

IQM

Welcome to IQM Quantum School!

IQM Quantum School

Presenters: Daniel Bulmash, Stefan Seegerer, Nadia Milazzo

02.12-04.12.2025

www.meetiqm.com



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— Agenda

Day 1: Foundations of Quantum Computing - For Quantum Newbies

Day 2: Implementing Your First Quantum Algorithms

Day 3: From Abstract Code to Physical Pulses

About your instructors



Stefan Seegerer



Danny Bulmash



Nadia Milazzo

— What to expect

Each day will have:

- About 1.5 hours of live lecture, with pauses for interactive activities.
- About 1.5 hours of lab/Q&A, where you can experiment with notebooks hosted in Google Colab
 - We will demonstrate some of the notebooks, then we will be present for Q&A time.
 - Each notebook has homework, which you are encouraged to complete on your own. Solutions will be posted.
 - These notebooks will guide you through running programs on IQM's quantum computers

Prerequisites

- We will be doing some coding in qrisp, which is a module within Python. If you have worked with lists and functions before, you should have enough coding background.
- The only math background we are assuming is high school algebra, but having worked with matrices will be helpful.

— Technical requirements

- You should have made/received an account on IQM Resonance. Make sure that is working.
- You will need access to Google Colab, which can be done through any Google account.

Day 1 – Foundations of Quantum Computing

— Find the Day 1 lab here

Please make a copy of the notebook (File -> Save a Copy). You will be able to modify and run the code in the modified notebook.



<https://tinyurl.com/25bj9hd4>

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Quantum School Day 1 LECTURE

Quantum School

Stefan Seegerer

Last Updated 06/2025

www.meetiqm.com



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— Outline of the day

In today's sessions we will ...

- ... learn what problems quantum computers can tackle.
- ... learn how quantum computers are different to classical computers.
- ... use qrisp to perform our first quantum computations on real quantum computers



Our Mission

 We build world leading quantum computers for the well-being of humankind, now and for the future

IQM in numbers

314

Employees

132

PhDs

\$600M

investments

30+

full systems
built

15

full systems
sold

2018

Founded

50+

Nationalities

150

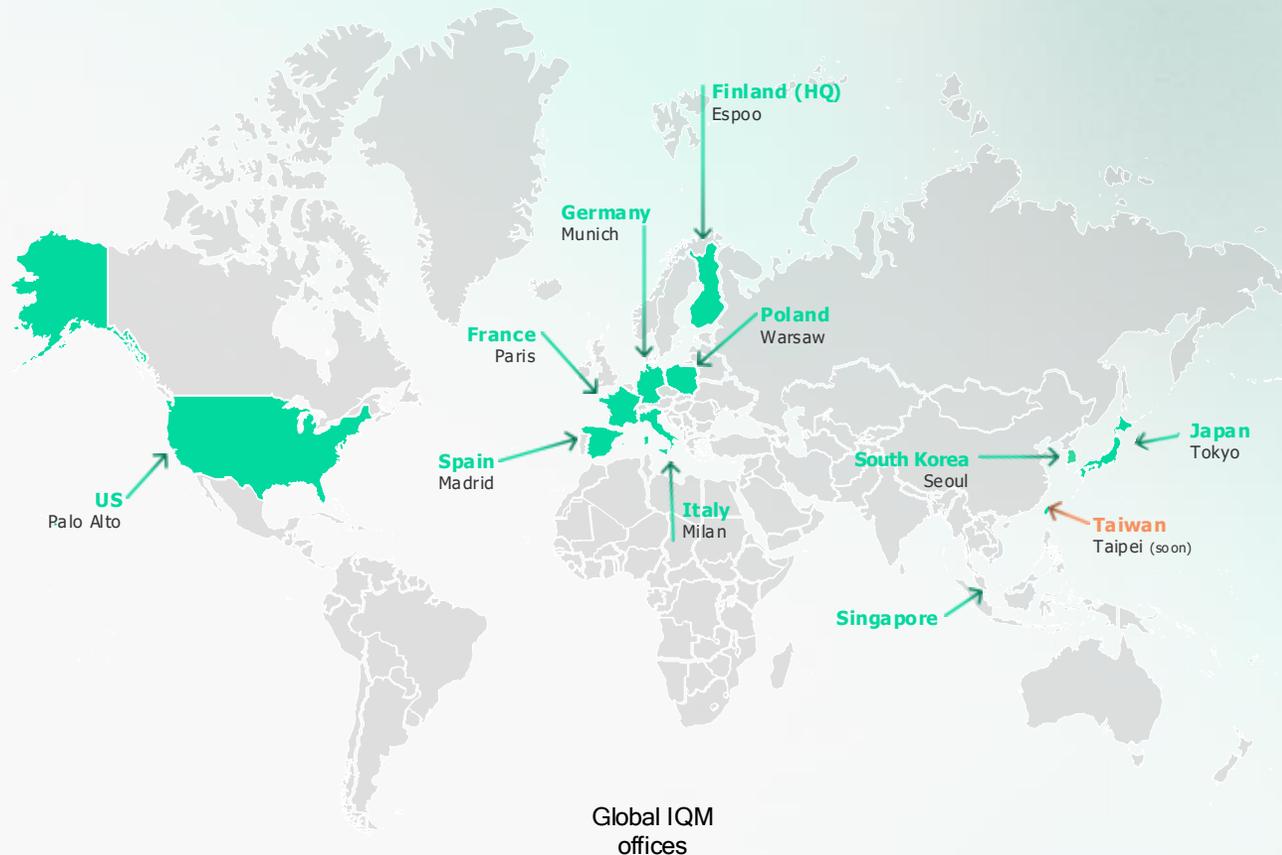
qubit chip in
development

10.000+

Cloud users

**On-prem
& cloud**

IQM builds and delivers full-stack quantum computers globally



- **15+ full systems sold**
- **Sold and installed** our flagship system **IQM Radiance** in **Germany** and **Finland**
- Most **comprehensive product portfolio** in the market for all price points and budgets
- **Superconducting technology** leader with the only **Quantum Fab** in Europe and proprietary Quantum **Error Correction technology**

IQM Customer Deliveries



**10+ full systems
delivered and installed**

Global Deliveries

About Quantum School

- Understand what quantum computing is about
- Get a feeling if quantum is something for you
- Be inspired and curious to learn and explore more
- You can expect more (and also deeper) events in the future
- We also do regular webinars, check out our website for these

Kickstart Your Career in Quantum

When?

2-4 Dec 2025
around 4 hours a day

Where?

Fully online with live Q&A
and feedback sessions

Who is it for?

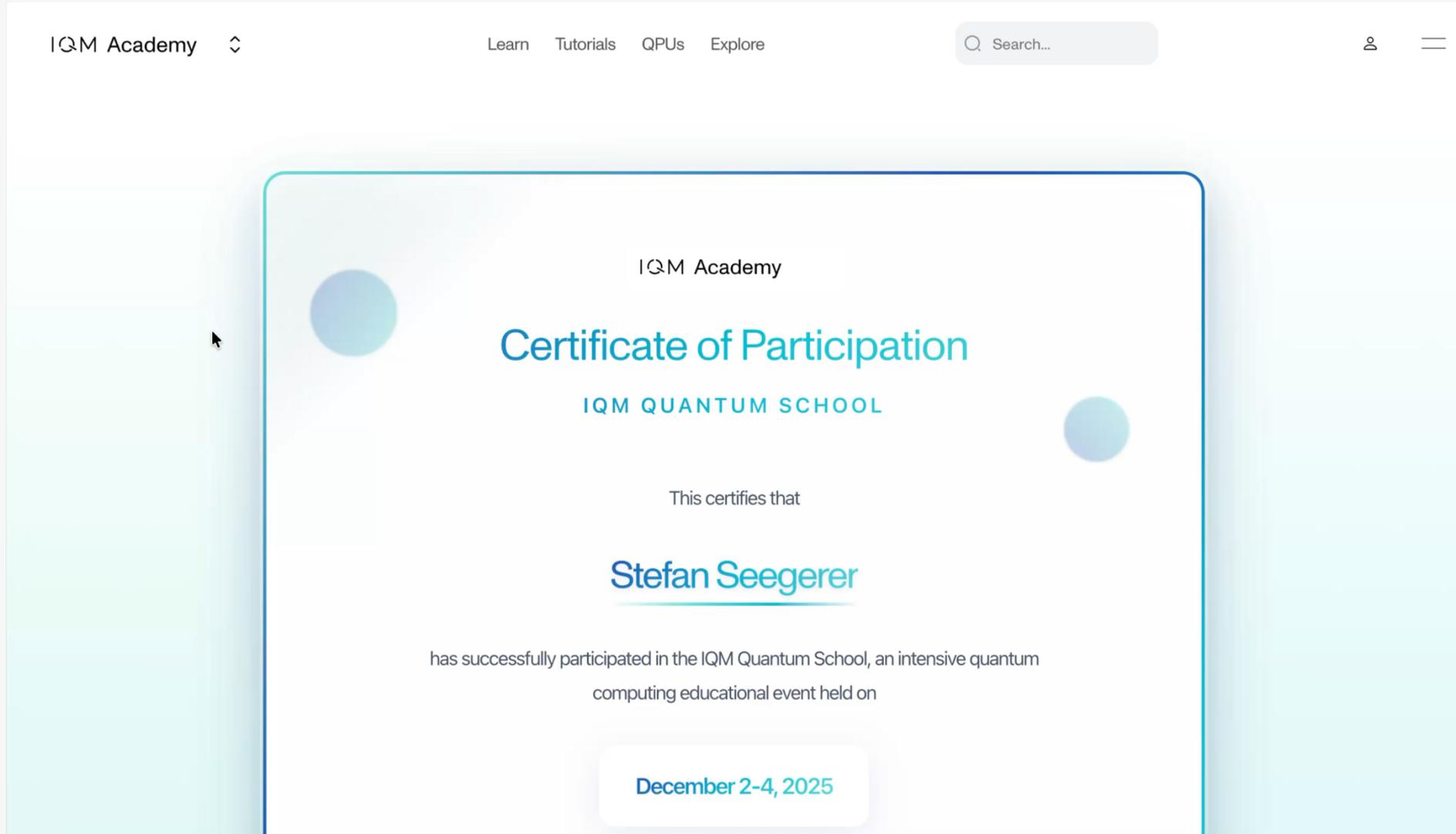
Students, **anyone** looking
to explore **quantum**

Sign up here

<https://resonance.meetiqm.com/signup/quantumschool>



Certificate

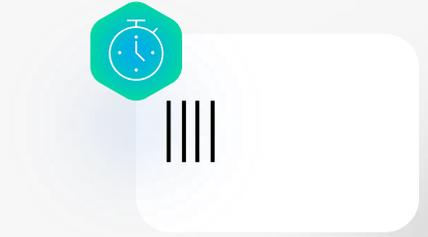




https://docs.google.com/forms/d/e/1FAIpQLSd9_RT_r5qN0U60m0q057q3w342jNADgPJRI5fKJU3woRr1UA/viewform

**Why think about
different
computing
paradigms?**

Sorting a list of numbers



8

2

5

3



Sorting a list of numbers



2

8

5

3



Sorting a list of numbers



2

3

5

8



Thinking about new
computing paradigms can
lead to more efficient
solutions



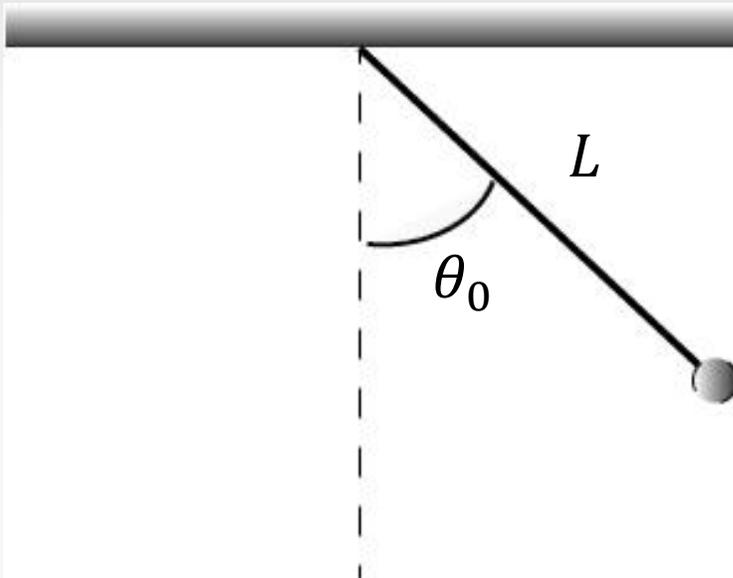
Information is Physical. (R Landauer, 1991)

- Example: Evaluate the complete elliptic integral of the first kind

$$K(k) = \int_0^{\pi/2} \frac{1}{\sqrt{1 - k^2 \sin^2 \phi}} d\phi \quad . \quad K(k) = \frac{\pi}{2} \sum_{n=0}^{\infty} \left[\frac{(2n-1)!!}{(2n)!!} \right]^2 k^{2n} .$$

- Use a **physical system** as a (specialized) computer:

- The period of a pendulum is $T = 4 \sqrt{\frac{L}{g}} K(k)$, $k = \sin \frac{\theta_0}{2}$.

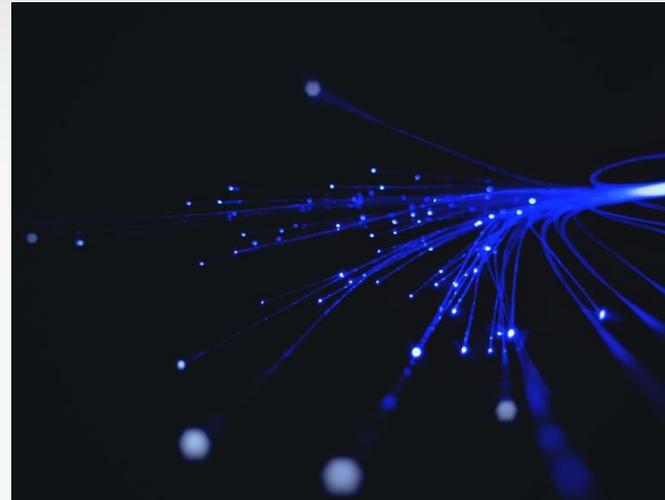
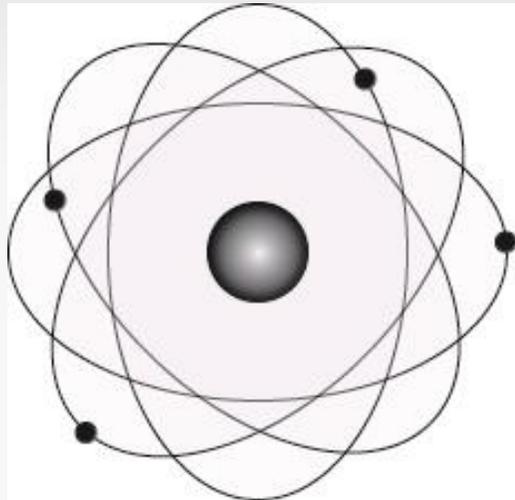


- It may take a few minutes to set up a pendulum. It is much shorter than the time required to build a digital computer from scratch.
- Pendulums are very effective at computing this integral!

Complexity depends on the device for processing

Complexity depends on **the physical system used to design an algorithm**.

- There is a very efficient algorithm that uses a pendulum to compute elliptic integrals, but not for most other tasks
- Efficient algorithms on digital computers exist for many problems, but not all (e.g. finding the prime factors of integers)
- Computers based on the laws of quantum physics allow efficient algorithms for some of the problems digital computers struggle with - let's use this!



There are problems a classical computer cannot (efficiently) solve

Problem with current computers:

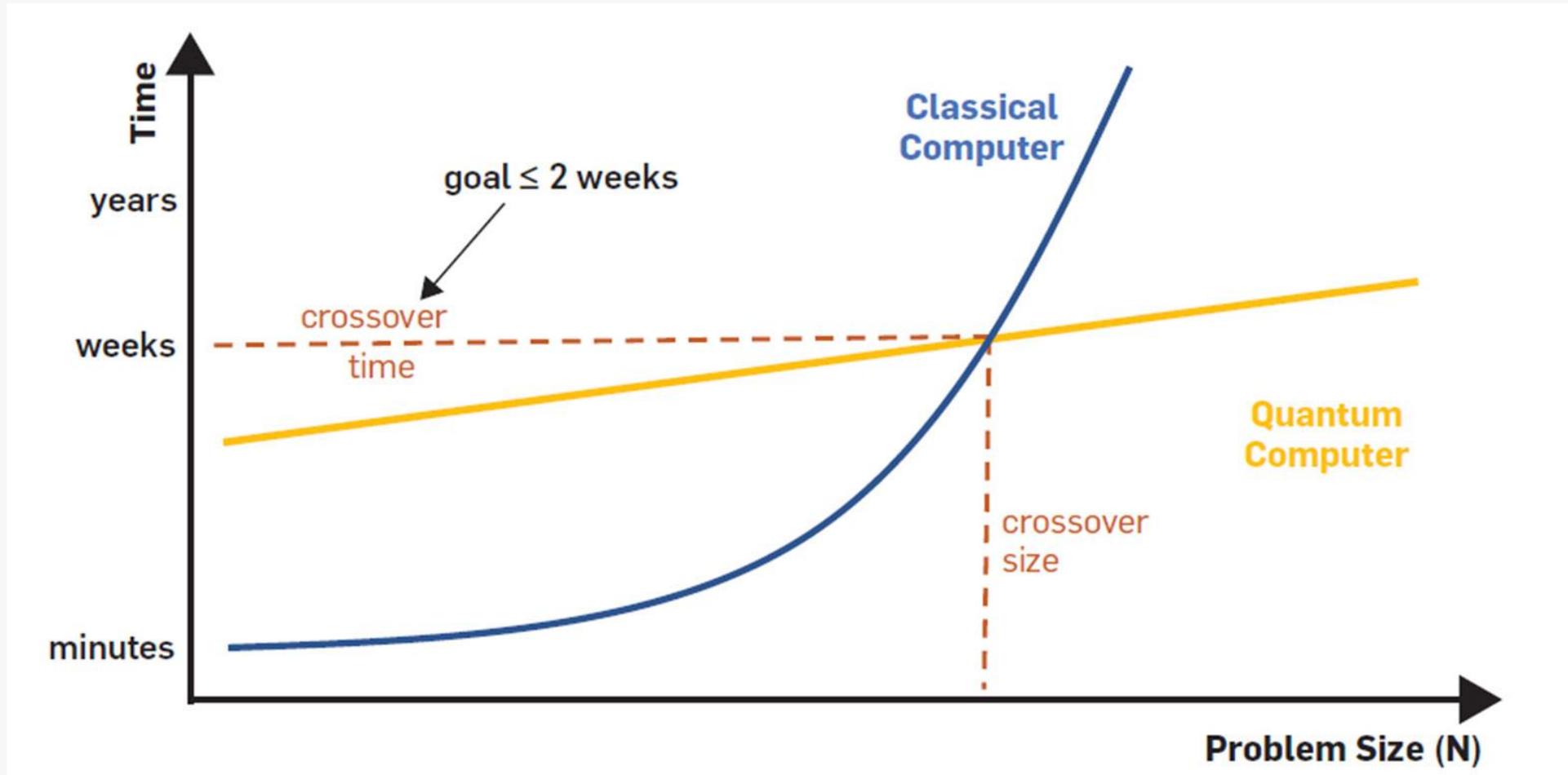
-  Mathematical limits
-  Physical limits
-  Time & power limits

Current approach is not scalable!

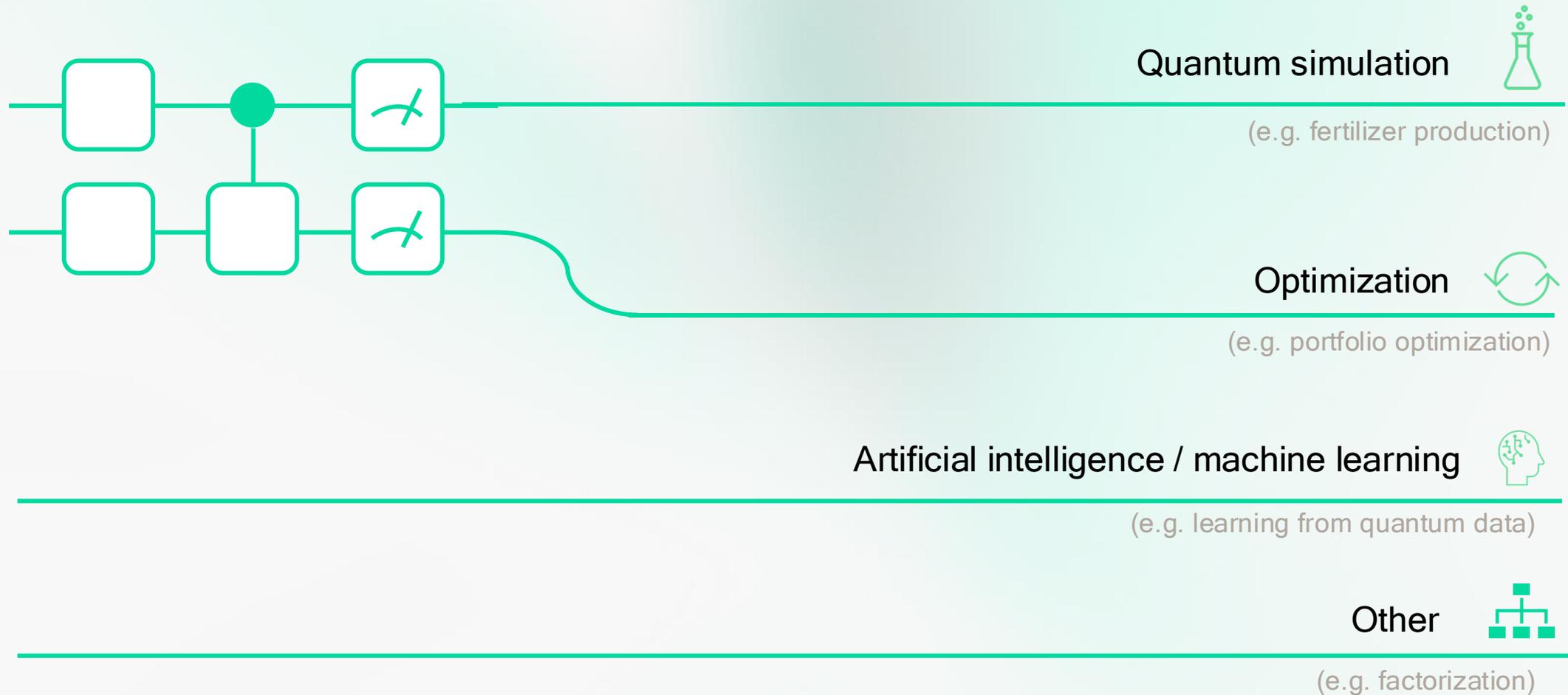


“Latest findings suggest global computing is more likely responsible for between 2.1% and 3.9% of greenhouse gas emissions.”

There are problems a classical computer cannot (efficiently) solve



Quantum computers can unlock powerful applications in the future



Solving problems that reduce carbon footprint: Battery optimization



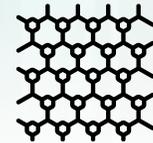
Batteries with a
higher lifetime



Batteries with
faster charge -
discharge cycles



Batteries with
higher energy
densities

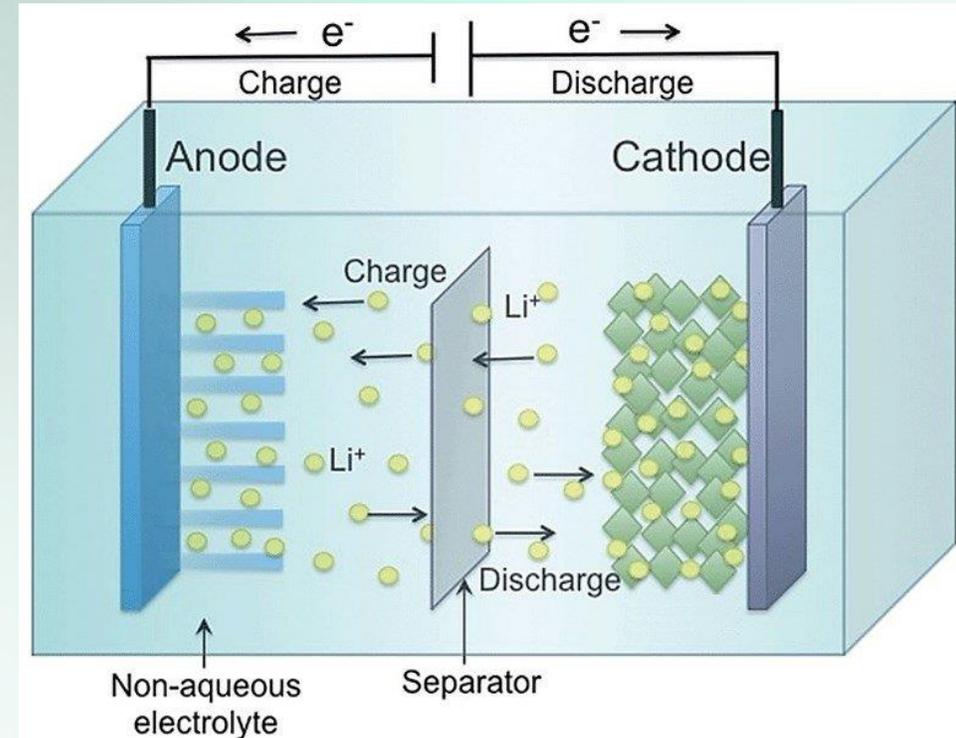


Battery materials
that are easier to
source

IQM x 

Solving problems that reduce carbon footprint: Battery optimization

- Understanding the chemical reactions of the electrolyte region is key to increase battery performance and longevity.
- This region contains electrons that are strongly correlated (heavily entangled): very hard to compute classically.



Fraud Detection

Partner
Global insurance company

Problem

→ Endpoint detection and response based on training normal behavior and flagging anomalous behavior in operation

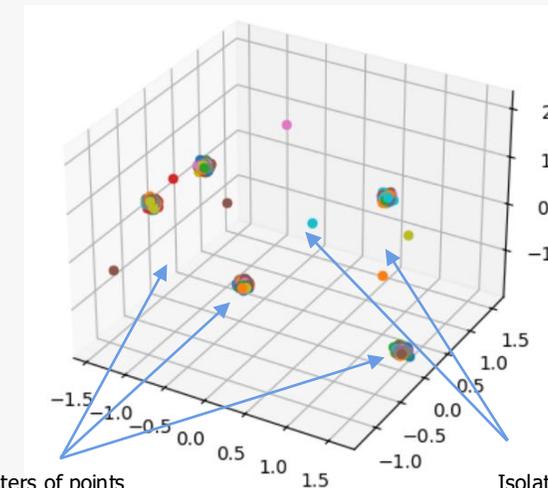
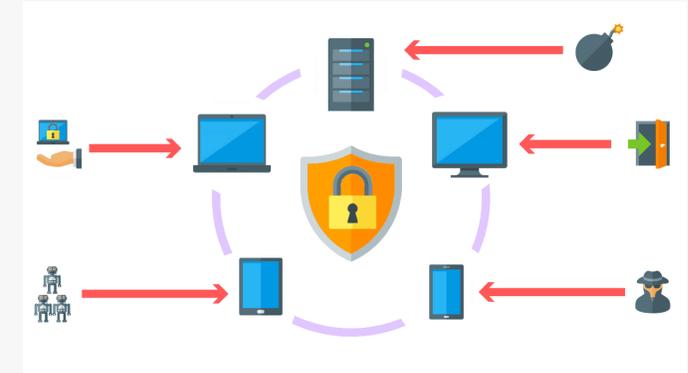
Solution

We use one-class support vector machine:

1. Using a quantum kernel method, we map data points into high-dimensional space where differences between normal and anomalous behaviour are easier to distinguish.
2. From the mapping we obtain a decision function to decide whether future data points are anomalies or not

Why Quantum

- Quantum kernels produce mappings intractable to classical computers.
- Quantum kernels can represent complex functions with fewer resources
- In summary, quantum may be able to capture more difficult patterns, which could result in high accuracy fraud detection



Clusters of points
represent normal activity

Isolated points represent
anomalous activity

Power Plant Maintenance Scheduling

Partner: **Électricité de France SA (EDF)**



Problem

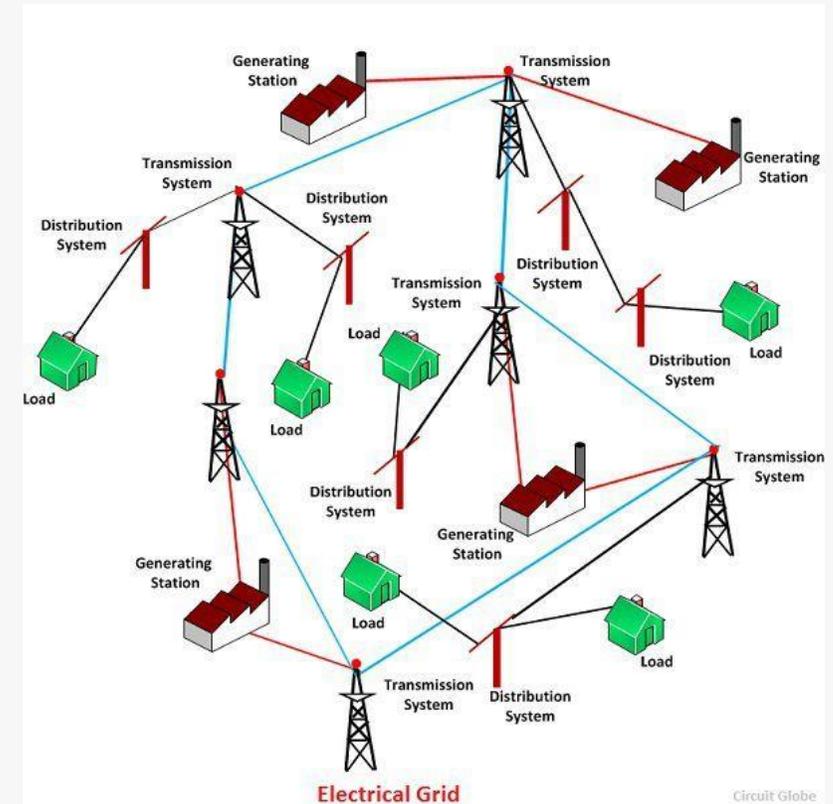
- Planning the maintenance schedule of power plants
- Satisfying constraints with regular maintenance intervals
- Prevent power grid failure because of multiple power plants being maintained at the same time, and therefore not providing power

Solution

1. Represent the problem as graph (nodes = individual schedules, edges = incompatibility)
2. Define a Maximum independent set (MIS) problem (NP complete) on the above defined graph
3. Solve the above MIS problem with tailored QAOA problem

Why Quantum

Quantum computers leverage quantum superposition for parallel exploration of the solution space, as well as entanglement for complex correlations. Once the HW is ready in terms of precision and qubit number, they may potentially outperform classical approaches both in accuracy and time-to-solution



Overview

- Some problems  **scale too fast** for ordinary digital computers, meaning digital computers need a lot of **time and/or memory** to solve them.
- Different  **physical systems** may offer different computational complexity
- Quantum information processing can **reduce computational complexity** for **some** tasks in
 - Optimization
 - Simulation
 - and machine learning.

Classical Computer vs. Quantum Computer

Classical computer



Quantum computer

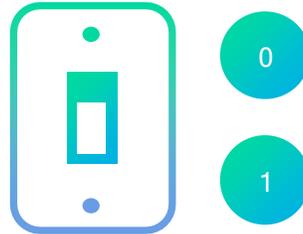


Bits and Qubits

Computers encode information in many *bits*

Classical bit

Ordinary physical object
with 2 distinct states



switch on/off

Measuring the
state does not
change the state

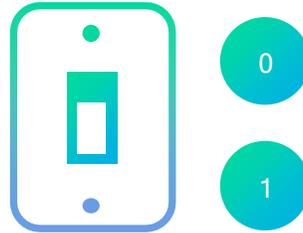
We can invent codes that
store information (or
messages) as bits, then
manipulate that message.

Message	Bits
I	01001001
Q	01010001
M	01001101
IQM	01001001 01010001 01001101

Classical Computer vs. Quantum Computer

Classical bit

Ordinary physical object with 2 distinct states

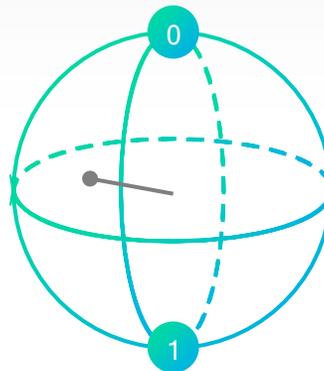


switch on/off

Measuring the state does not change the state

Quantum bit

Physical object which can be in a “quantum superposition” of 2 states



Point on the surface of a sphere

Measurement of the state will cause it to **irreversibly change** to 0 or 1

What is quantum computing?

Classical vs quantum computer

Quantum computers follow different rules than classical computers - those of quantum physics.

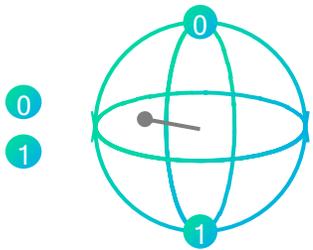
- 1 qubit can be in a superposition of 2 basis states
- 1 bit can be in just one state

Basis states:

- 0
- 1

Bit vs qubit (quantum bit)

A bit can be either 0 or 1, while a qubit can be in a **superposition**: qubit can be both 0 and 1 at the same time. Measurement will yield either 0 or 1.



Two qubits can be **entangled**. Changing one directly impacts the other.

1Qubit

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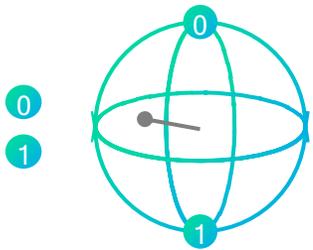
- 2 qubits can be in a superposition of all 4 basis states
- 2 bits can be in just one state

Basis states:

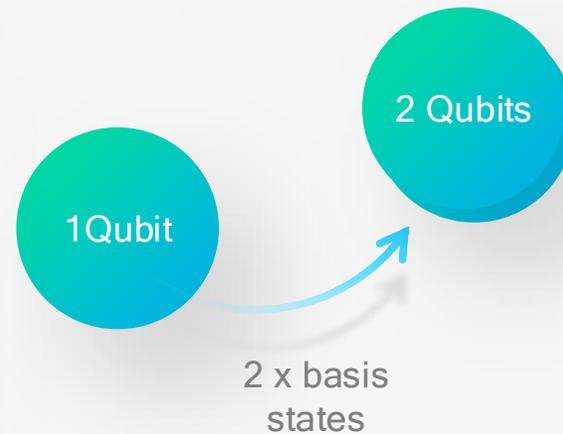
- 00
- 01
- 10
- 11

Bit vs qubit (quantum bit)

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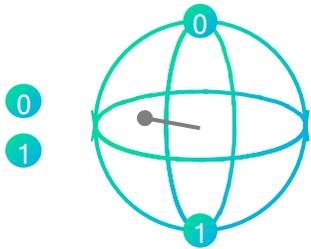
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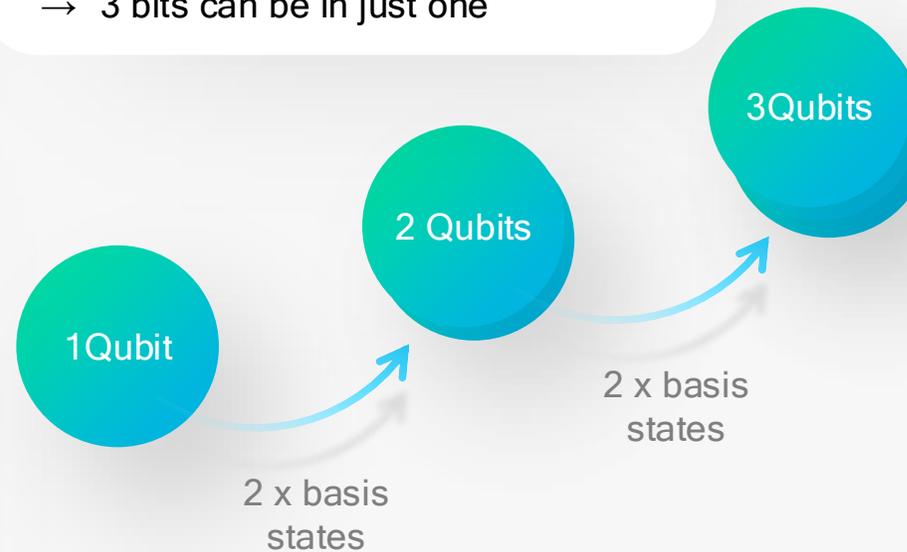
000	001	010	011
100	101	110	111

→ 3 qubits can be in a superposition of all $2^3 = 8$ basis states

→ 3 bits can be in just one

Basis states:

- 000
- 100
- 010
- 110
- 001
- 101
- 011
- 111



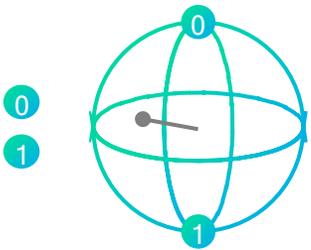
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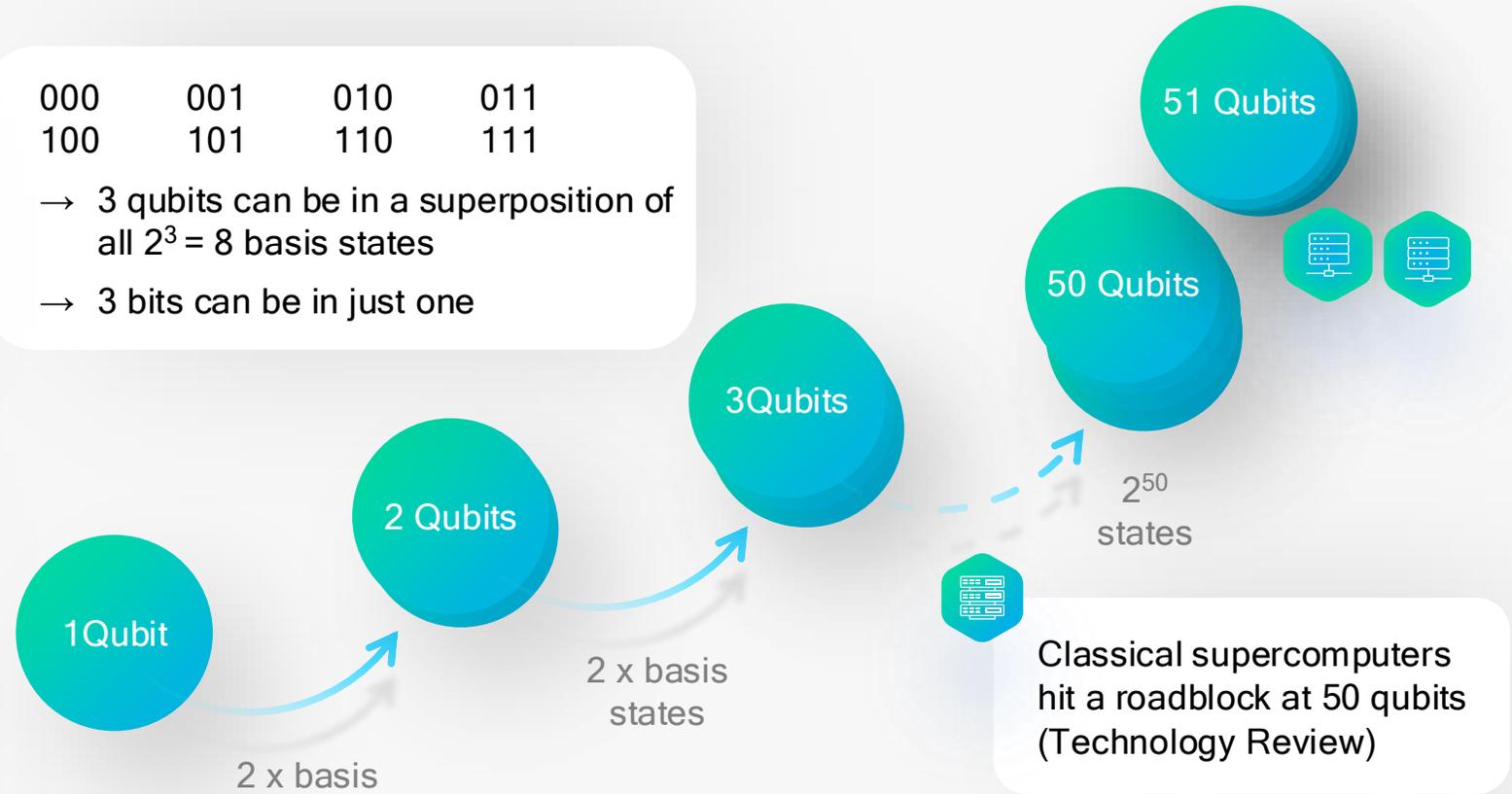


Two qubits can be **entangled**. Changing one directly impacts the other.

000	001	010	011
100	101	110	111

→ 3 qubits can be in a superposition of all $2^3 = 8$ basis states

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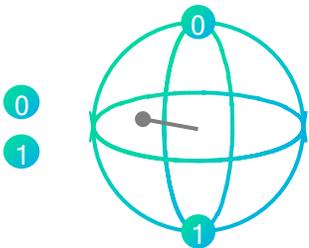
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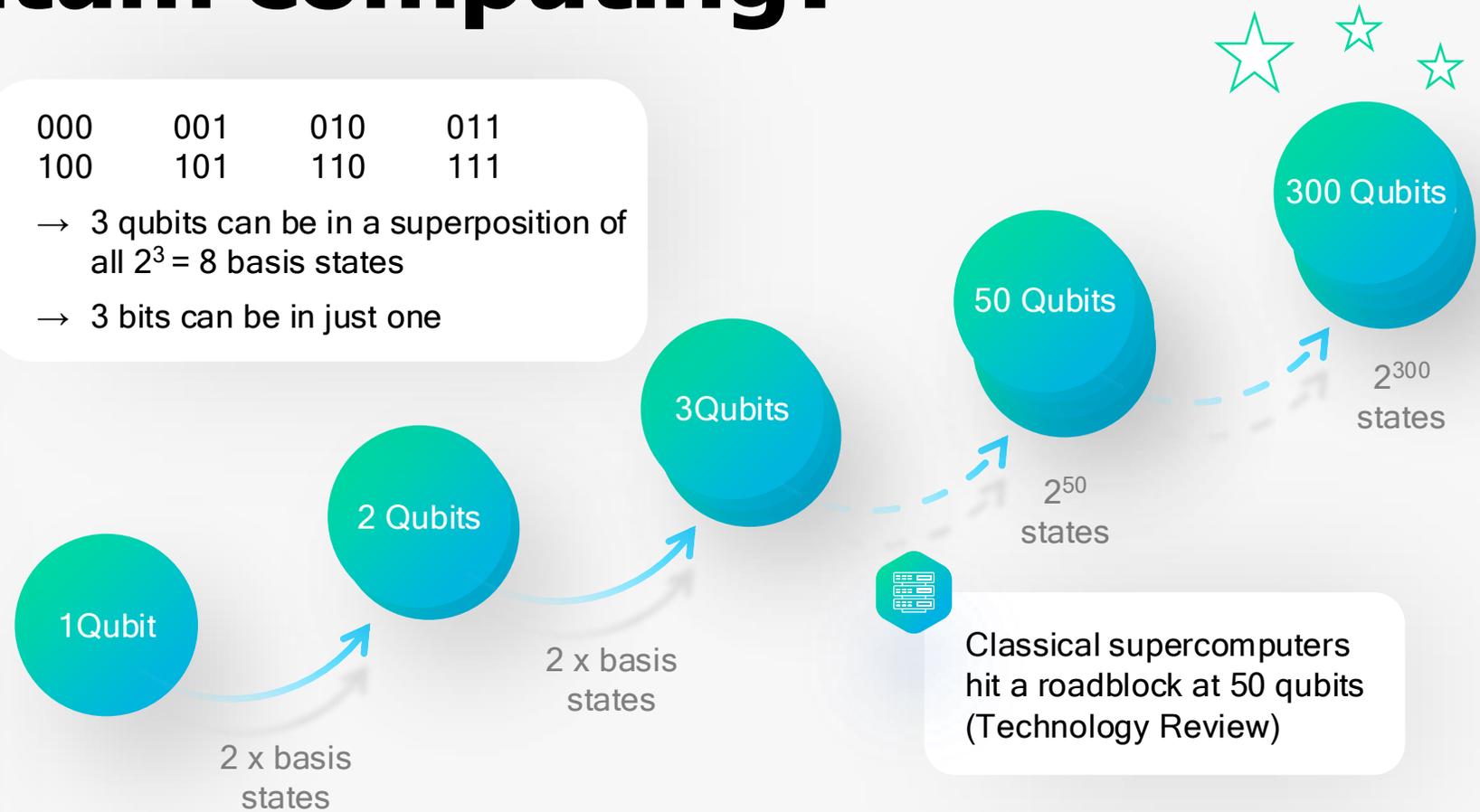


Two qubits can be **entangled**. Changing one directly impacts the other.

000	001	010	011
100	101	110	111

→ 3 qubits can be in a superposition of all $2^3 = 8$ basis states

→ 3 bits can be in just one



→ Exponential increase in computational capacity

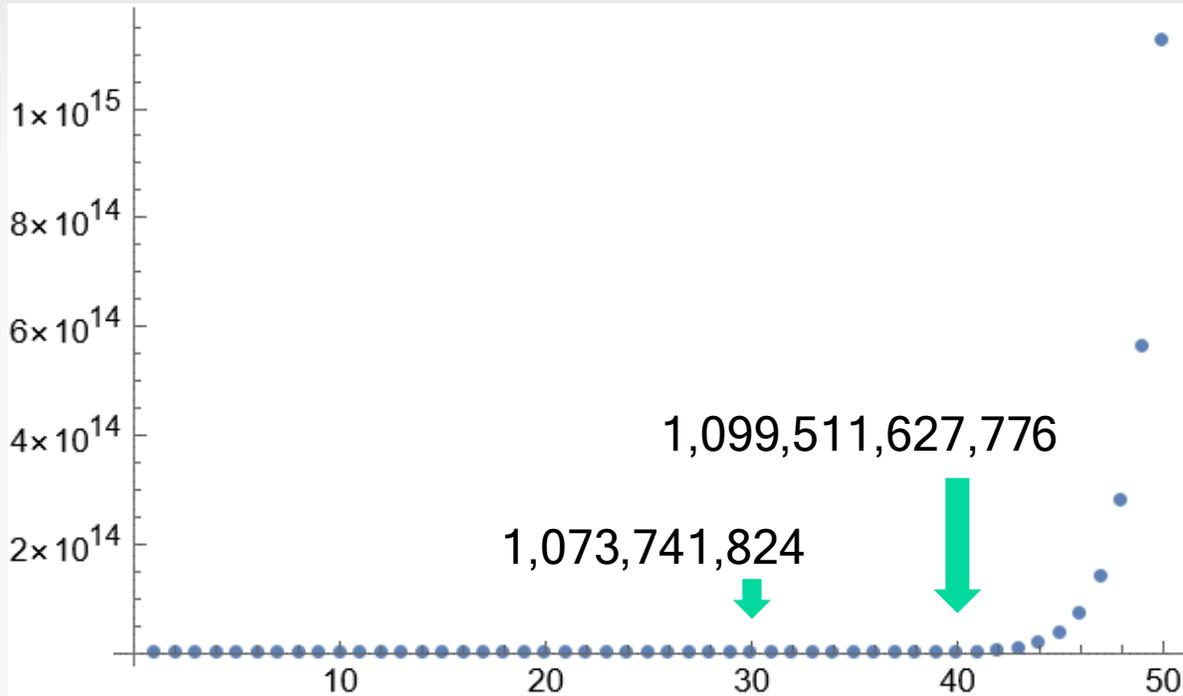
→ Enables new algorithms and solutions to previously intractable problems

“Quantum Parallelism”

Bit is replaced by **qubit** in quantum computing.

n qubits represent up to 2^n different states

“simultaneously”.

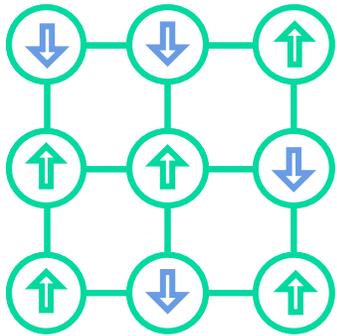


n	2^n
1	2
10	1,024
20	1,048,576
30	1,073,741,824
40	1,099,511,627,776
50	1,125,899,906,842,624 $\sim 10^{15}$
60	$\sim 10^{18}$
70	$\sim 10^{21}$
80	$\sim 10^{24}$
90	$\sim 10^{27}$
100	$\sim 10^{30}$
1,000	$\sim 10^{301}$

Eddington number $\sim 10^{80}$. The number of atoms in the visible universe.

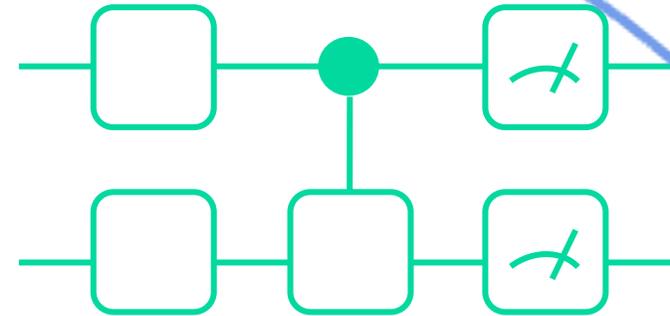
**How to work
with qubits?**

Different ways to work with qubits



Quantum annealing

designed for particular optimization problems

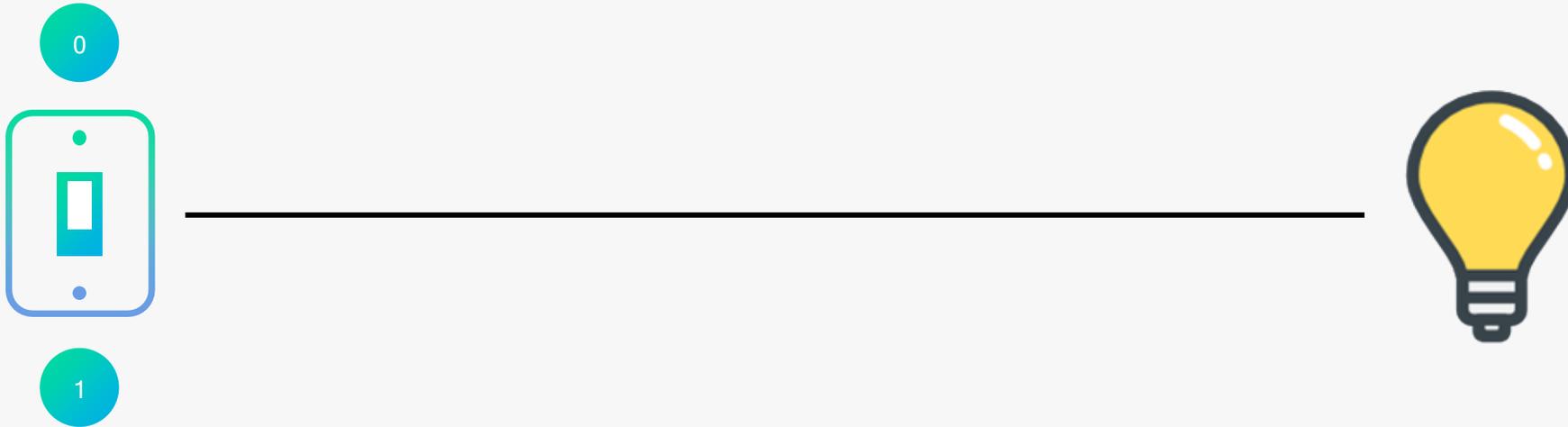


Gate-based quantum computing

designed for universal (quantum) computing

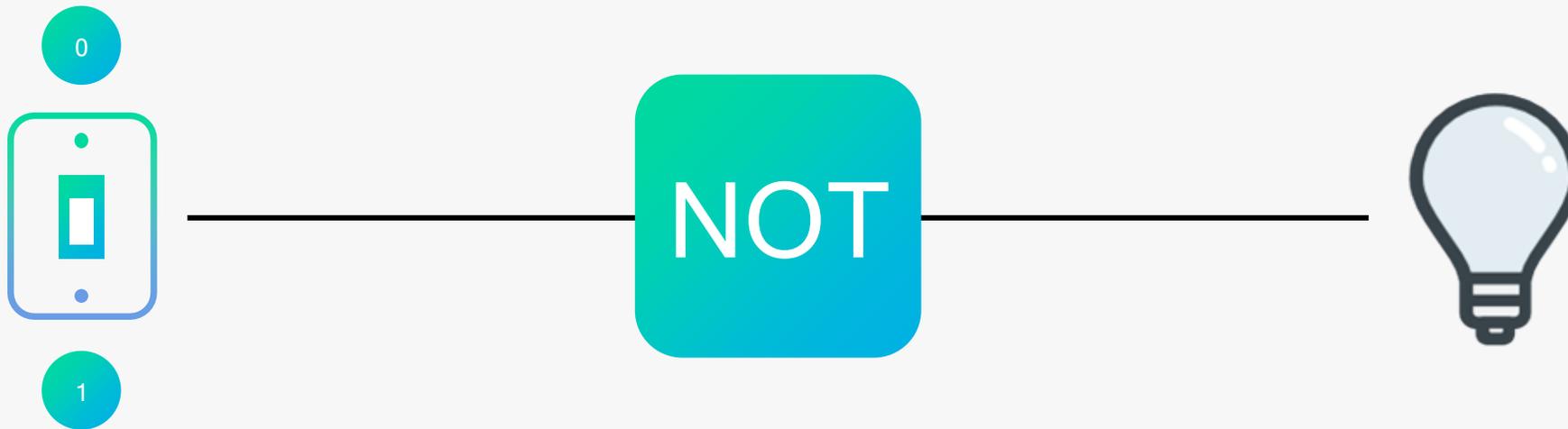
Conventional computer: bits

- Bits are the foundation of conventional computers



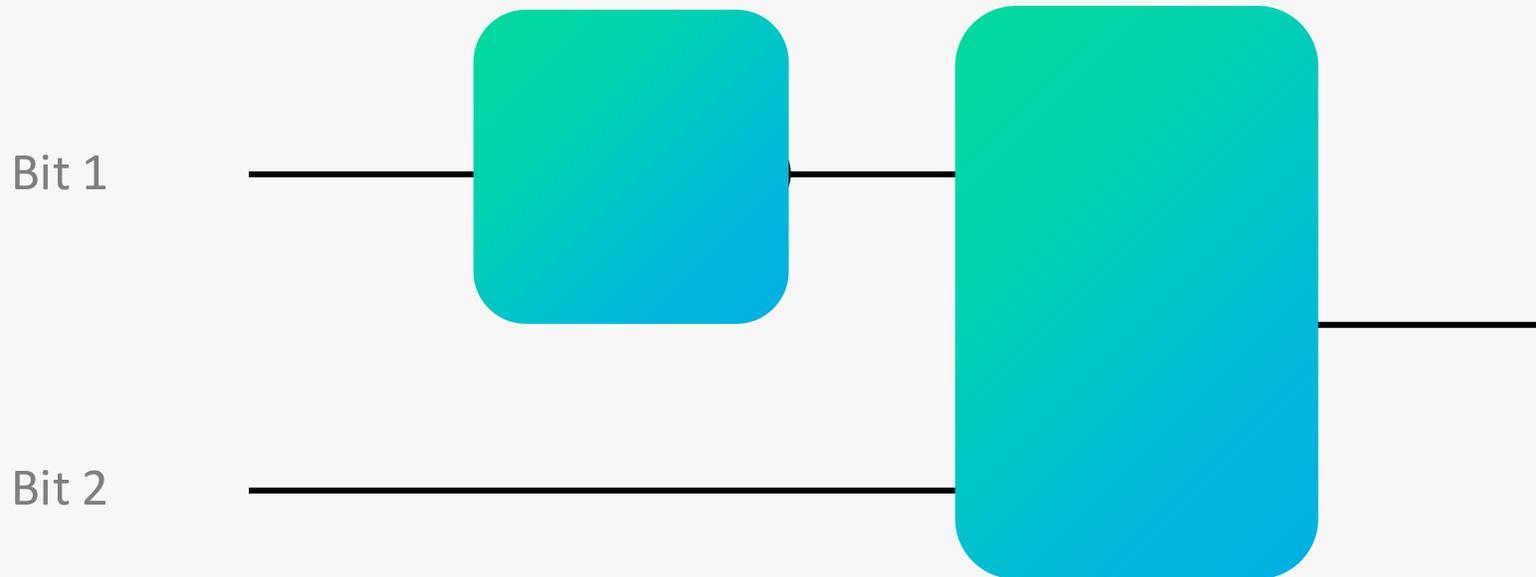
Conventional computer: working with bits

- Information processing is performed with the help of logical gates



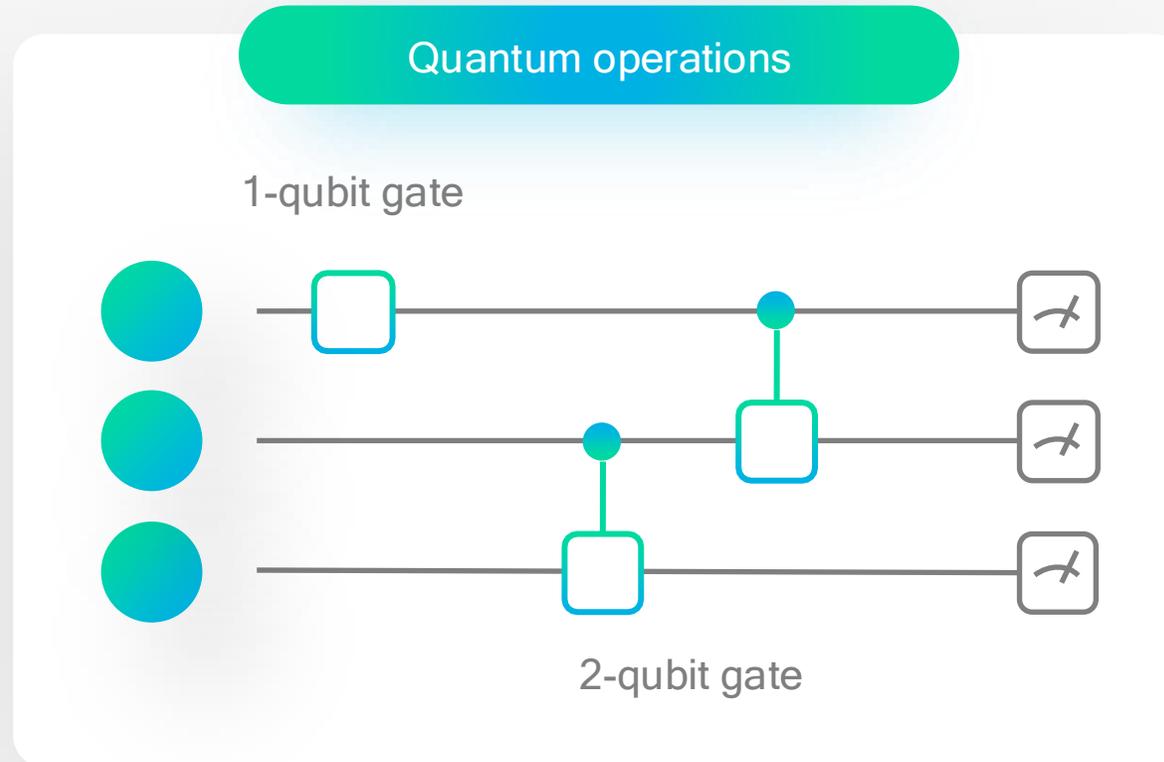
Conventional computer: algorithms

- Multiple gates form a circuit
- An algorithm is implemented in a sequence of gates
- Circuits are represented as a time sequence like musical notes



- Classical circuits are irreversible: Two inputs, but just one output in above case

Quantum computing: algorithms



Activity 1: Exploring the **H** gate

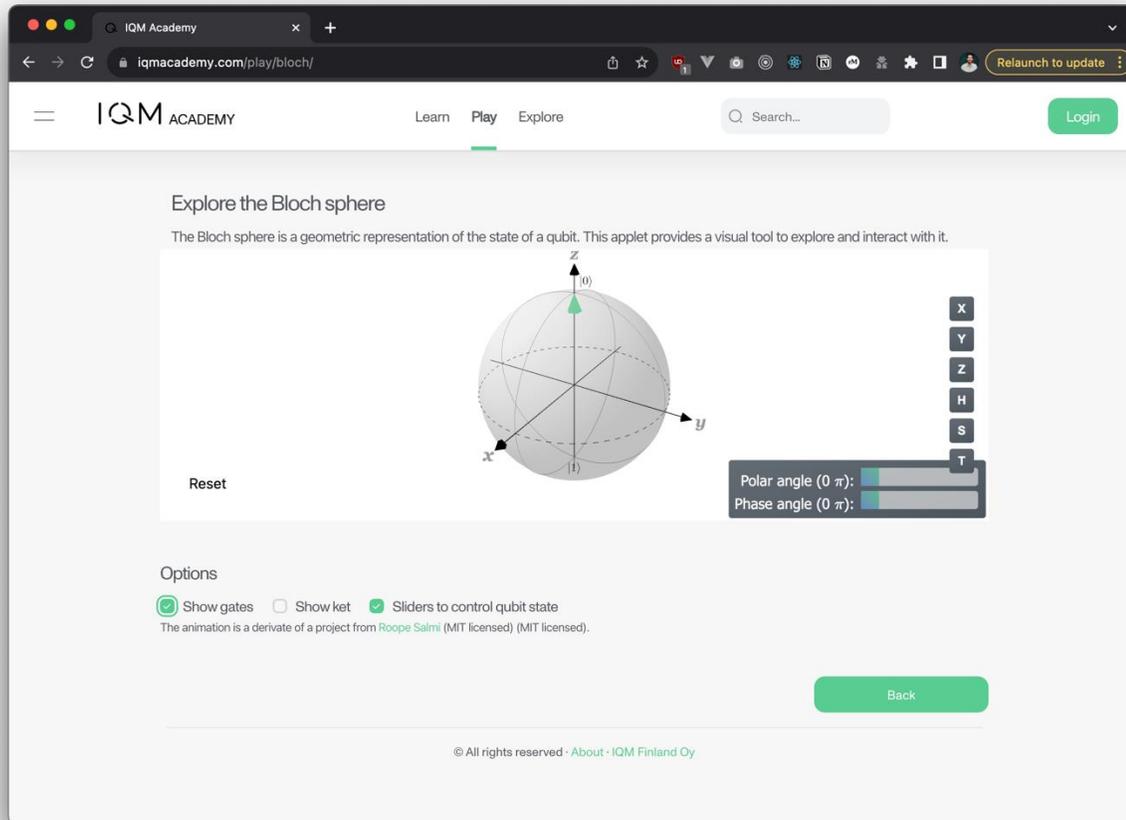
Open <https://www.iqmacademy.com/curriculum/workshop-en-1.html> and investigate the effects of gate **H** and gate **X**!



Take it further:

- Apply the Hadamard gate **H** two times in a row while choosing 0 and 1 as starting values. Describe your observation! What does it mean for the information stored in the qubit?

Activity 1: Bloch Sphere



Open

<https://www.iqmacademy.com/play/bloch/>

and investigate the effects of gate **H** and gate **X** again! See what happens if you apply the **H** gate twice.

Activity 1: Description of a quantum state

A single-qubit quantum state $|\psi\rangle$ can be described mathematically as

$$|\psi\rangle = a|0\rangle + b|1\rangle \text{ with } |a|^2 + |b|^2 = 1$$

with $a, b \in \mathbb{C}$

*This is called a ket,
Dirac notation for
vectors*

Activity 1: Description of a quantum state

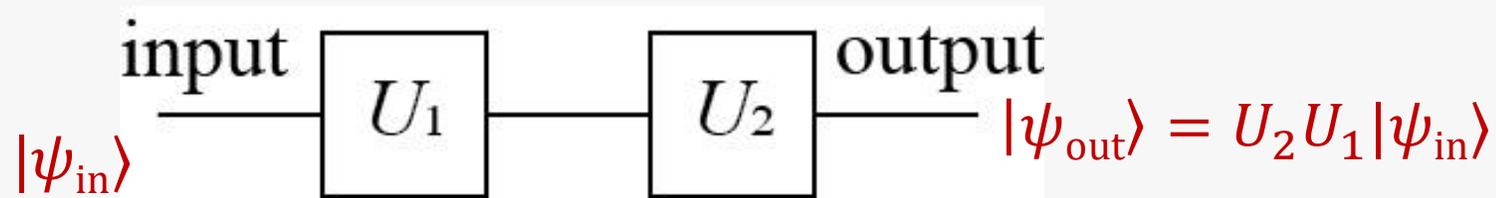
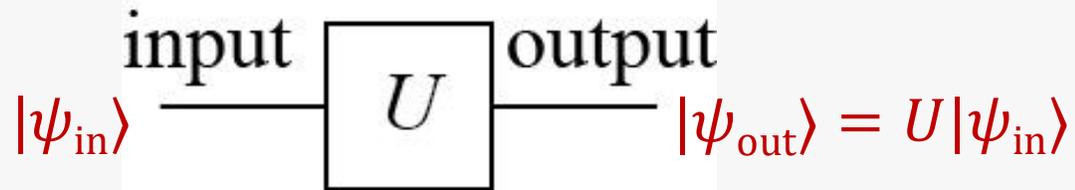
A single-qubit quantum state $|\psi\rangle$ can be described mathematically as

$$|\psi\rangle = a \begin{pmatrix} 1 \\ 0 \end{pmatrix} + b \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} \text{ with } |a|^2 + |b|^2 = 1$$

with $a, b \in \mathbb{C}$

One-Qubit Gates

- A quantum gate that acts on a single qubit is called a **1-qubit gate**.



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



This is how it looked last time

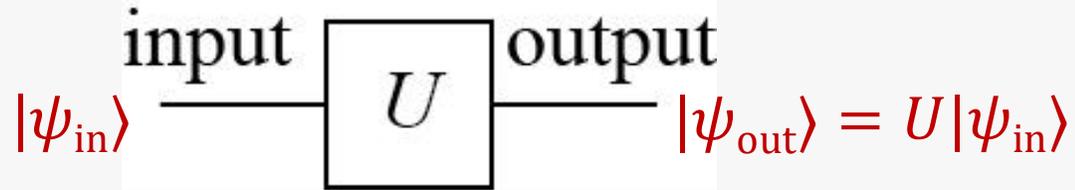
- $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. $X|0\rangle = |1\rangle$ & $X|1\rangle = |0\rangle$. $X \leftrightarrow$ **NOT**.

- Hadamard gate** $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$. It maps $|0\rangle$ and $|1\rangle$ to **superposition states**.

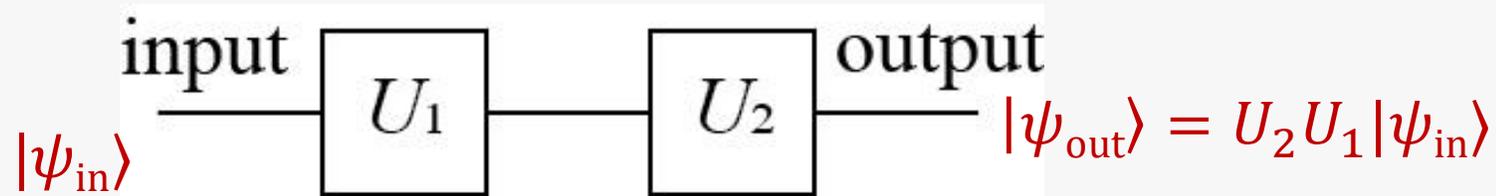
$$H|0\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle), H|1\rangle = \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle).$$

One-Qubit Gates

- A quantum gate that acts on a single qubit is called a **1-qubit gate**.



The line denotes a qubit. Time flies from left to right.



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



This is how it looked last time

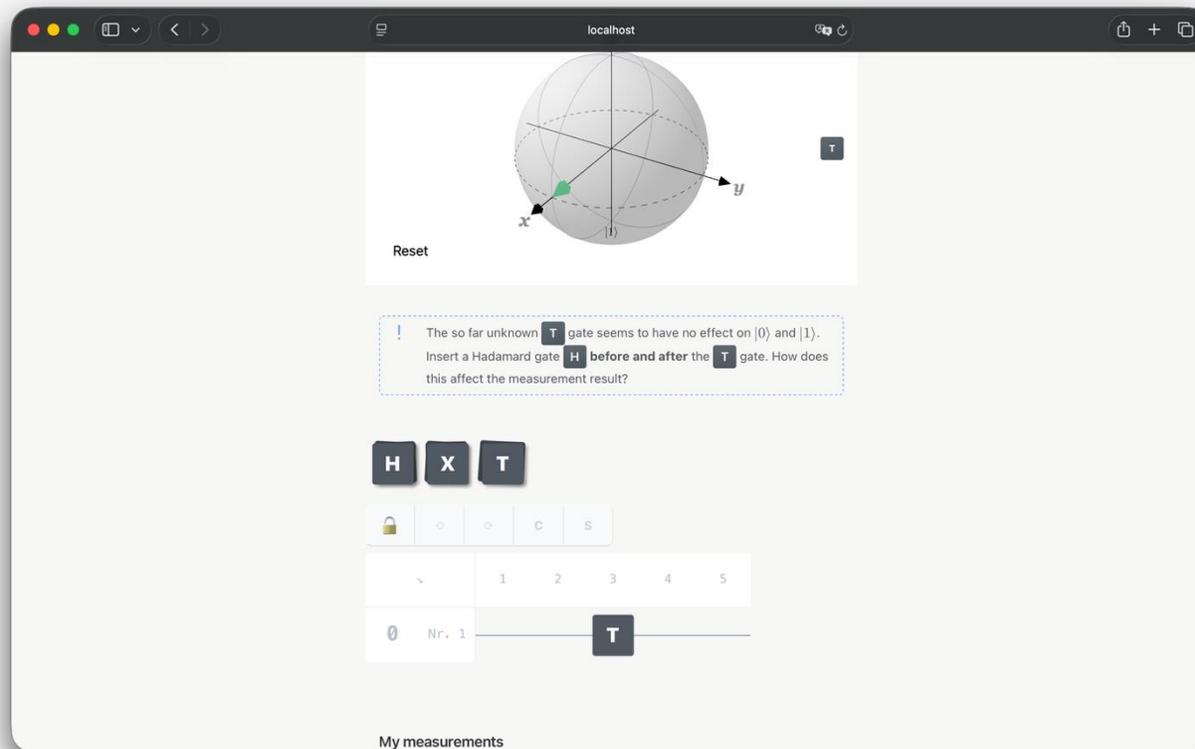
- $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. $X|0\rangle = |1\rangle$ & $X|1\rangle = |0\rangle$. $X \leftrightarrow$ **NOT**.
- $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$; $Z|0\rangle = |0\rangle$ & $Z|1\rangle = -|1\rangle$. No classical counterpart.
- $Y = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}$. $Y = -iZX$. No classical counterpart.

Exercise: Exploring another gate

- Open <https://iqmacademy.com/curriculum/workshop-en-1b.html> and investigate the effects of the new **T** gate! See what happens if sandwich the **T** gate between two **H** gates.

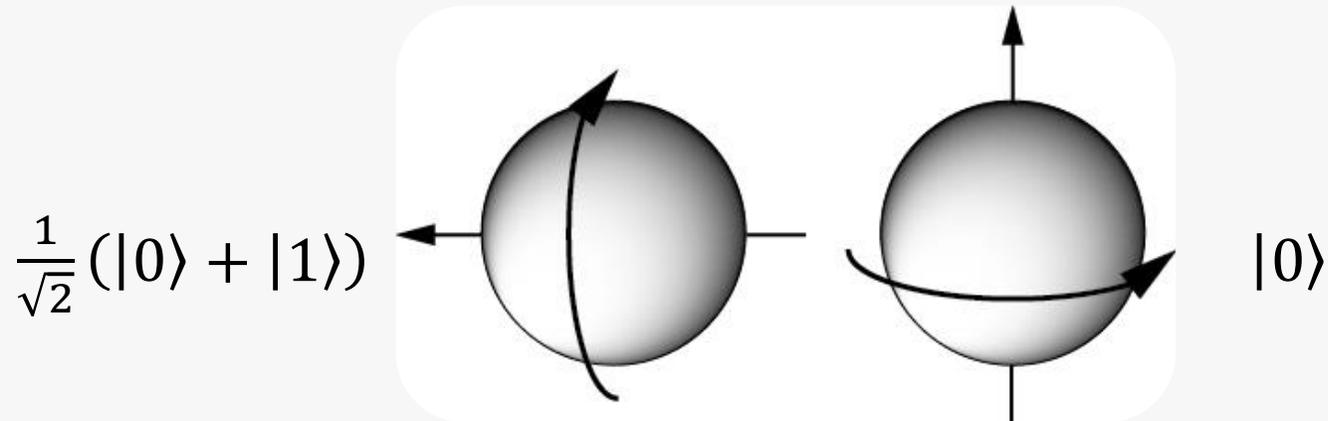


<https://iqmacademy.com/curriculum/workshop-en-1b.html>



Multi-qubit Systems and Entanglement

- Consider a system made of 2 qubits. If the state of the first qubit is $|0\rangle$ and the second qubit is $|1\rangle$, the total state is written as $|0\rangle|1\rangle$ or $|01\rangle$ or $|0\rangle \otimes |1\rangle$.
- A state $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|0\rangle)$ is decomposed as $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|0\rangle$. It is a **tensor product state** or a **product state**.

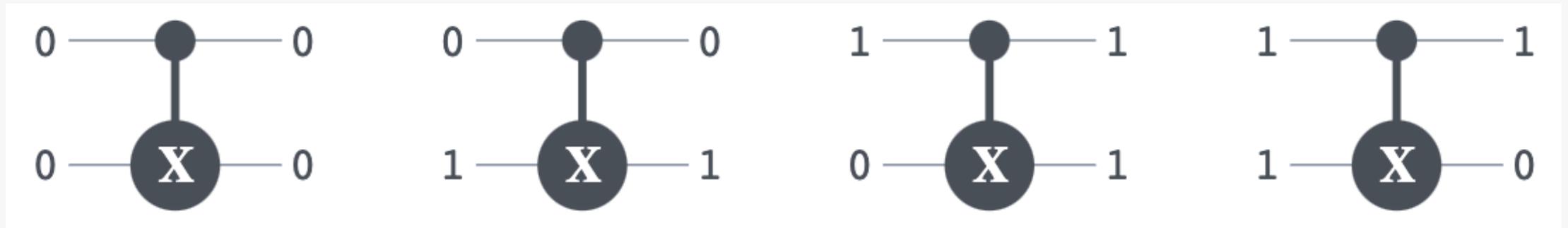


- Measure the first qubit \rightarrow 50% $|0\rangle$, 50% $|1\rangle$. Measure the second qubit \rightarrow 100% $|0\rangle$ **independently of the outcome of the first qubit**. They are **not** correlated.

Activity 2: A 2-qubit gate



- With two qubits, the gate flips the second (target qubit) if the first (control qubit) is in state $|1\rangle$
- If the control qubit is in the $|0\rangle$ state, nothing happens to the target qubit..



- This gate is called **CNOT** (short for Controlled NOT)

Activity 2: What happens, if the control qubit is in a superposition state of both $|0\rangle$ and $|1\rangle$?

Open <https://bit.ly/iqm-2> to check it out!

Activity 2 - Discussion

- If the **control qubit** is in a superposition, the measurement result of the target qubit depends on which value the control qubit now assumes.
- This combination of gates "**entangles**" the two qubits.
- If the state of one of the qubits is then measured, the state of the other qubit is automatically known.
- Viewed as a whole, the two qubits have a well-defined state, but the individual qubits cannot be assigned their own well-defined state.
- Only with entanglement is it possible to create truly arbitrary states

Auswertung

Nach 1000 Messungen zeigt sich folgende Ergebnisverteilung:

1	00>	██████████	50% Wahrscheinlichkeit
2	01>	░░░░░░░░	0% Wahrscheinlichkeit
3	10>	░░░░░░░░	0% Wahrscheinlichkeit
4	11>	██████████	50% Wahrscheinlichkeit

Activity 2: Description of a two-qubit quantum state

A two-qubit quantum state $|\psi\rangle$ can be described mathematically as

$$|\psi\rangle = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$$

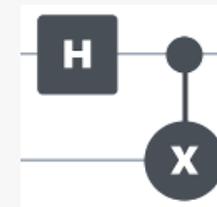
$$\text{with } |a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$$

The entangled state we just created can be written as

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

Entanglement

“Viewed as a whole, the two qubits have a well-defined state, but the individual qubits cannot be assigned their own well-defined state.”



The state we generated was: $\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$

Let's assume, it is comprised of two independent qubits, meaning we could write:

$$\begin{aligned}\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle &\stackrel{?}{=} (a|0\rangle + b|1\rangle) \otimes (c|0\rangle + d|1\rangle) \\ \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle &\stackrel{?}{=} ac|00\rangle + ad|01\rangle + bc|10\rangle + bd|11\rangle\end{aligned}$$

Symbol for
tensor product

Comparing both sides yields to:

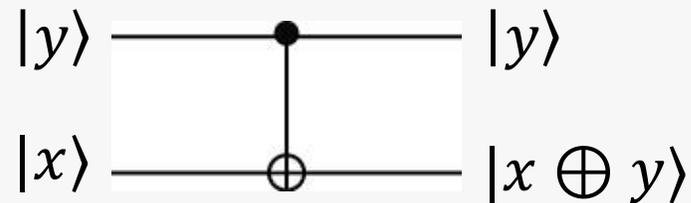
$$\frac{1}{\sqrt{2}} = ac, 0 = ad, 0 = bc, \frac{1}{\sqrt{2}} = bd$$



Two-Qubit Gates

- Classical logic circuits require two-bit gates such as **NAND** and **XOR** for universality.
- This is also true for quantum circuits. Two-qubit gates are required for universal quantum computation.

- Examples



$$x \oplus y = x + y \pmod{2}$$

$$0 \oplus 0 = 0$$

$$0 \oplus 1 = 1$$

$$1 \oplus 0 = 1$$

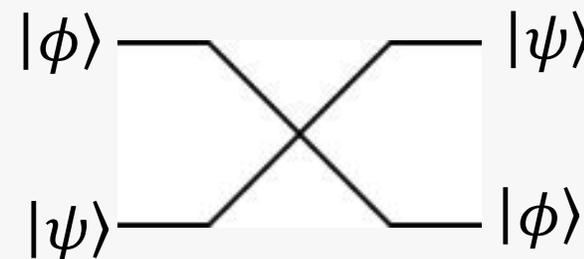
$$1 \oplus 1 = 0$$

- $$U_{\text{CNOT}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$U_{\text{CNOT}}|x\rangle|y\rangle = |x \oplus y\rangle|y\rangle$. U_{CNOT} flips $|x\rangle$ if $|y\rangle = |1\rangle$. Does nothing to $|x\rangle$ if $|y\rangle = |0\rangle$. Similar to XOR.

- $$U_{\text{SWAP}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$U_{\text{SWAP}}|\psi\rangle|\phi\rangle = |\phi\rangle|\psi\rangle$.

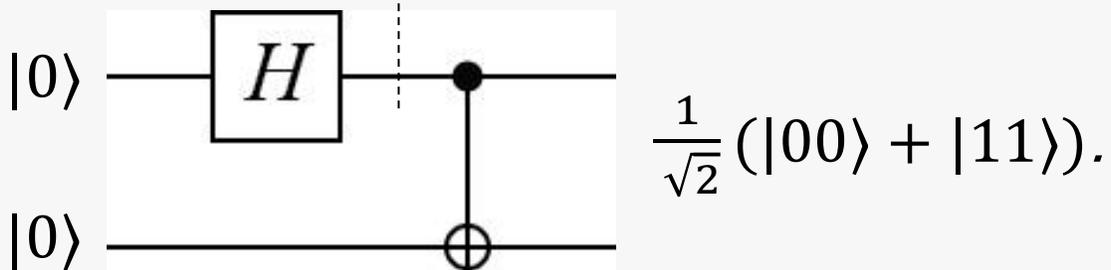


Two-Qubit Gates

- **Universality Theorem:** Any n -qubit unitary ($\in U(2^n)$) gate can be decomposed into one-qubit gates and CNOT gates.

The proof is highly technical. See Nielsen & Chuang or Nakahara & Ohmi.

- CNOT above may be replaced by most 2-qubit gates. The SWAP gate and tensor products of 1-qubit gates are exceptions.
- Two-qubit gates are necessary to entangle tensor product states.



Activity 3 – More qubits, more fun

Open <http://iqmacademy.com/play/composer> and create a circuit that entangles all five qubits.



Conclusion

Conclusion: Foundations

- Qubits can not only be in the two states $|0\rangle$ and $|1\rangle$, but also in a **superposition** of $|0\rangle$ and $|1\rangle$. In this case, they have a certain probability of being measured as $|0\rangle$ or $|1\rangle$. However, a measurement destroys the superposition.
- Quantum computers use **quantum gates** to manipulate the state of qubits.
- Even though the measurement results of a qubit are random, the qubit is still always in a precisely defined state.
- Two qubits can **entangled** with each other. If you then measure the state of one of the qubits, you automatically know the state of the other qubit.

IQM

Quantum School

Day 1

LAB

Quantum School

Stefan Seegerer

Last Updated 06/2025

www.meetiqm.com



IQM

The tools

IQM Resonance™

QFISIP



IQM Resonance™

<https://resonance.meetiqm.com/signup>

The screenshot displays the IQM Resonance dashboard. At the top, there's a navigation bar with 'IQM Resonance' and a dropdown menu, and tabs for 'Dashboard', 'Jobs', 'Documentation', and 'Organization'. The main content area is divided into several sections:

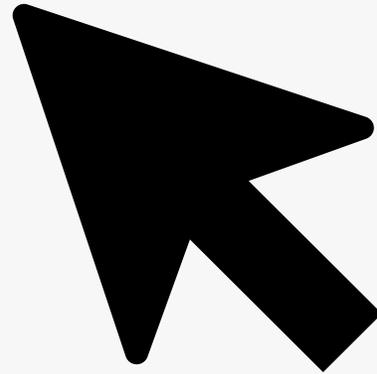
- QUANTUM COMPUTERS:** Three cards for IQM Emerald (54 jobs, 22 in queue), IQM Garnet (20 jobs, 4 in queue), and IQM Sirius (16 jobs, 1 in queue). All are 'Active'.
- AVAILABILITY:** A calendar view for IQM Garnet showing 'Pay-as-you-go' (green) and 'Booked Timeslot' (blue) slots.
- YOUR LATEST JOBS:** A table listing recent jobs with columns for Job ID, Created, Completed, Runtime, QC, Status, and Mode.

YOUR LATEST JOBS Table:

Job ID	Created	Completed	Runtime	QC	Status	Mode
123456	19 Jan, 14:52	19 Jan, 14:52	1 s	IQM Garnet	⌚ Waiting	Pay-as-you-go
123456	19 Jan, 14:52	19 Jan, 14:52	5 s	IQM Garnet:mock	⌚ Completed	Mock run
123456	19 Jan, 14:52	19 Jan, 14:52	10 min 17 s	IQM Deneb	⌚ Completed	Pay-as-you-go
123456	19 Jan, 14:52	19 Jan, 14:52	9 s	Garnet:mock	⌚ Completed	Mock run
123456	19 Jan, 14:52	19 Jan, 14:52	7 s	IQM Garnet	⌚ Completed	Pay-as-you-go
123456	19 Jan, 14:52	19 Jan, 14:52	40 min 59 s	IQM Garnet:mock	⌚ Completed	Mock run

→ See all jobs

— IQM Resonance Intro





- qrisp is a high level programming framework for working with quantum computing programs
- It's pythonic

```
pip install „qrisp[iqm]“
```

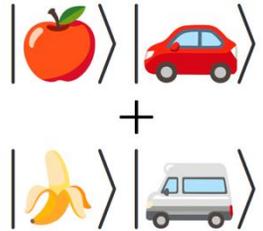
- It's open source

<https://github.com/eclipse-qrisp/Qrisp>

- Created at Fraunhofer Fokus, IQM actively contributing to development



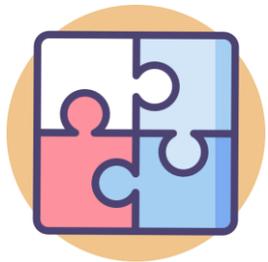
Features of qrisp



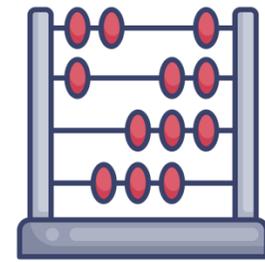
Typed quantum variables



Automatic uncomputation,
i.e. garbage collection



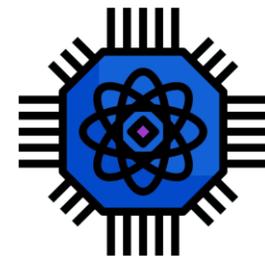
Modularity



Arithmetics



Compatibility



Full support for
IQM hardware

There are different quantum computing frameworks, but qrisp will enable you to learn what matters

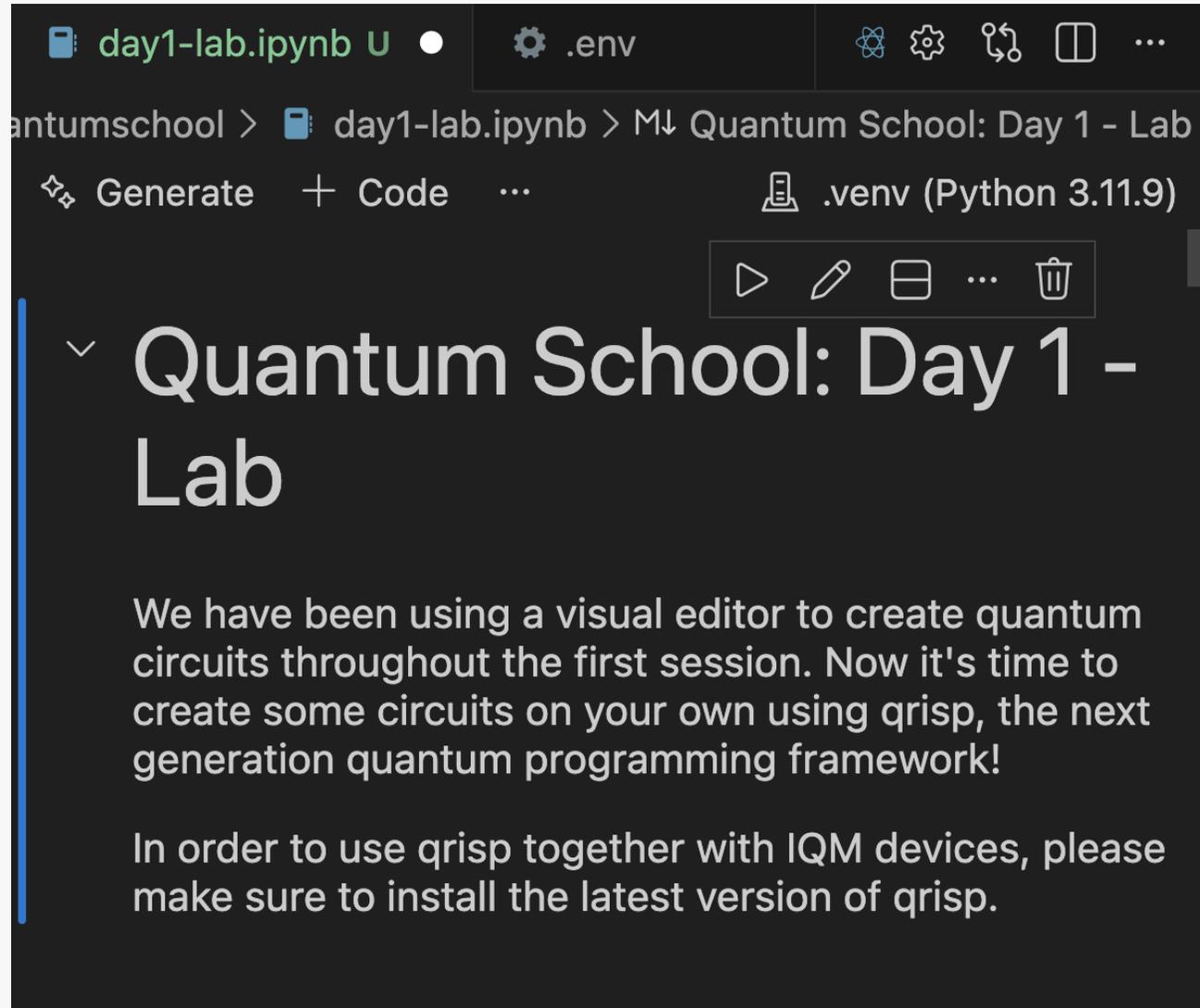


```
from qrisp import QuantumFloat
n = 6
a = QuantumFloat(n)
b = QuantumFloat(n)
a[:] = 3
b[:] = 4
res = a*b
print(res)
#Yields: {12: 1.0}
```

```
from qiskit import (QuantumCircuit, QuantumRegister,
                    ClassicalRegister, Aer, execute)
from qiskit.circuit.library import RGQFTMultiplier
n = 6
a = QuantumRegister(n)
b = QuantumRegister(n)
res = QuantumRegister(2*n)
cl_res = ClassicalRegister(2*n)
qc = QuantumCircuit(a, b, res, cl_res)
for i in range(len(a)):
    if 3 & 1<<i: qc.x(a[i])
for i in range(len(b)):
    if 4 & 1<<i: qc.x(b[i])
qc.append(RGQFTMultiplier(n, 2*n),
          list(a) + list(b) + list(res))
qc.measure(res, cl_res)
backend = Aer.get_backend('qasm_simulator')
counts_dic = execute(qc, backend).result().get_counts()
print({int(k, 2) : v for k, v in counts_dic.items()})
#Yields: {12: 1024}
```

```
import pennylane as qml
import numpy as np
w_m = [0, 1, 2]
w_k = [3, 4, 5]
w_sol = [6, 7, 8, 9]
dev = qml.device("default.qubit", wires=w_m + w_k + w_sol, shots=1)
n_wires = len(dev.wires)
def add(k, wires):
    for j in range(len(wires)):
        qml.RZ(k * np.pi / (2**j), wires=wires[j])
def multiplication(w_m, w_k, w_sol):
    qml.QFT(wires=w_sol)
    for i in range(len(w_k)):
        for j in range(len(w_m)):
            coeff = 2 ** (len(w_m) + len(w_k) - i - j - 2)
            qml.ctrl(add, control=[w_k[i], w_m[j]])(coeff, w_sol)
    qml.adjoint(qml.QFT)(wires=w_sol)
@qml.qnode(dev)
def mul(m, k):
    qml.BasisEmbedding(m, wires=w_m)
    qml.BasisEmbedding(k, wires=w_k)
    multiplication(w_m, w_k, w_sol)
    return qml.sample(wires=w_sol)
print(f"The ket representation of 3*7 is {mul(3,4)}")
#Yields: The ket representation of 3*7 is [10101]
```

Setting up qrisp & first gates



The screenshot shows a JupyterLab interface with a dark theme. At the top, there are tabs for 'day1-lab.ipynb' and '.env'. Below the tabs, the breadcrumb path is 'antumschool > day1-lab.ipynb > M↓ Quantum School: Day 1 - Lab'. There are buttons for 'Generate', '+ Code', and a dropdown menu for '.venv (Python 3.11.9)'. A toolbar with icons for play, edit, and other actions is visible. The main content area shows a notebook cell with the following text:

```
Quantum School: Day 1 - Lab
```

We have been using a visual editor to create quantum circuits throughout the first session. Now it's time to create some circuits on your own using qrisp, the next generation quantum programming framework!

In order to use qrisp together with IQM devices, please make sure to install the latest version of qrisp.

— Find the Day 1 lab here

Please make a copy of the notebook (File -> Save a Copy). You will be able to modify and run the code in the modified notebook.



<https://tinyurl.com/25bj9hd4>

Interview with Raphael Seidel

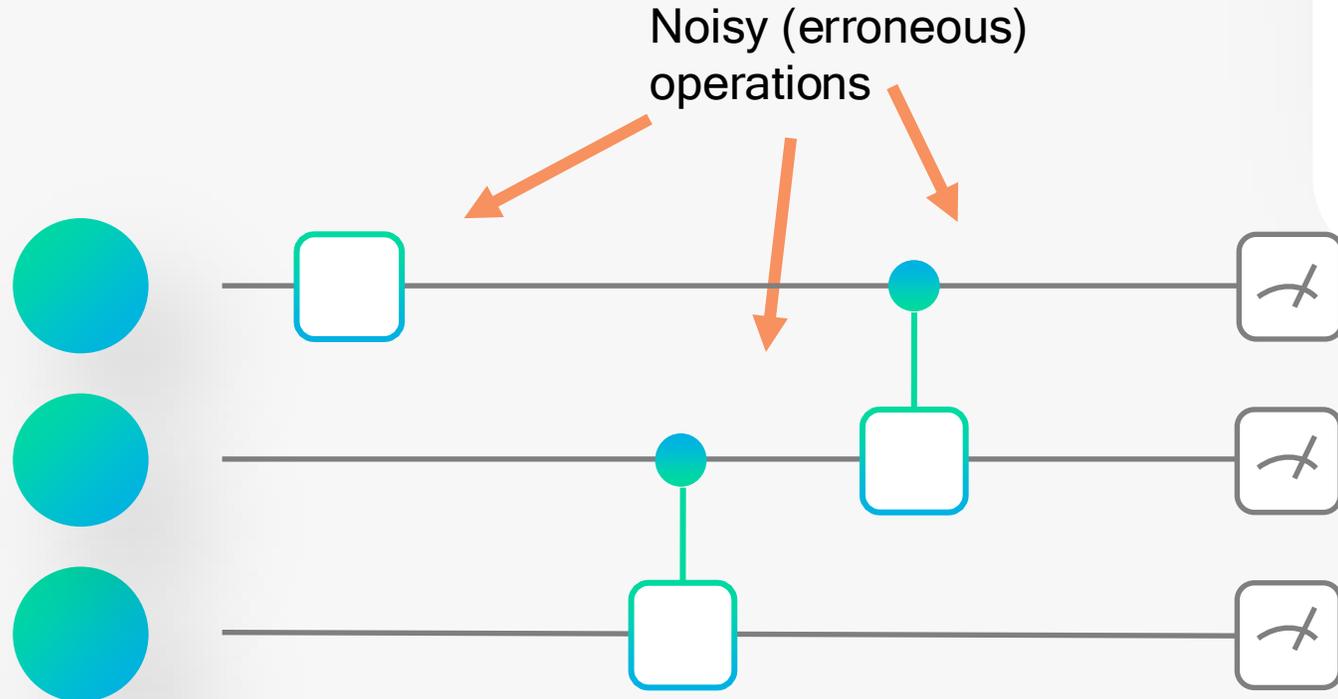
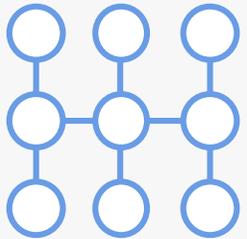
Creating a GHZ state in qrisp



Quantum Computing Eras

Quantum computers: NISQ era

Moderate number of qubits with limited connectivity (*intermediate scale*)



Limited circuit depth

# gates in algorithm	Algorithm fidelity
----------------------	--------------------

1	99.9%
---	-------

10	99.0%
----	-------

100	90.5%
-----	-------

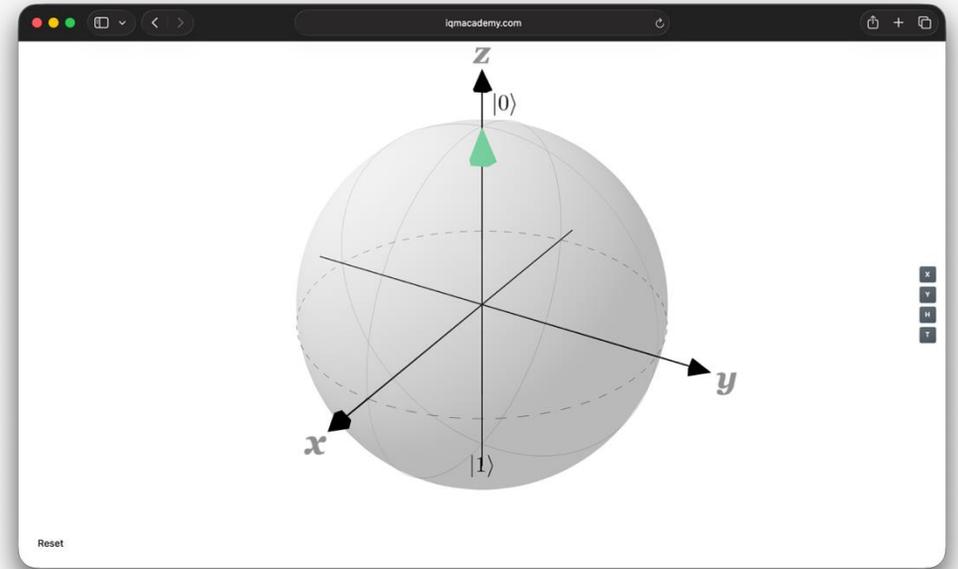
1000	36.8%
------	-------

Error rate: $1/1000 = 0.1\%$

One type of noise: slightly imperfect gates

If we apply a gate such as the **X** gate multiple times in a row, we see the error stacking up

<http://iqmacademy.com/curriculum/assets/bloch-viz/index.html?gates=H,X,T,Y&noKet&noise>

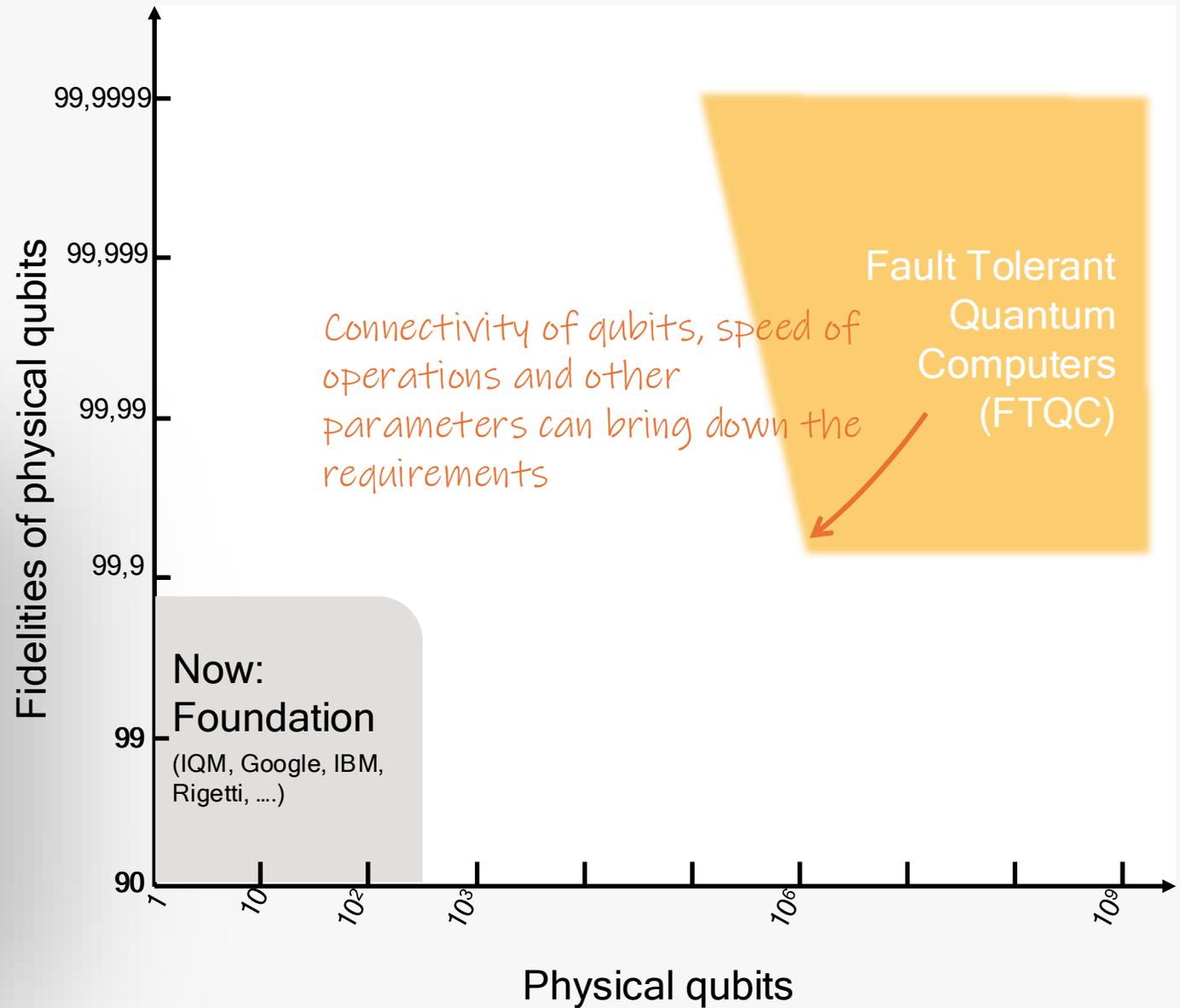


NISQ and FTQC

- Horizon: Fault Tolerant (FT) area

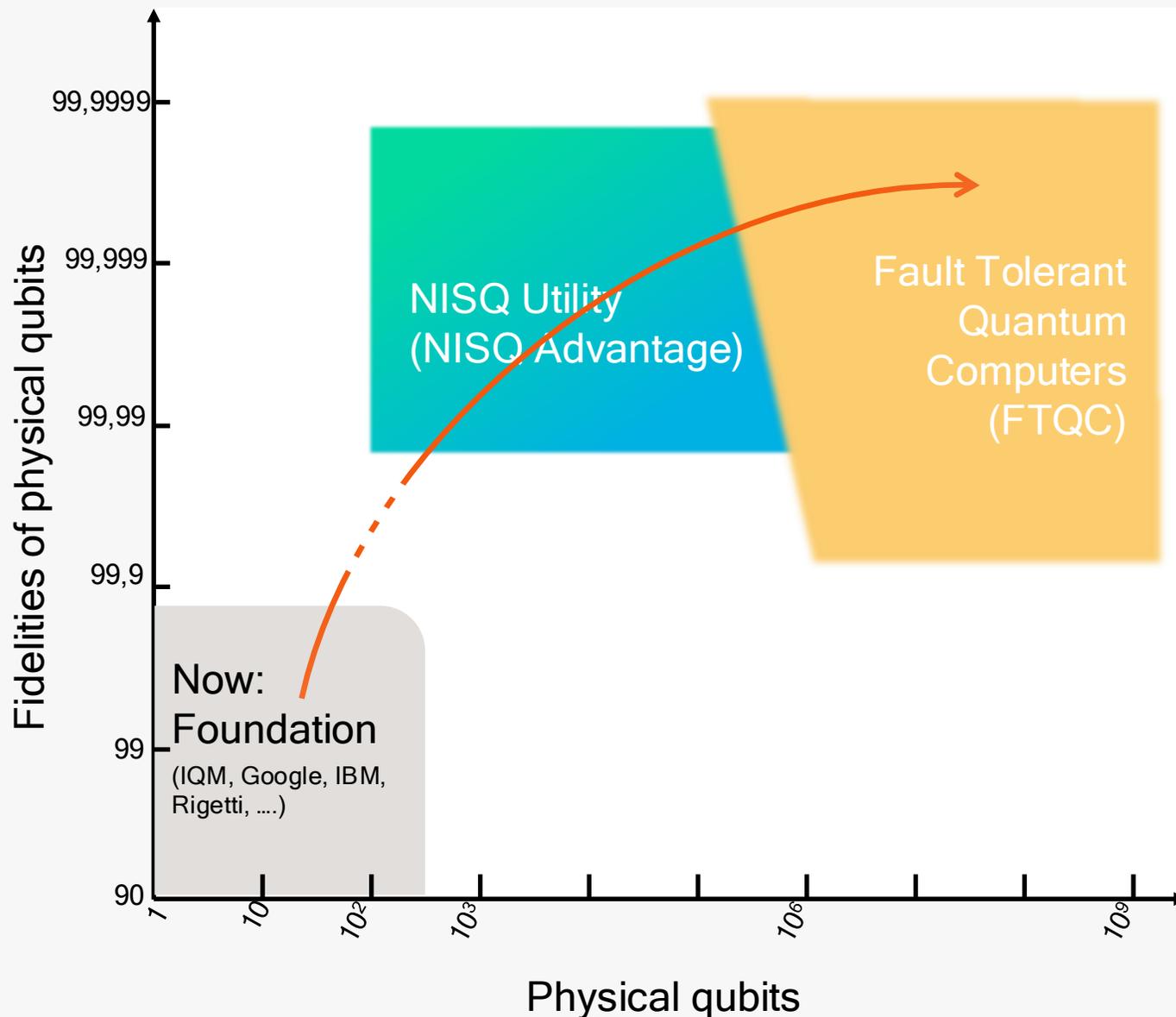
Why so complex?

- Error correction is based on redundancy
- 1 single fault tolerant qubit requires multiple physical qubits
- Noise needs to be reduced below a certain threshold



NISQ and FTQC

- Horizon: Fault Tolerant (FT) area
- But before that: NISQ Utility (NISQ Advantage)
 - Hybrid approaches
 - Potential for NISQ quantum utility
 - Solving tasks
 - faster,
 - better,
 - or using less energy



**Thank you for
joining!
See you tomorrow**
