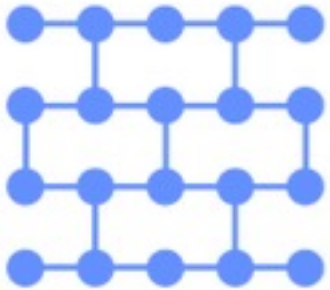
Poughkeepsie
Johannesburg



Cambridge

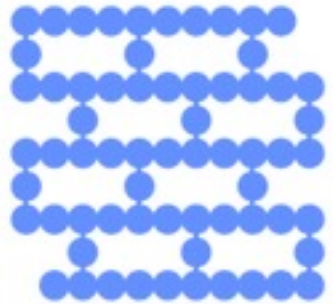


Montreal
Paris
Toronto



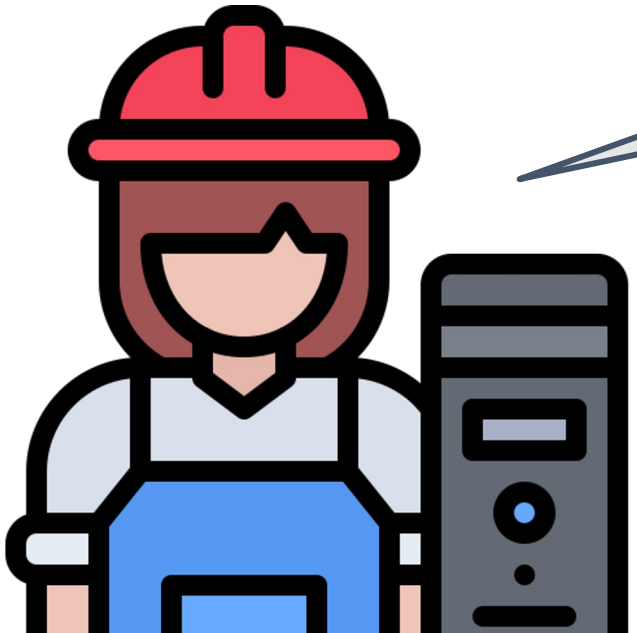
Almaden
Singapore
Boebligen

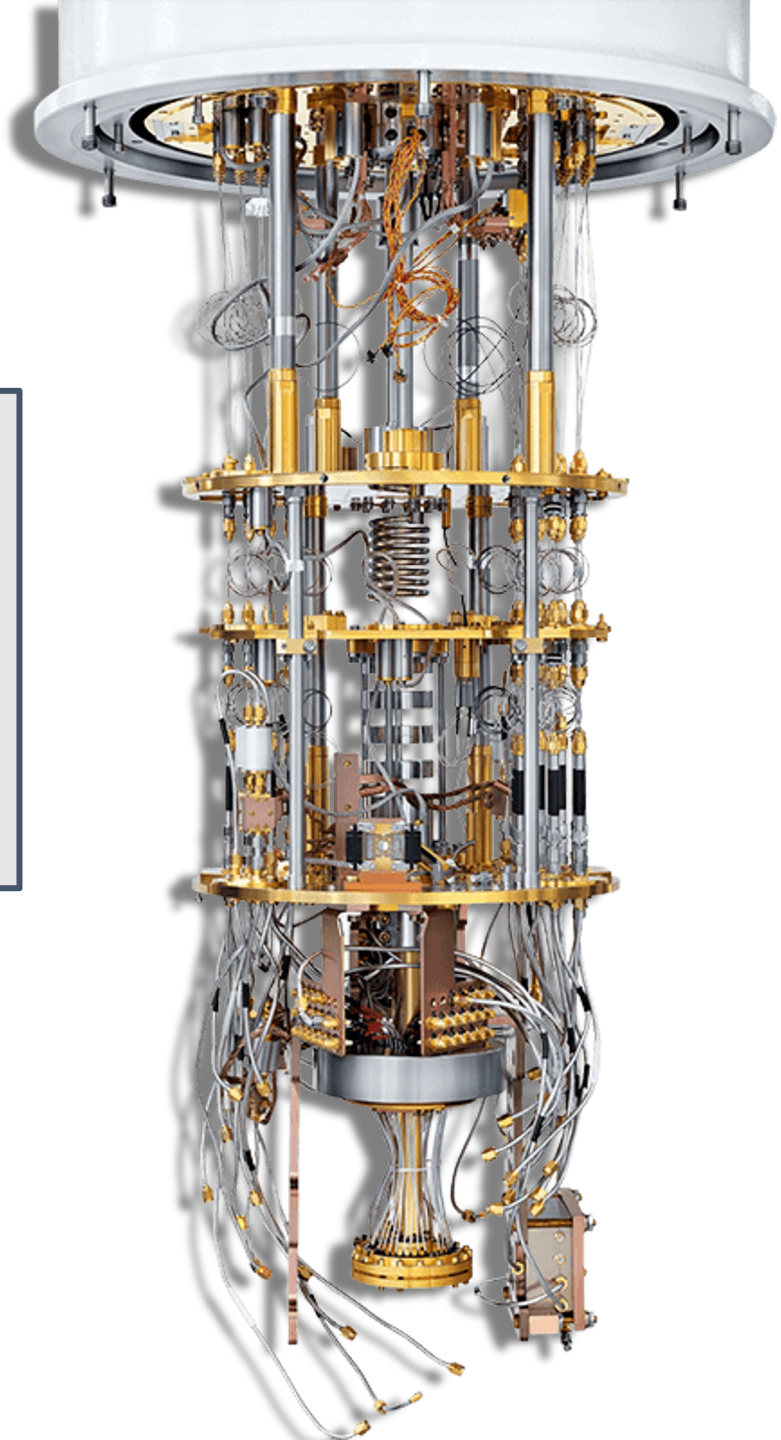
Rochester



Manhattan

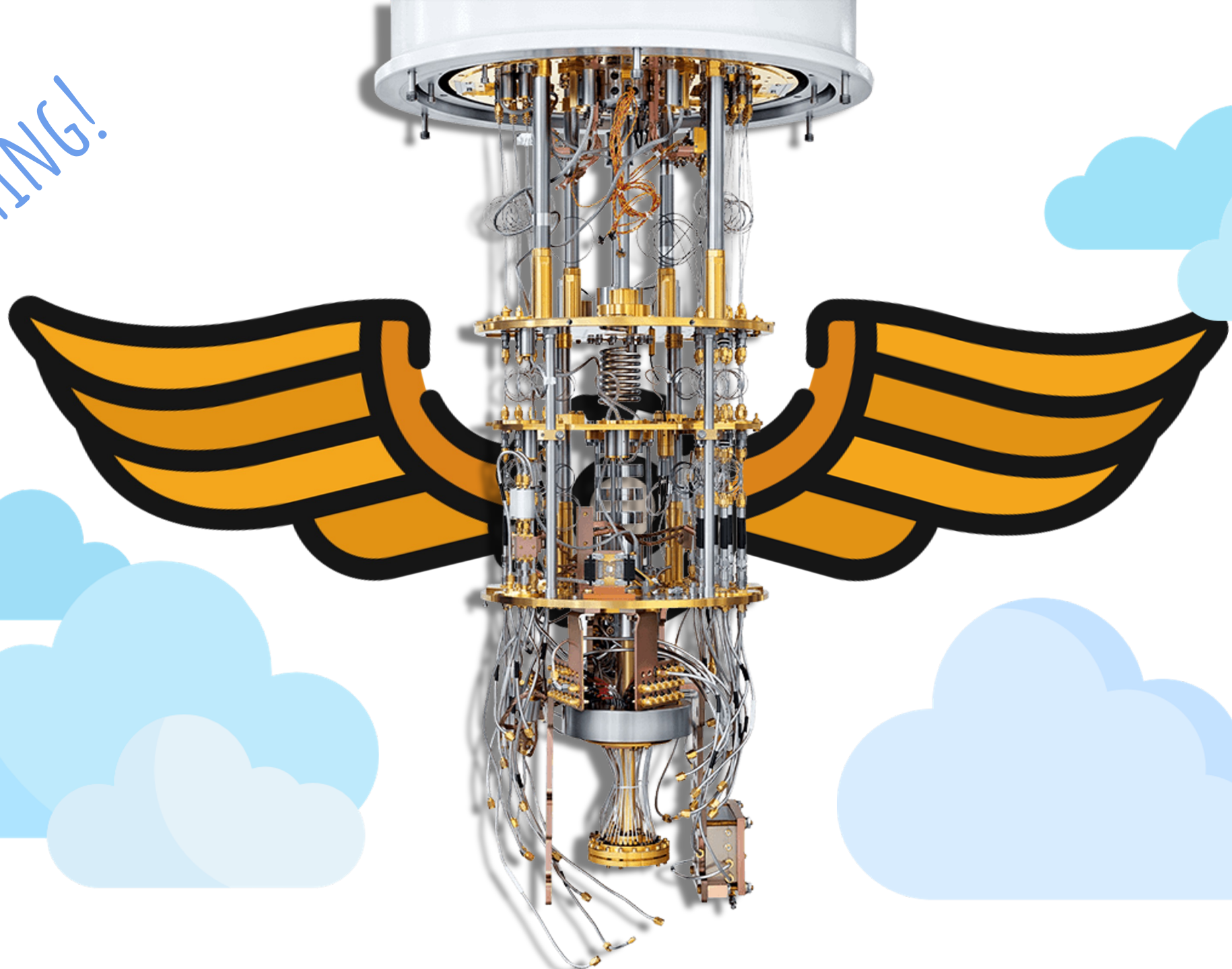
How can I access a Quantum Computer?

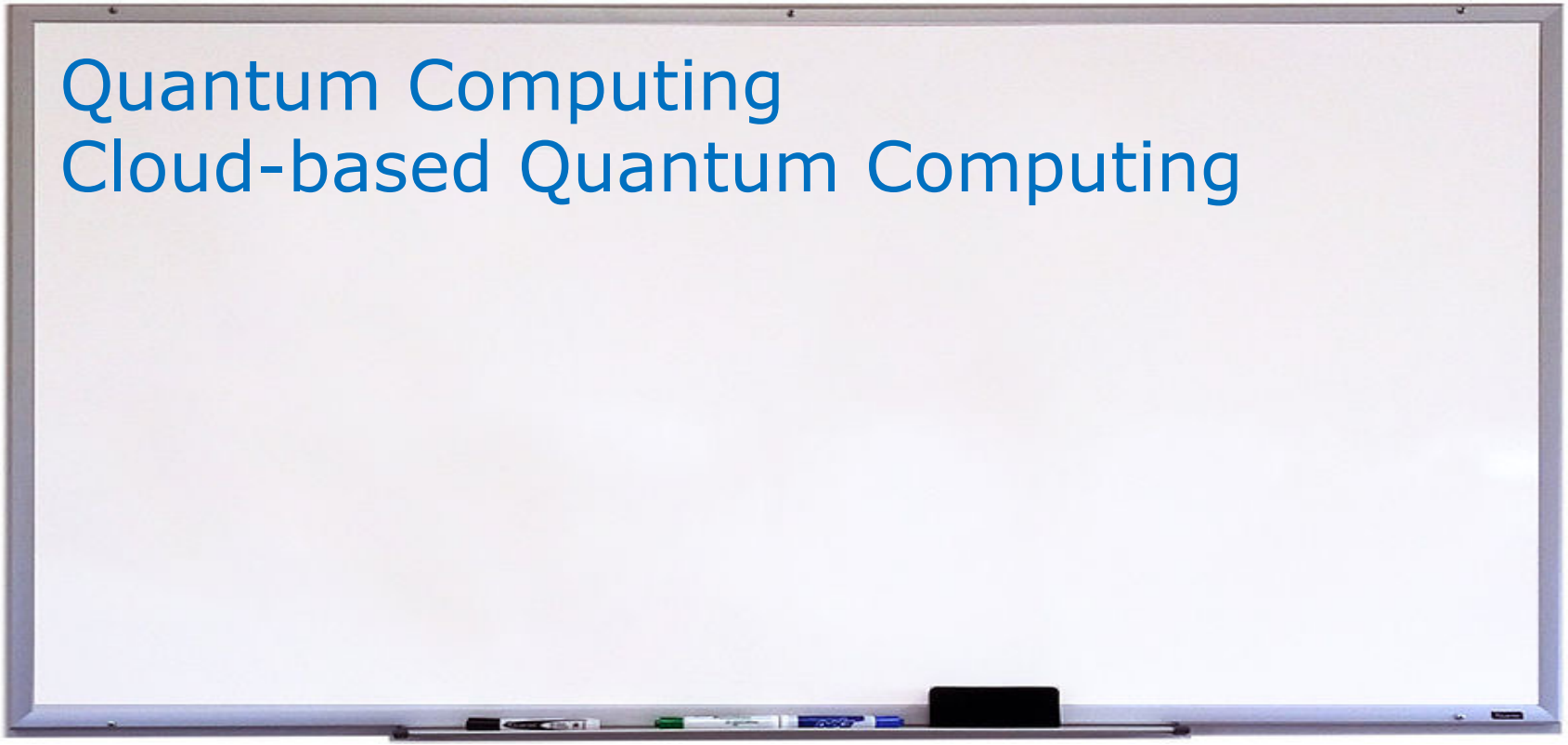





IBM Quantum
System One
IBM

Cloud Computing!




Quantum Computing
Cloud-based Quantum Computing

Well, Actually...


IBM Q


XANADU
Photonic Quantum Computing


D-Wave
The Quantum Computing Company™


Google AI
Quantum


rigetti


AQT


aws
Amazon Braket


Microsoft Azure


OQC


QCWARE
Forge


Quantum Inspire
By QuTech

ibm_cairo		27	64	2.4K	Online	16	Falcon r5.11	premium	OpenQASM 3
ibm_auckland	Exploratory	27	64	2.4K	Online	1818	Falcon r5.11	premium	OpenQASM 3
ibm_hanoi		27	64	2.3K	Online - Queue paused	540	Falcon r5.11	premium	OpenQASM 3
ibm_peekskill	Exploratory	27	-	-	Online	1	Falcon r8	premium	OpenQASM 3
ibmq_guadalupe		16	32	2.4K	Online - Queue paused	37	Falcon r4P	premium	
ibm_perth		7	32	2.9K	Online	126	Falcon r5.11H	open	OpenQASM 3
ibm_lagos		7	32	2.7K	Online - Reserved	64	Falcon r5.11H	open	OpenQASM 3

IonQ IonQ	Quantum Computing	Azure Quantum Credits
Microsoft Quantum Computing Microsoft	Quantum Computing	Learn & Develop
Quantinuum Quantinuum	Quantum Computing	Azure Quantum Credits
Rigetti Quantum Rigetti Computing	Quantum Computing	Azure Quantum Credits

Amazon Web Services	SV1	AVAILABLE NOW
Amazon Web Services	TN1	AVAILABLE NOW
Amazon Web Services	DM1	AVAILABLE NOW
IonQ	Harmony	02:44:47
IonQ	Aria 1	02:44:47
Oxford Quantum Circuits	Lucy	00:44:47
QuEra	Aquila	1 day 06:44:47
Rigetti	Aspen-M-3	05:44:47

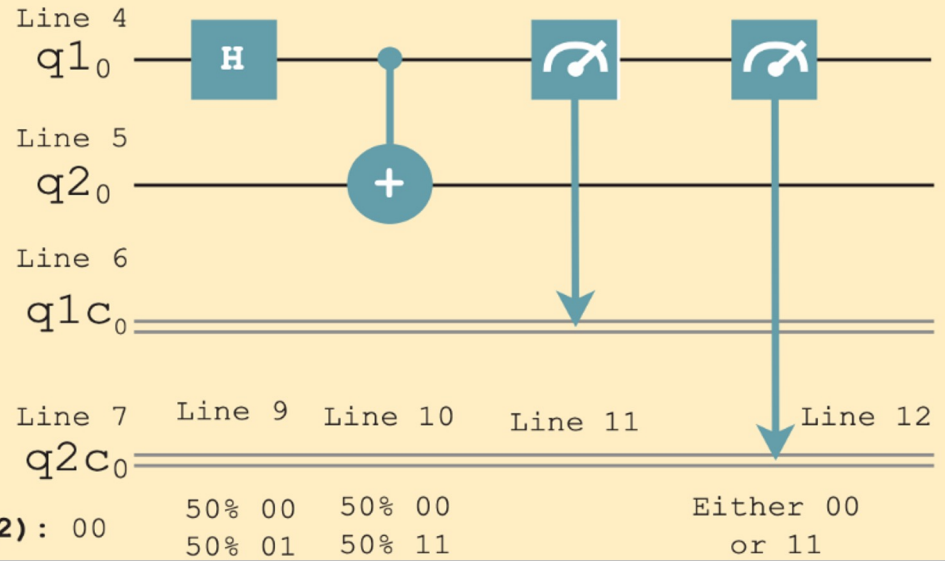
How I can program a Quantum Computer?

Code

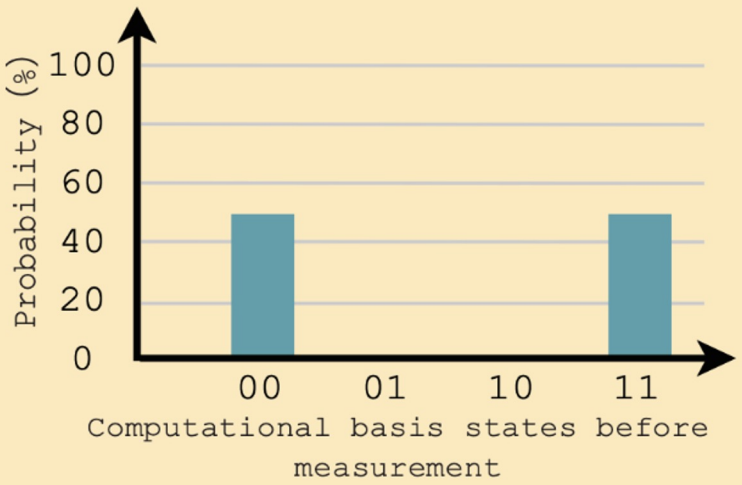
```
1  OPENQASM 2.0;
2  include "qelib1.inc";
3
4  qreg q1[1];
5  qreg q2[1];
6  creg q1c[1];
7  creg q2c[1];
8
9  h q1[0];
10 cx q1[0],q2[0];
11 measure q1[0] -> q1c[0];
12 measure q2[0] -> q2c[0];
```

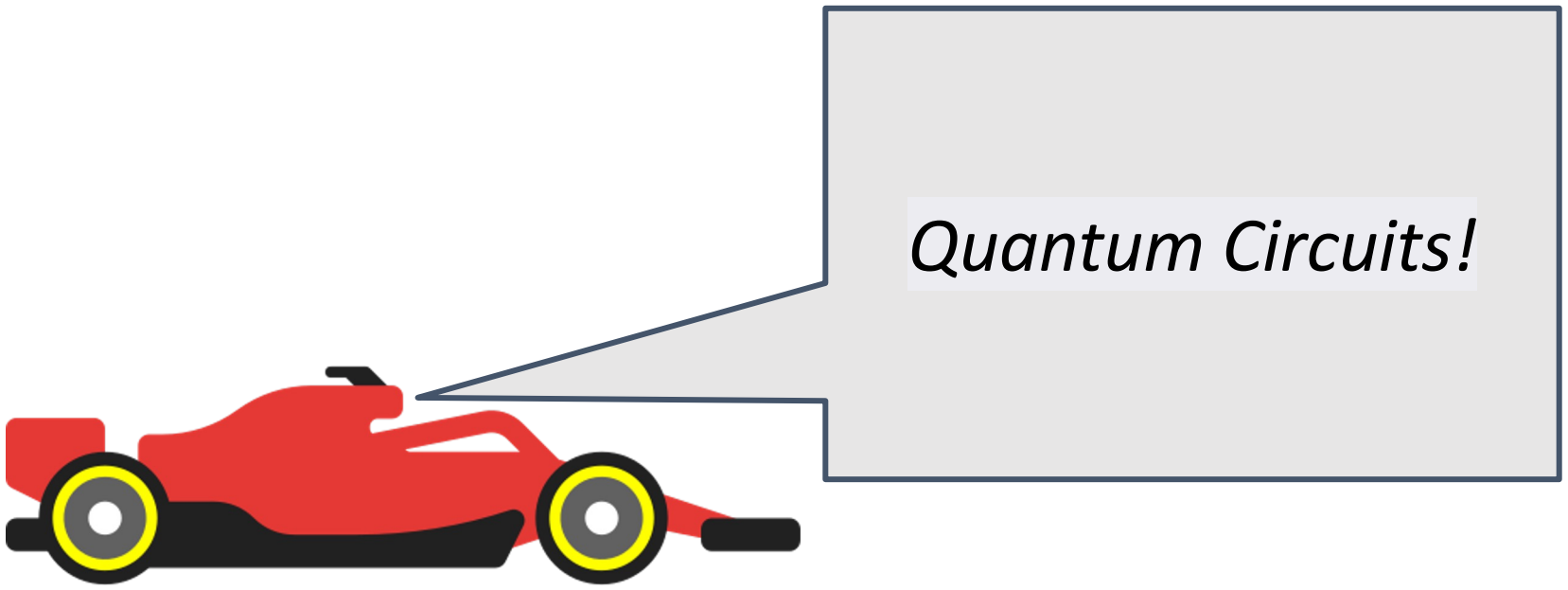
State(q1q2): 00

Quantum Circuit



Execution Result



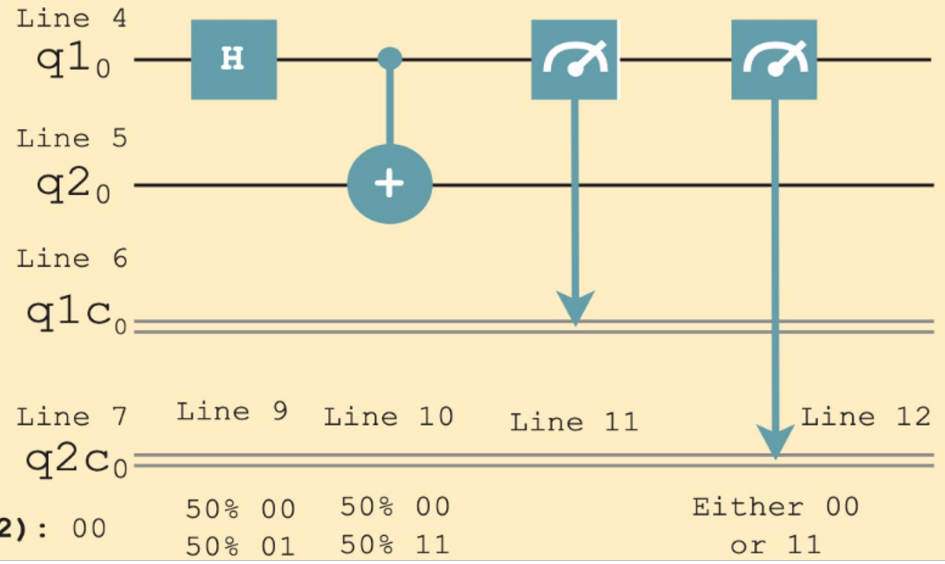


Code

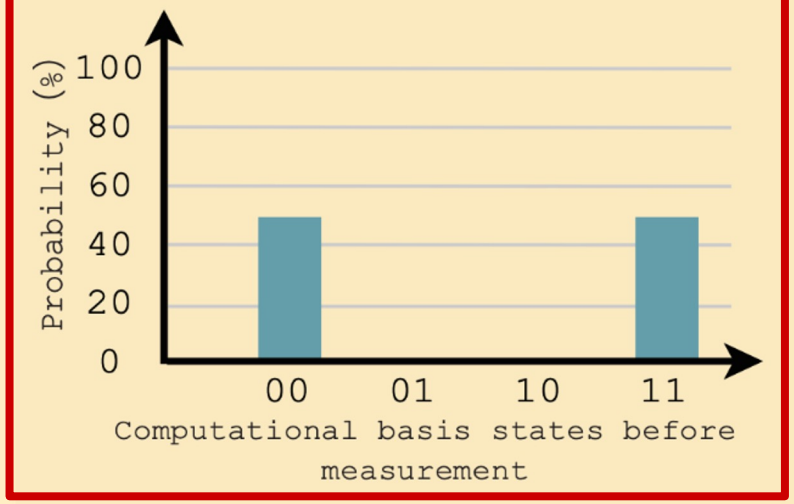
```
1  OPENQASM 2.0;
2  include "qelib1.inc";
3
4  qreg q1[1];
5  qreg q2[1];
6  creg q1c[1];
7  creg q2c[1];
8
9  h q1[0];
10 cx q1[0],q2[0];
11 measure q1[0] -> q1c[0];
12 measure q2[0] -> q2c[0];
```

State(q1q2): 00

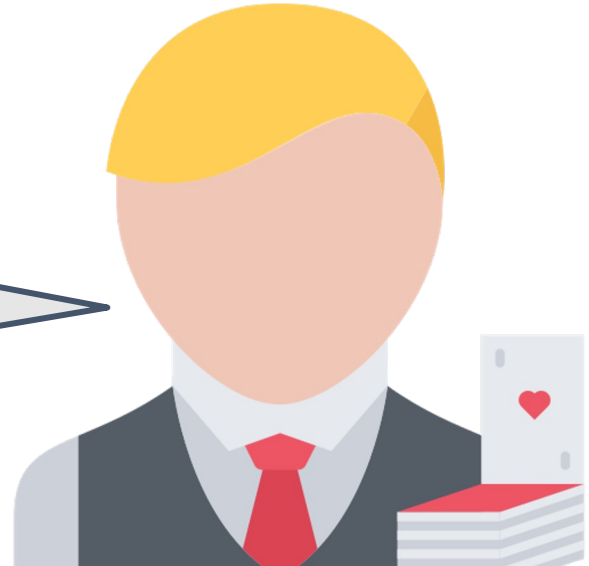
Quantum Circuit



Execution Result



The output is ***probabilistic!***

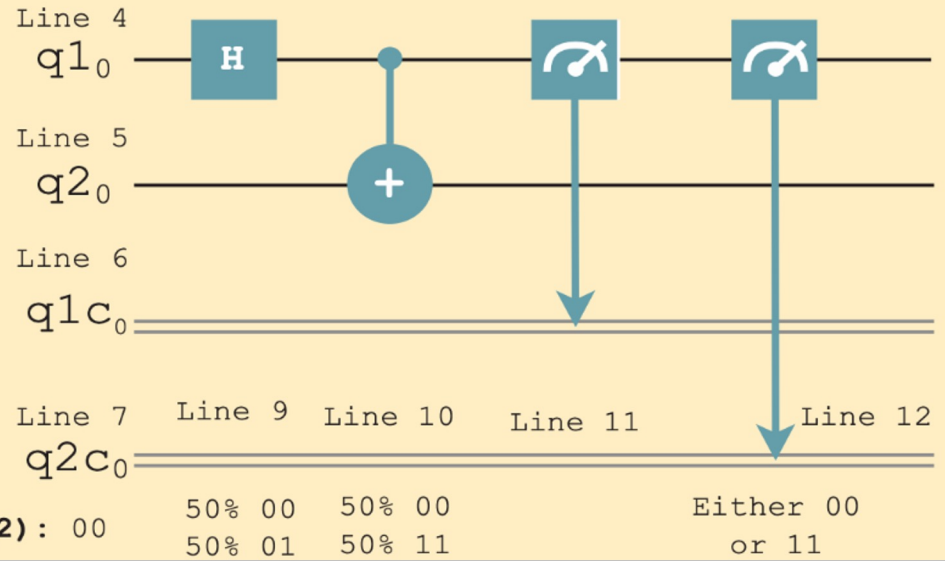


Code

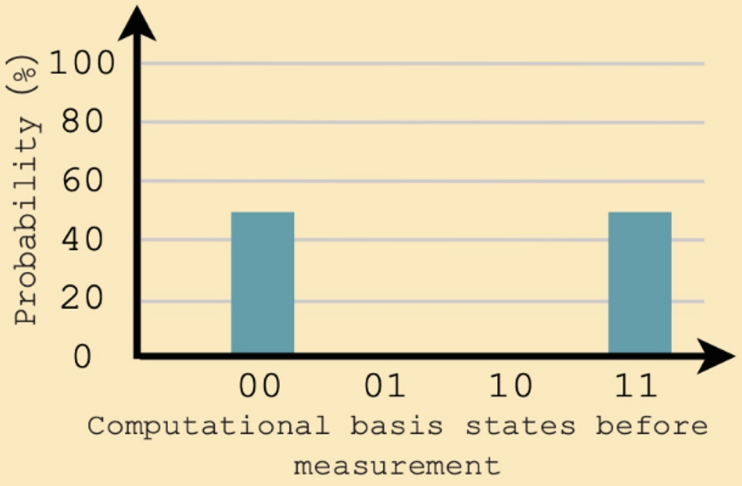
```
1  OPENQASM 2.0;
2  include "qelib1.inc";
3
4  qreg q1[1];
5  qreg q2[1];
6  creg q1c[1];
7  creg q2c[1];
8
9  h q1[0];
10 cx q1[0],q2[0];
11 measure q1[0] -> q1c[0];
12 measure q2[0] -> q2c[0];
```

State(q1q2): 00

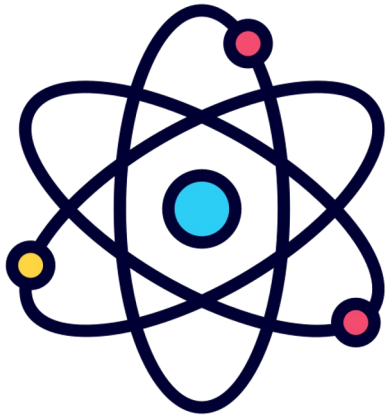
Quantum Circuit

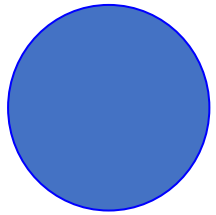
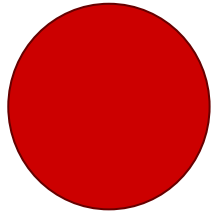


Execution Result

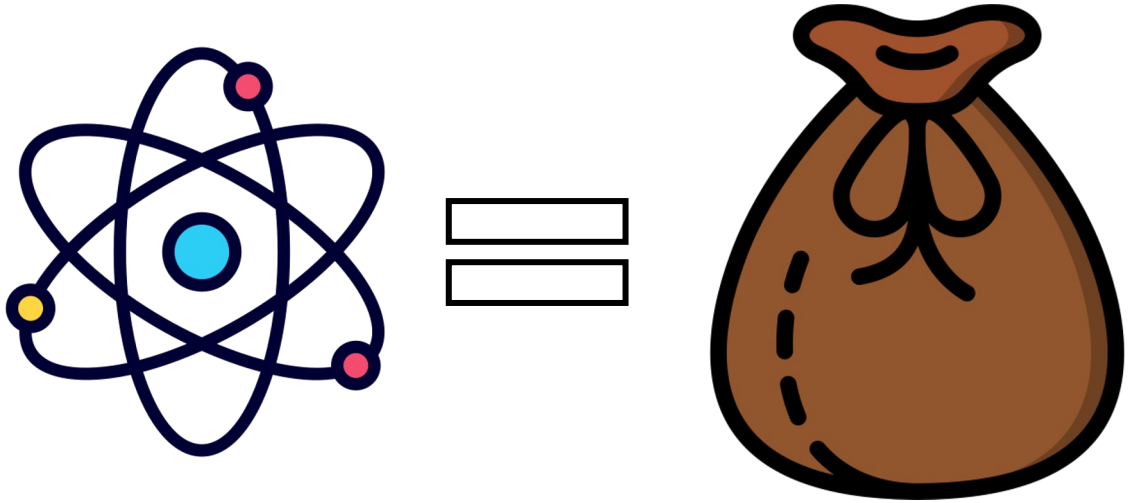


*We need multiple iterations (**shots**)!*

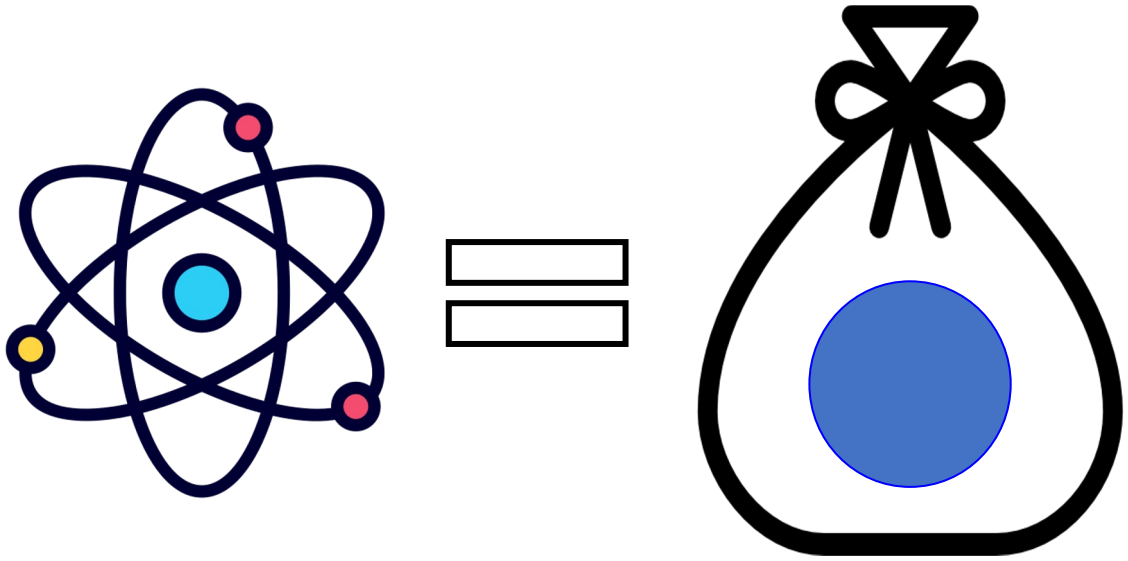


$\equiv$ 60%  40% 

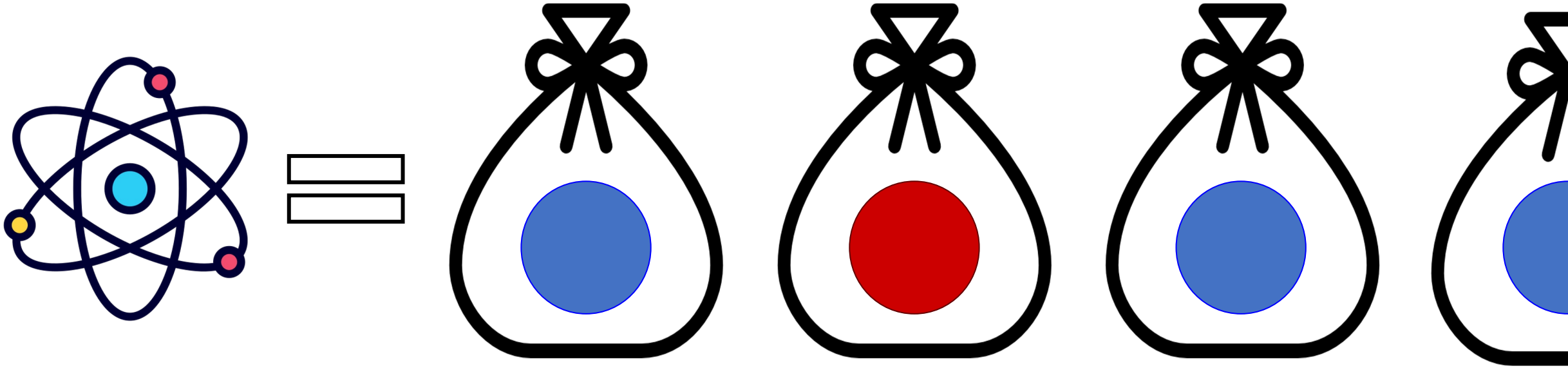
After the execution of a quantum circuit the quantum state is usually in a ***superposition*** *of multiple final states*



*Unfortunately, laws of physics prevent us to **directly observe** the quantum state*



*We can only **measure** the quantum state. When measuring the quantum state, it **collapses** to a single output state*

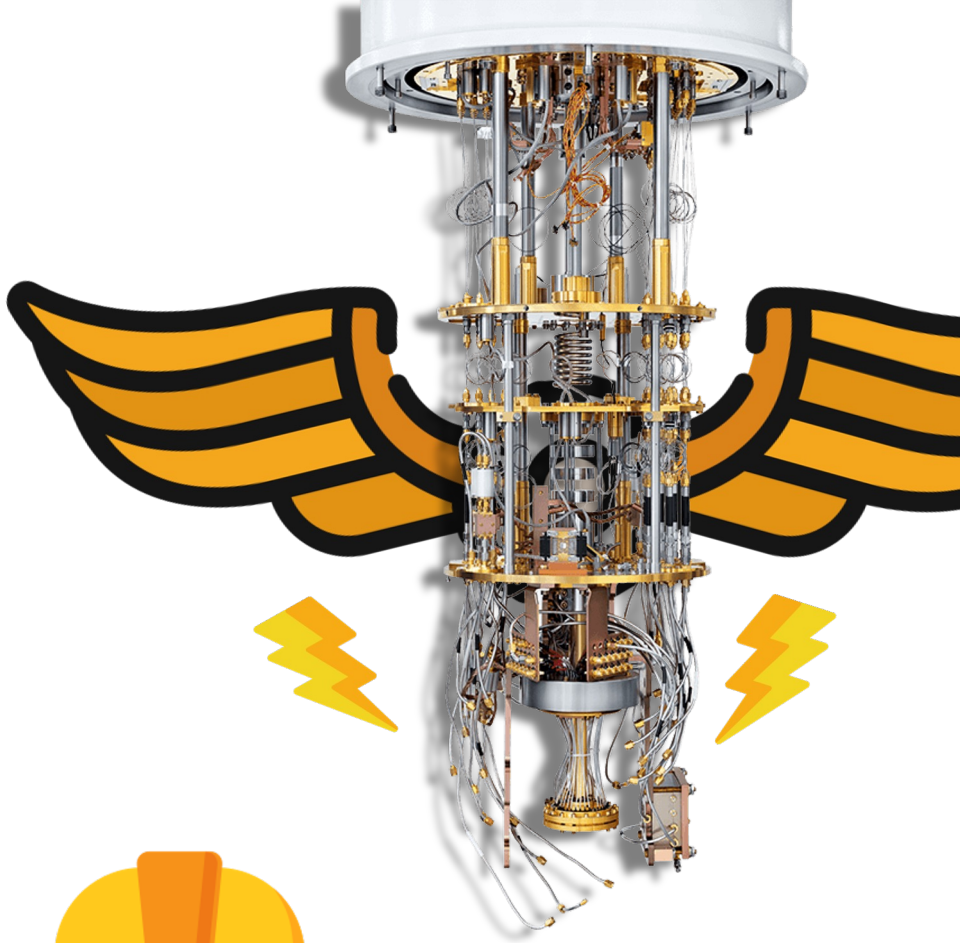


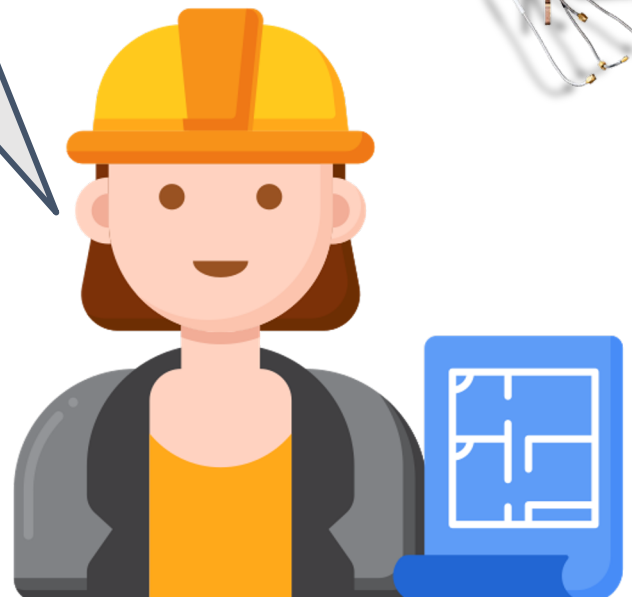
*We can execute the same circuit for the same input numerous times (**shots**) to **approximate** the **real quantum state distribution!***

NISQ Era

***N**oisy*
***I**ntermediate*
***S**cale*
***Q**uantum*

Currently, we can execute only small circuits…





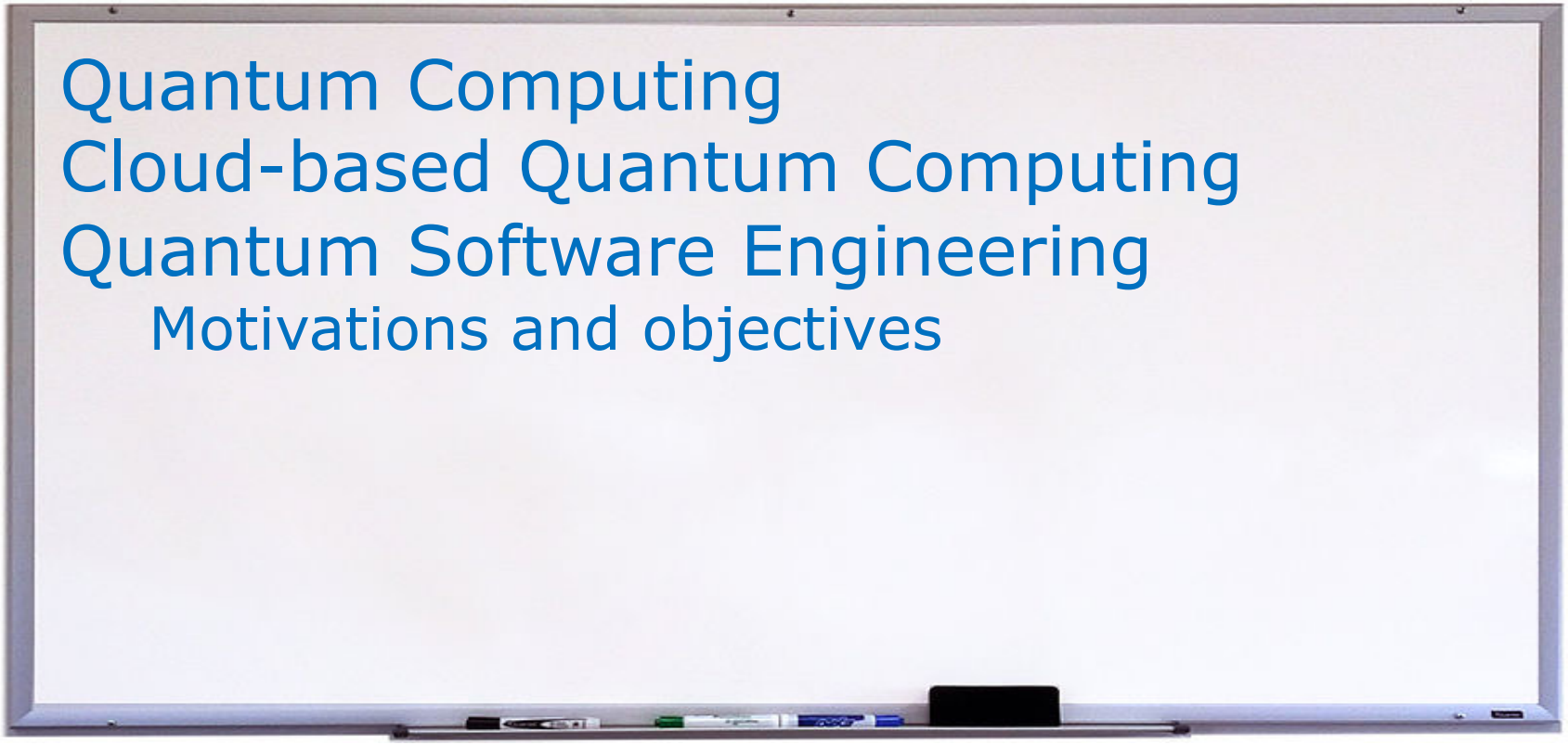
NISQ Devices:

- very **sensitive** to **external interferences** *(noise)*
- **cannot scale** their **size** *(number of qubits)* easily

Consequently:

- can **execute** only *Quantum programs* featuring a **small number** of qubits and **consecutive steps**

<u>Longer programs</u> would be **<u>highly affected by noise!</u>**

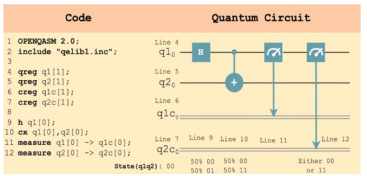

Quantum Computing
Cloud-based Quantum Computing
Quantum Software Engineering
Motivations and objectives

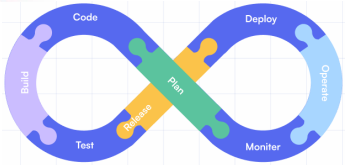
Some current limitations of available quantum computers

- Reliability (error rates)
- Scalability (#qubits)
- Cost

Some current limitations of quantum software development

- Still mainly combining low-level gates into circuits
- Limited software/machine interoperability
- Little support for the whole software lifecycle





Quantum Software Engineering

"The use of **sound engineering principles** for the **development**, **operation**, and **maintenance** of quantum software and the associated document to obtain **economically** quantum software that is **reliable** and works **efficiently** on quantum computers"

(Zhao, 2020)

Talavera Manifesto

QSE should

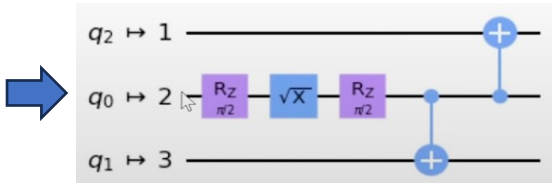
1. be **agnostic** regarding quantum programming languages and technologies
2. embrace the **coexistence** of classical and quantum computing
3. support the **management** of quantum software development projects
4. consider the **evolution** of quantum software
5. aim at delivering quantum programs with desirable **zero defects**
6. assure the **quality** of quantum software
7. promote quantum software **reuse**
8. address **security** and **privacy** by design
9. cover the **governance** and **management** of software

(M. Piattini et al., 2020)

Quantum Software Engineering: examples

Improving **transpilers**

```
qc = QuantumCircuit(3)
qc.h(0)
qc.cx(0, 1)
qc.cx(0, 2)
qc.draw(output='mpl')
```



Enabling **code reusability**

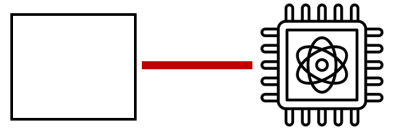
Q Module Template

Enabling **program verification**

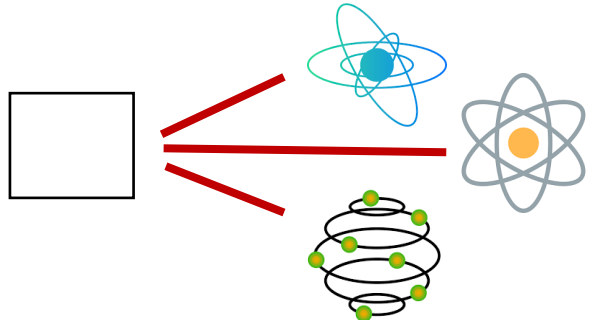
$$P \sim Q \qquad P \preceq Q$$

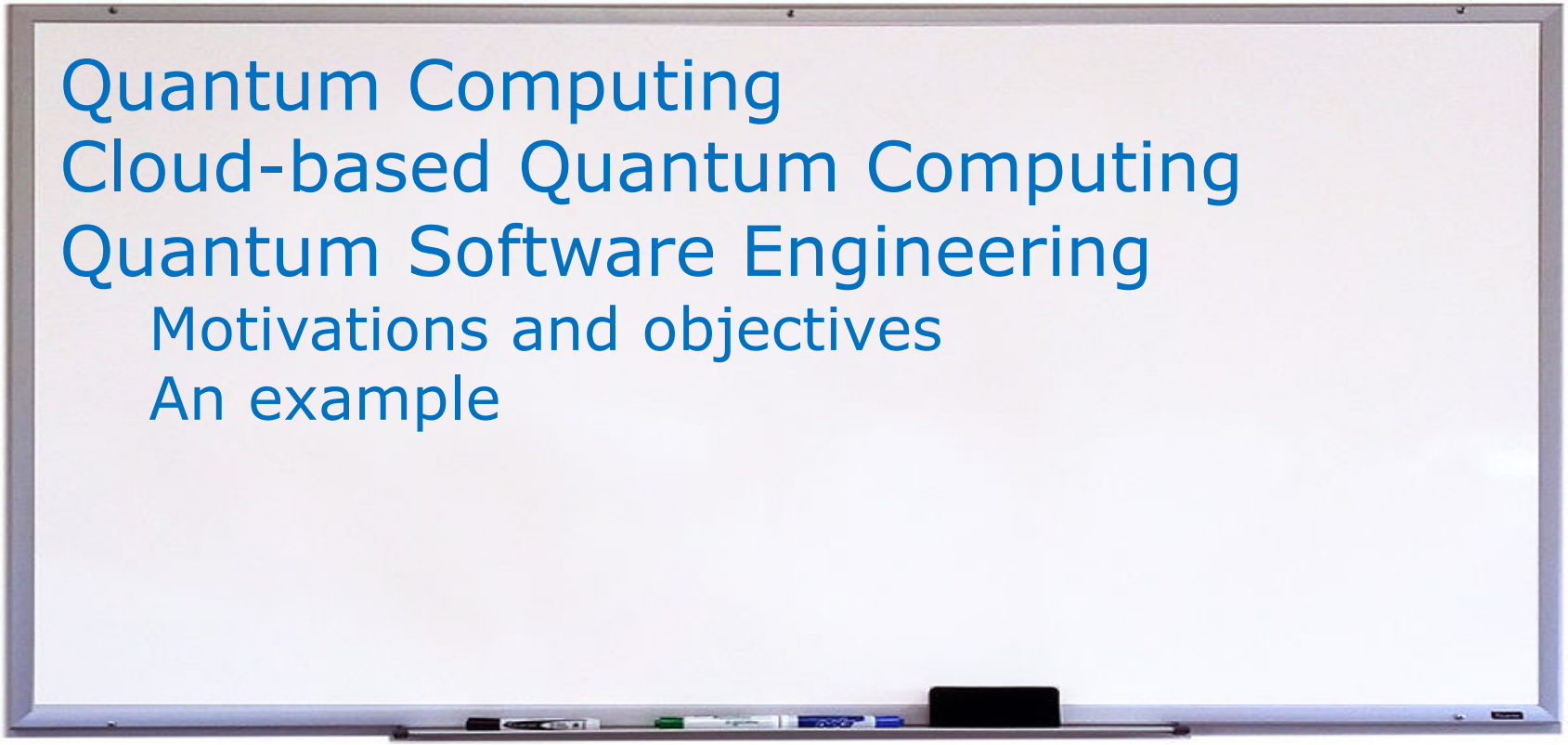
Enabling the **coexistence** of classical & quantum computations

```
x = f(y) ⊕ q(z)
```



Better exploiting **heterogeneous unreliable** Quantum computers



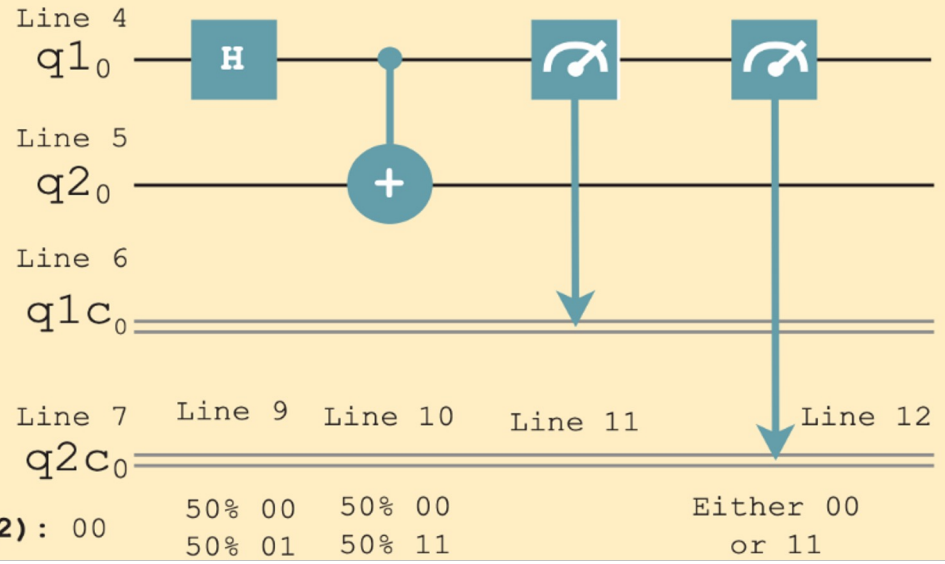

Quantum Computing
Cloud-based Quantum Computing
Quantum Software Engineering
Motivations and objectives
An example

Code

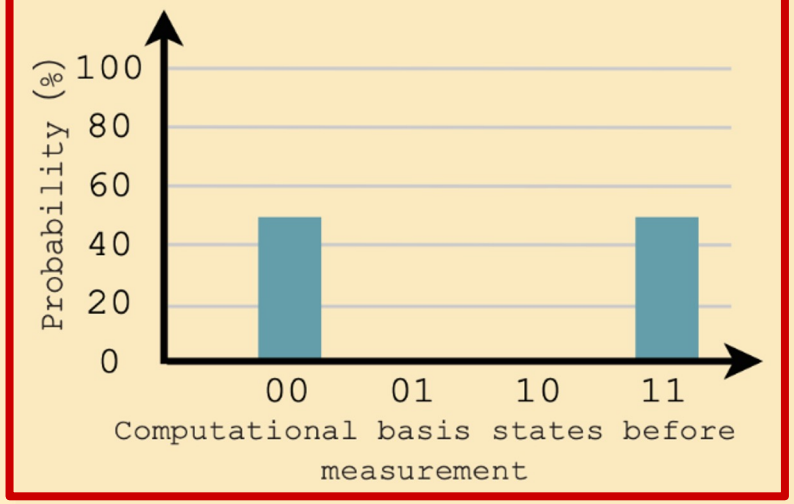
```
1  OPENQASM 2.0;
2  include "qelib1.inc";
3
4  qreg q1[1];
5  qreg q2[1];
6  creg q1c[1];
7  creg q2c[1];
8
9  h q1[0];
10 cx q1[0],q2[0];
11 measure q1[0] -> q1c[0];
12 measure q2[0] -> q2c[0];
```

State(q1q2): 00

Quantum Circuit



Execution Result

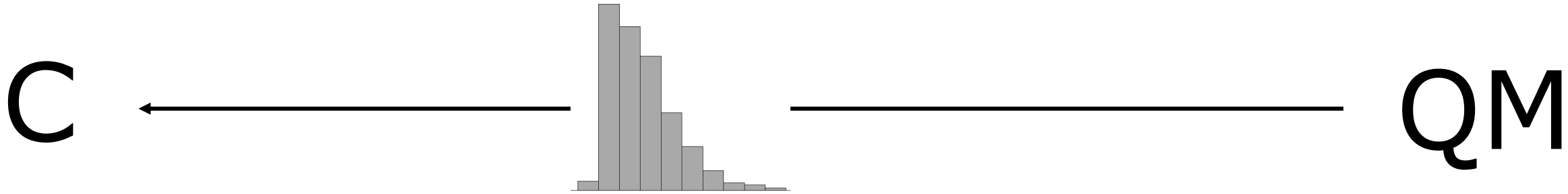


*The output of a quantum computation is **probabilistic**!*

*We need multiple iterations (**shots**)!*

Executing a circuit on a single QM

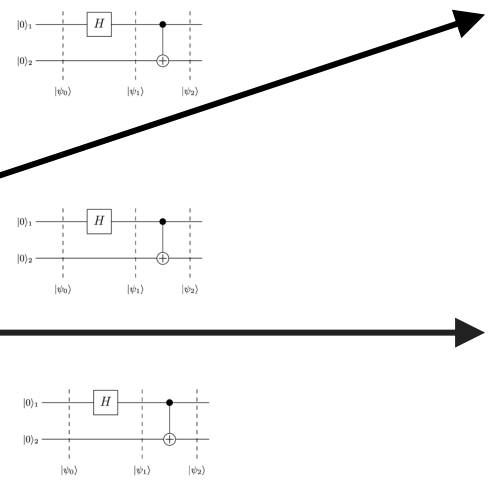
Executing a circuit on a single QM



Introducing a broker

C

B



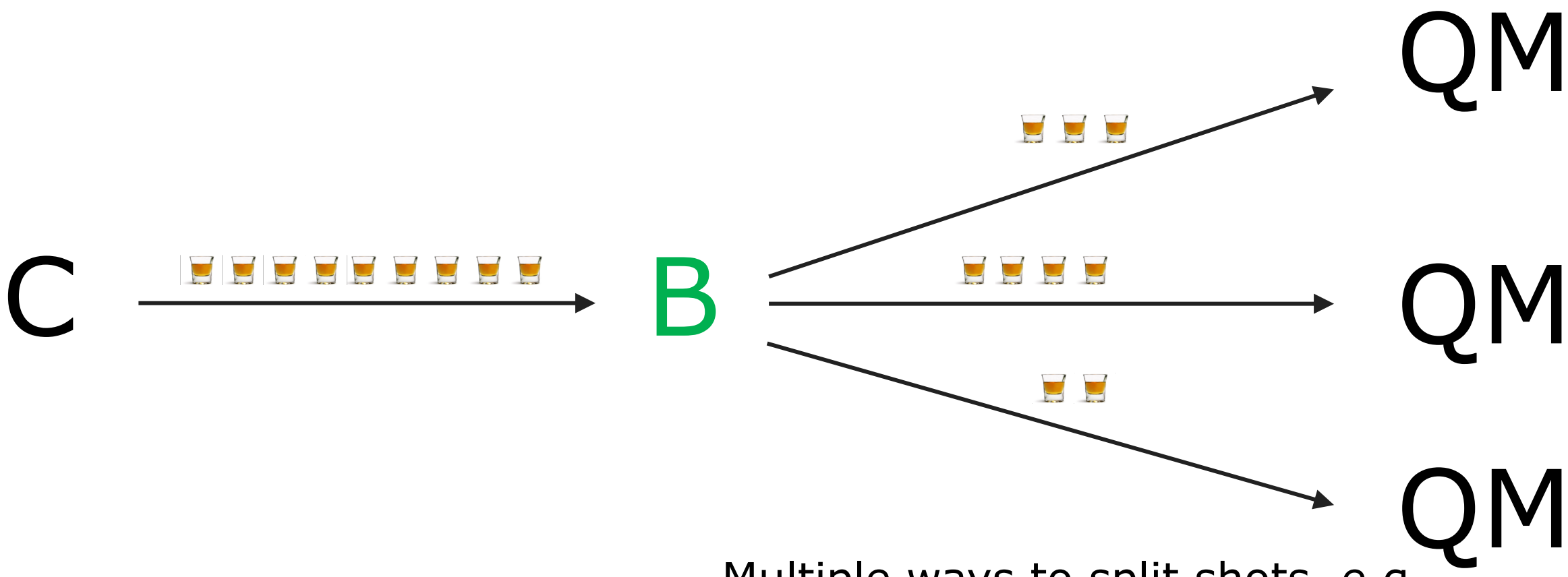
QM_1

QM_2

QM_3

Calibration: executing a set of simple circuits to estimate reliability of each QM_i

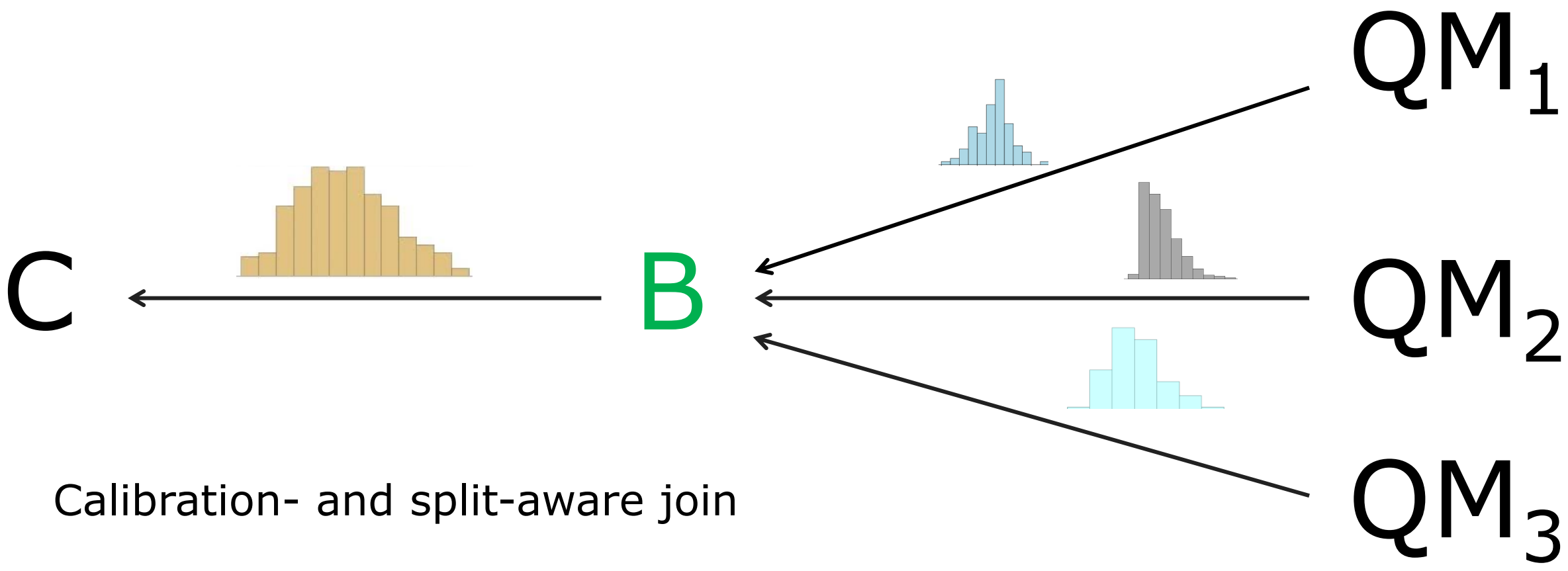
Splitting shots



Multiple ways to split shots, e.g.

- Uniform
- Random
- Noise-aware
- Cost-aware

Joining results



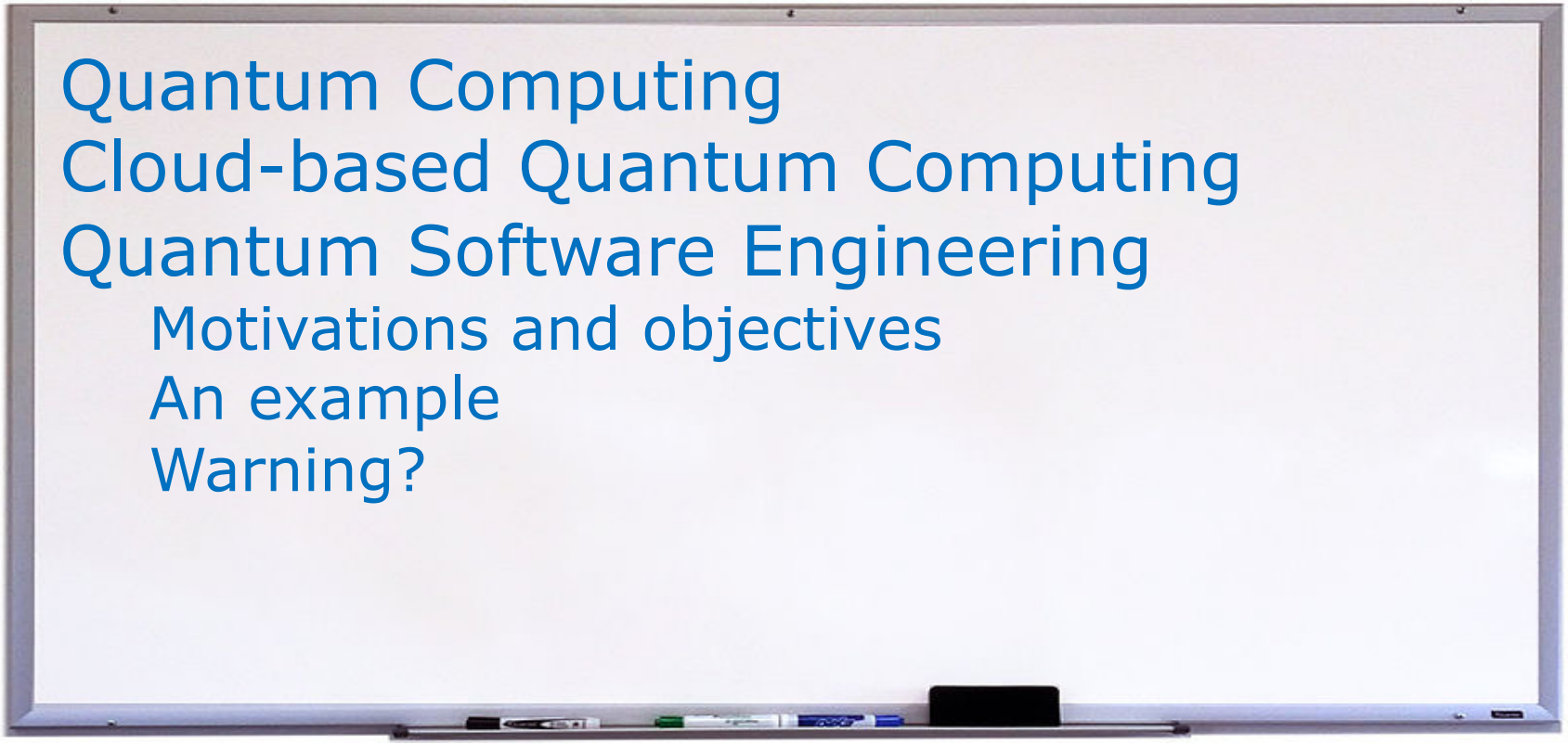
Calibration- and split-aware join

Why splitting shots across different QMs?

1 +1 +1 > 3 ?

Yes!

reliability
cost
better results


Quantum Computing
Cloud-based Quantum Computing
Quantum Software Engineering
Motivations and objectives
An example
Warning?

QSE: warning?

QSE: warning?