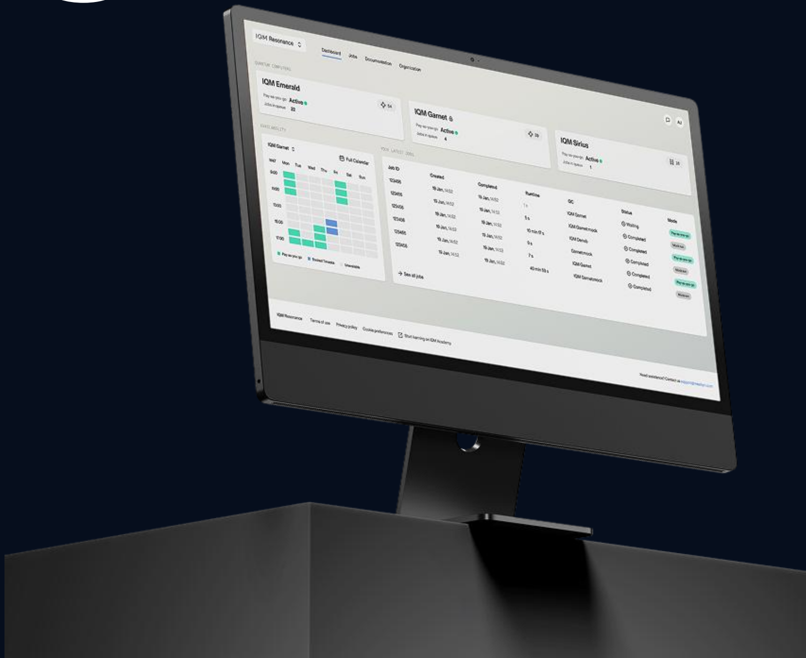
IQM Autumn School - Day 3

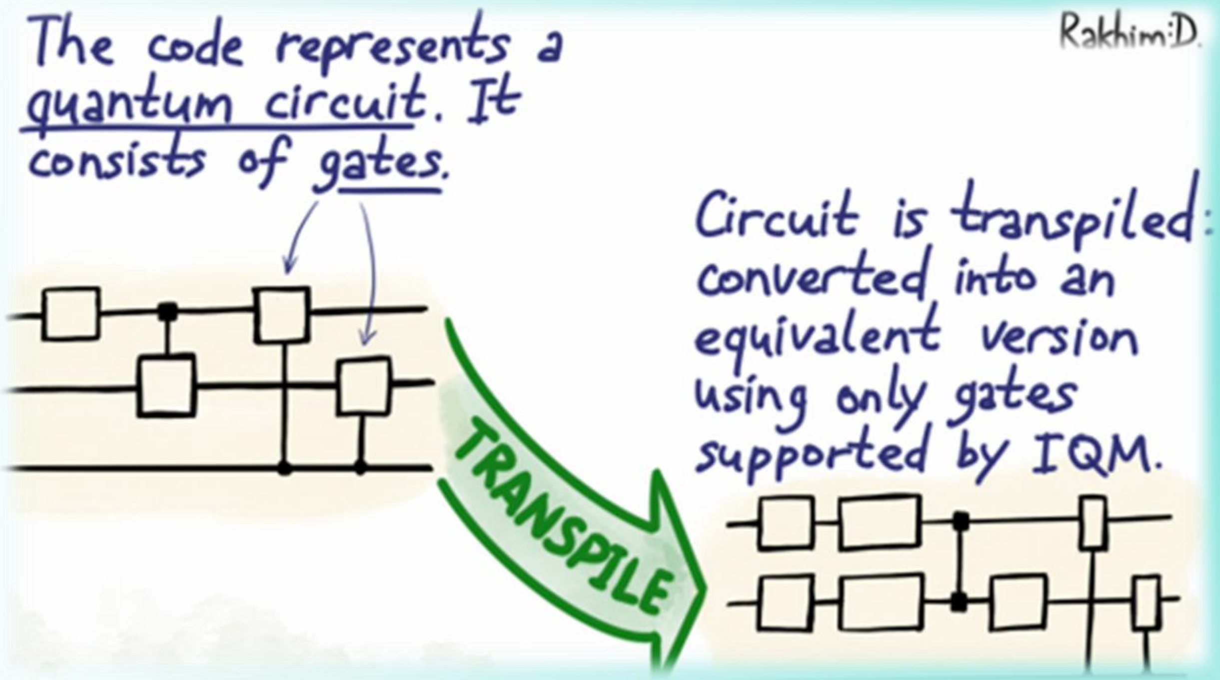
Daniel Bulmash, Niklas Steinmann and Nadia Milazzo



Transpilation

What happens on a real quantum computer?

Transpilation



⇢ **Transpiling** describes the process of converting a quantum circuit into an equivalent quantum circuit that is compatible with a specific quantum hardware's constraints and gate set.

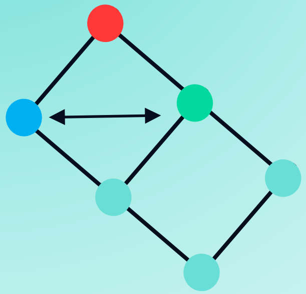
Circuit routing

Routing (= solving QPU connectivity constraints)

- Quantum algorithms assume arbitrary, even all-to-all connectivity
- Connectivities of QPU's are usually limited to nearest neighbor graphs
- Solution: dynamically remap **logical qubits** ("qubit 1" in the program") to the graph of **physical qubits** ("qubit 1" on the physical hardware) with SWAP gates

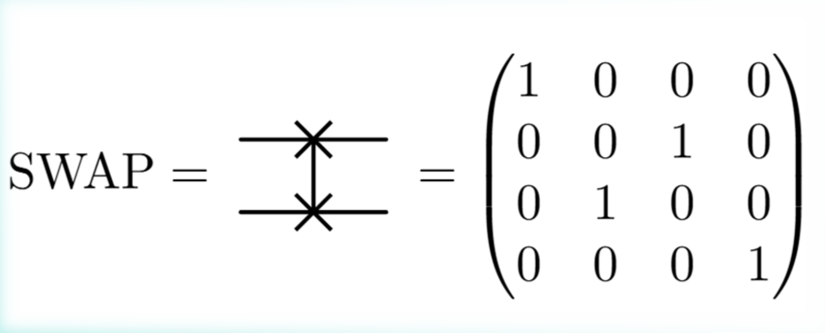
Algorithm's connectivity

QPU's connectivity



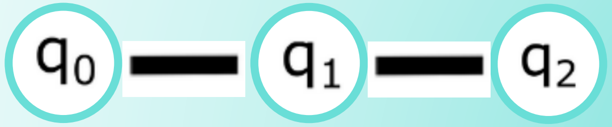
Dynamical remapping

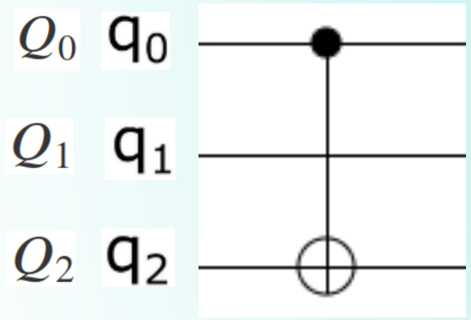
Routing example



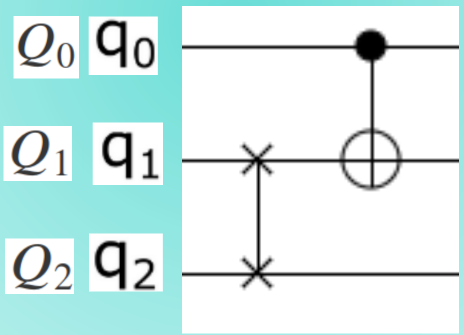
SWAP gate swaps the states of two qubits

Consider the following connectivity:



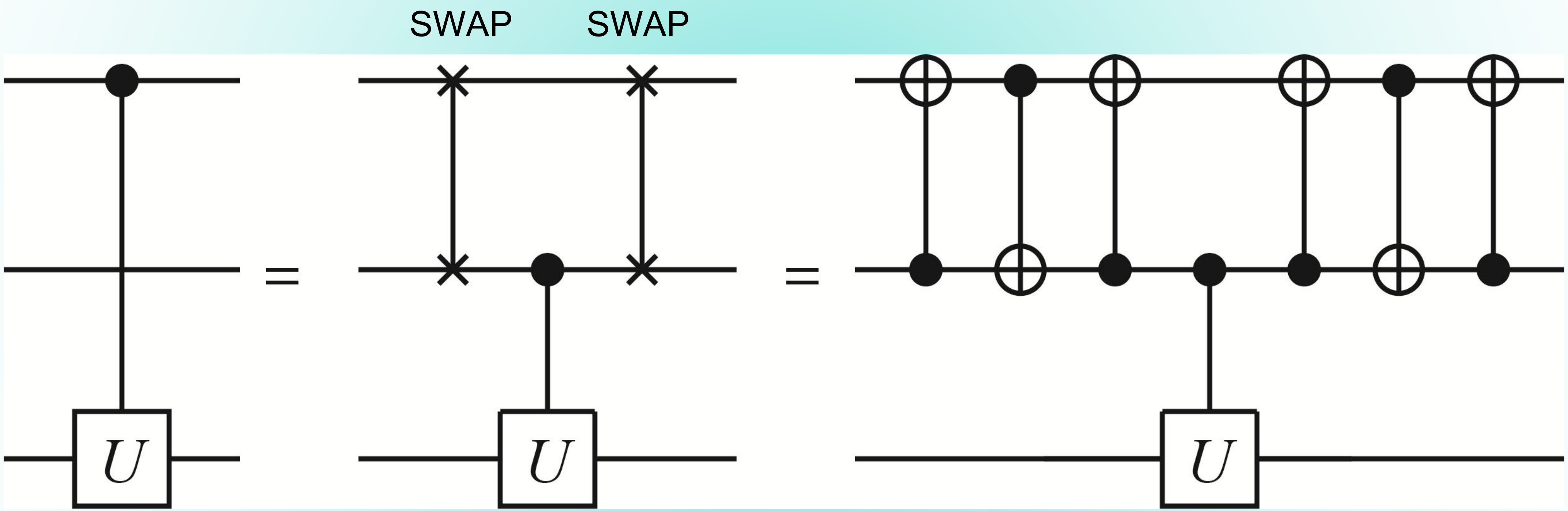


Routing incompatible operation



Routing compatible operation

SWAP is expensive!



Gate decomposition

Implementing gates on a QPU

- We need to be able to implement *any* unitary operation on our quantum computer. But not all operations are simple on all hardware.
- The set of simple gates used on a *specific* quantum device is called the native gate set of the device.
    - All operations must be rewritten as a sequence of native gates.

IQM systems support arbitrary X and Y rotations as the native single-qubit gates and CZ as the native two-qubit gate.

Exercise

- Imagine your QPU's only native gates are X gates on each qubit. Find a gate you can't implement on your QPU.
- Repeat the above if your native gate set also includes Y gates on each qubit.
- Repeat the above if your native gate set includes arbitrary rotations about the x and y axes on each qubit.

Universal gate set

- We need to be able to implement *any* unitary operation on our quantum computer. But we need enough native gates to do that.

- Our native gate set should be universal. What does that mean?

A set of gates S is said to be universal if **any** unitary operation can be approximated to any desired precision by composing only the gates in the set S.

Universal gate set

A universal set of gates for quantum computing can:

- Create superposition of states
- Create entangled states
- Contains gates with real AND complex entries
- Contains more than the "Clifford group"

Special quantum circuits which can be efficiently simulated by a classical computer.
To read more: "Gottesman-Knill theorem"

Universal gate set

Is there only one universal set of gates? If so, we'd be forced to use hardware with a very specific set of native gates...

No, there exist different universal gate sets, such as:

$\{CNOT, H, S, T\}$

$\{CZ, R_x(\theta), R_y(\phi)\}$

$\{H, TOFF\}$

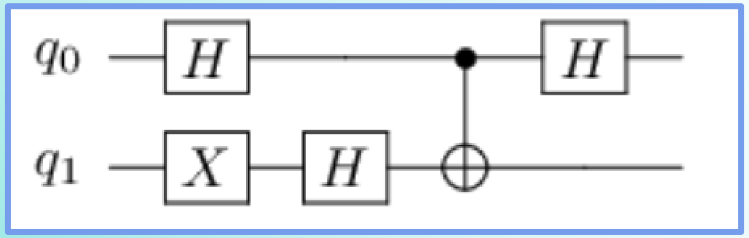
$S =$ *phase gate*
$T = \pi/8$ *gate*

$TOFF =$ "*Toffoli gate*"

Decomposing (= writing a gate a series of native gates)

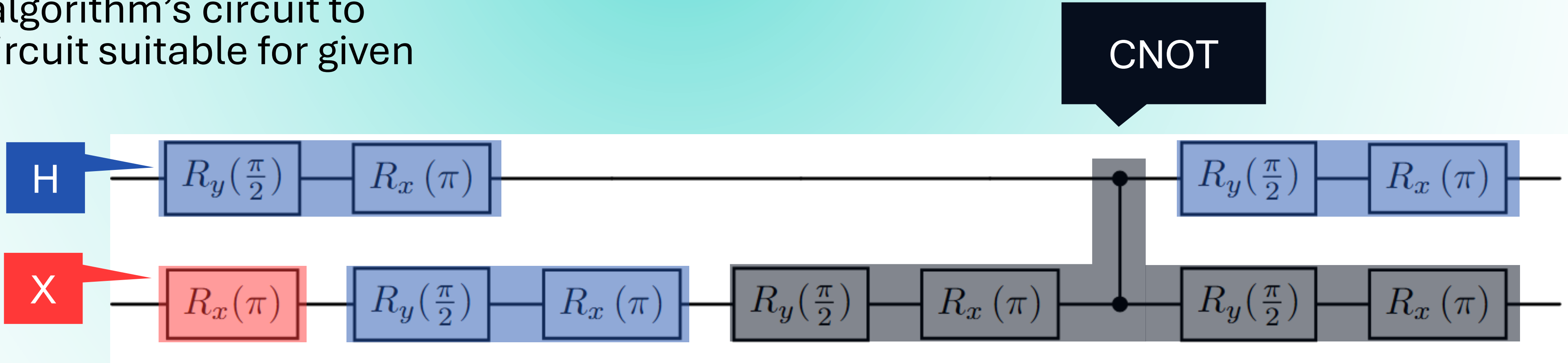
- Circuits of quantum algorithms usually use 'intuitive' gates like CNOT, X, H, P, SWAP
- Real QPU's use only few *native,* hardware friendly gates to process their qubits
- Solution: gate identities can convert the algorithm's circuit to equivalent circuit suitable for given QPU

Circuit for Deutsch's algorithm with CNOT as the oracle



Example QPU native gates

$\{R_x(\theta), R_y(\phi), CZ\}$



Redefining more precisely...

Transpiling = routing circuit to connectivity of a QPU and decomposing gates to its native gates

Attendance link for today

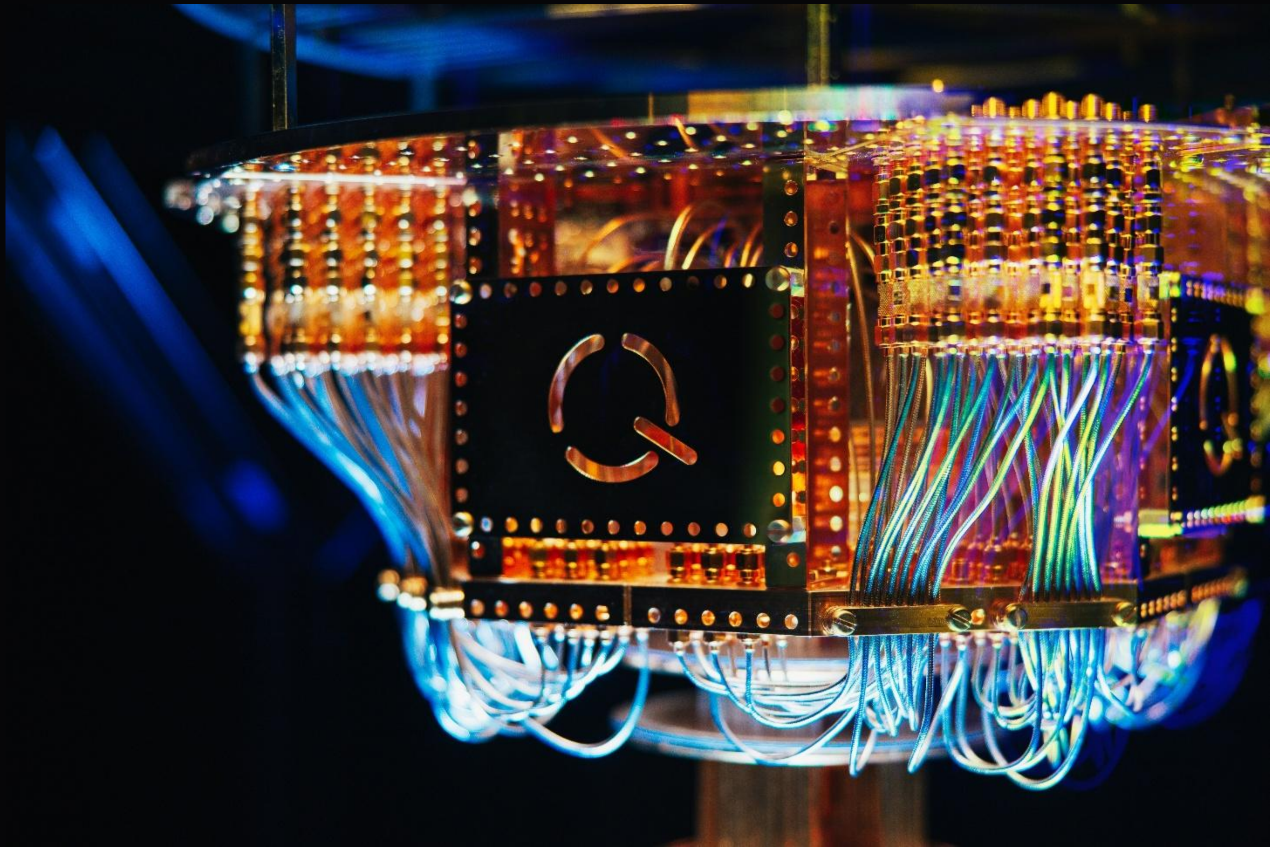
https://tinyurl.com/bdd57ksd

Lab – part 1

Please don't worry about debugging everything during the lab session! It will be more useful to follow along and debug later on your own.

https://tinyurl.com/QS2026Day3-Lab1-participant

Part 2 – From Abstract Code to Physical Pulses



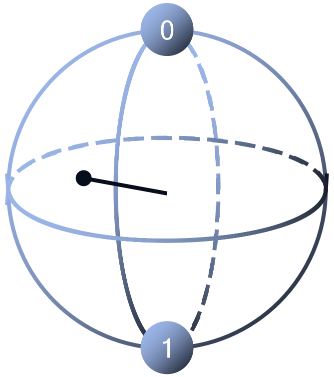
IQM Quantum Computers, Built for Real Impact

Introduction

In the past days, you have become familiar with how **a single qubit** behaves…

Quantum bit

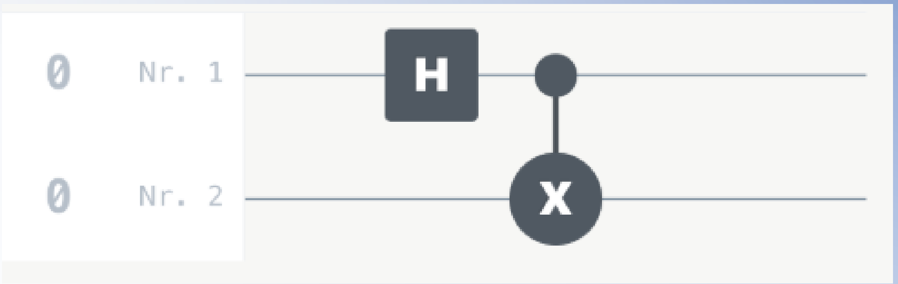
Superposition of
2 basis states

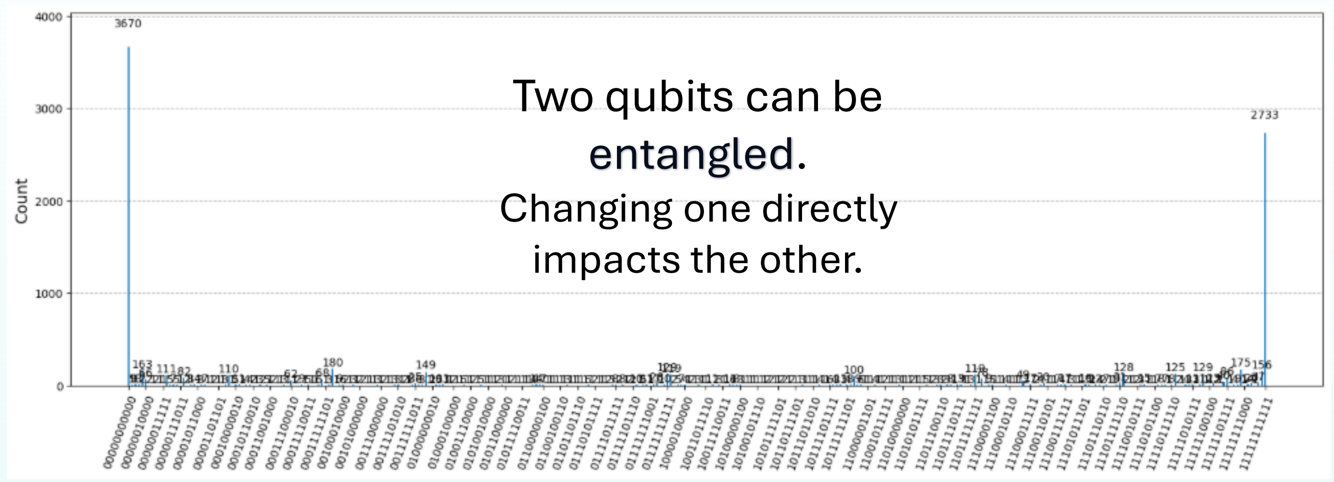


Point on the surface of a sphere

Measurement of the state will cause it to 'collapse', no repeated measurement

…what **many qubits** together can do:





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

Introduction

But would you know how a qubit **looks like**?

Photon

Electron

Atom

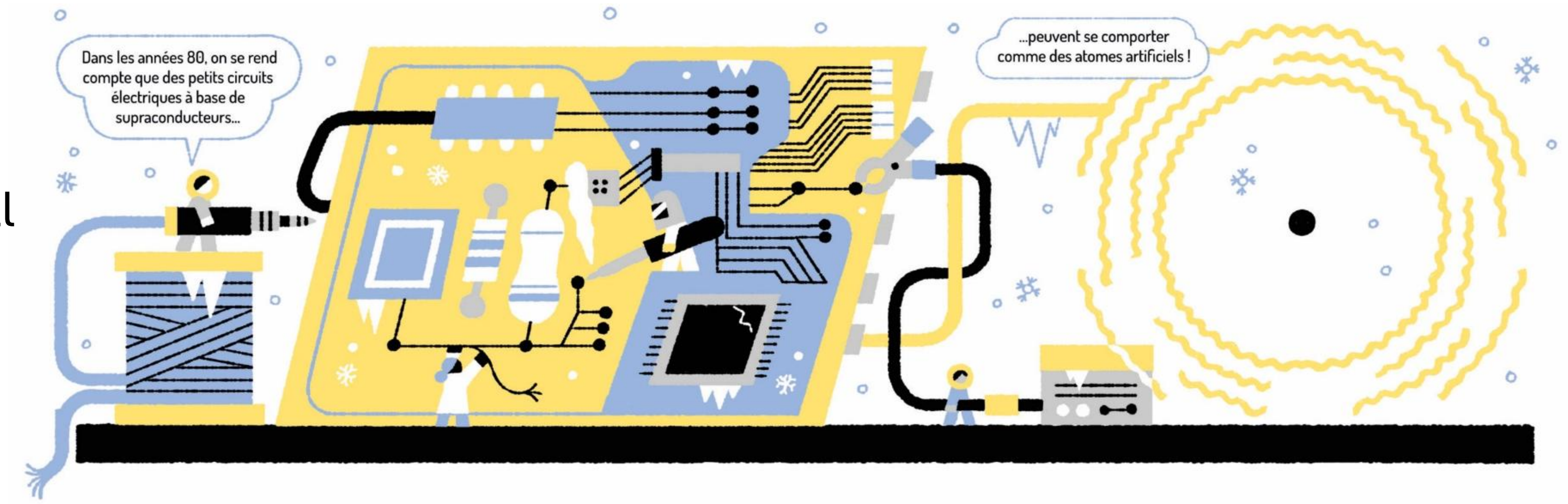
”Artificial atom”

All these platforms can be used as qubits, and there are even more out there!

Superconducting qubits

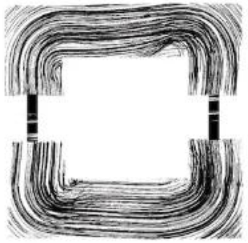
Some metals at **low temperatures** conduct electric current perfectly, without any resistance: they are called **superconductors.**

In the 1980s it was discovered that small circuits with superconducting elements..



...they could behave like **artificial atoms**

The superconducting qubit was born!

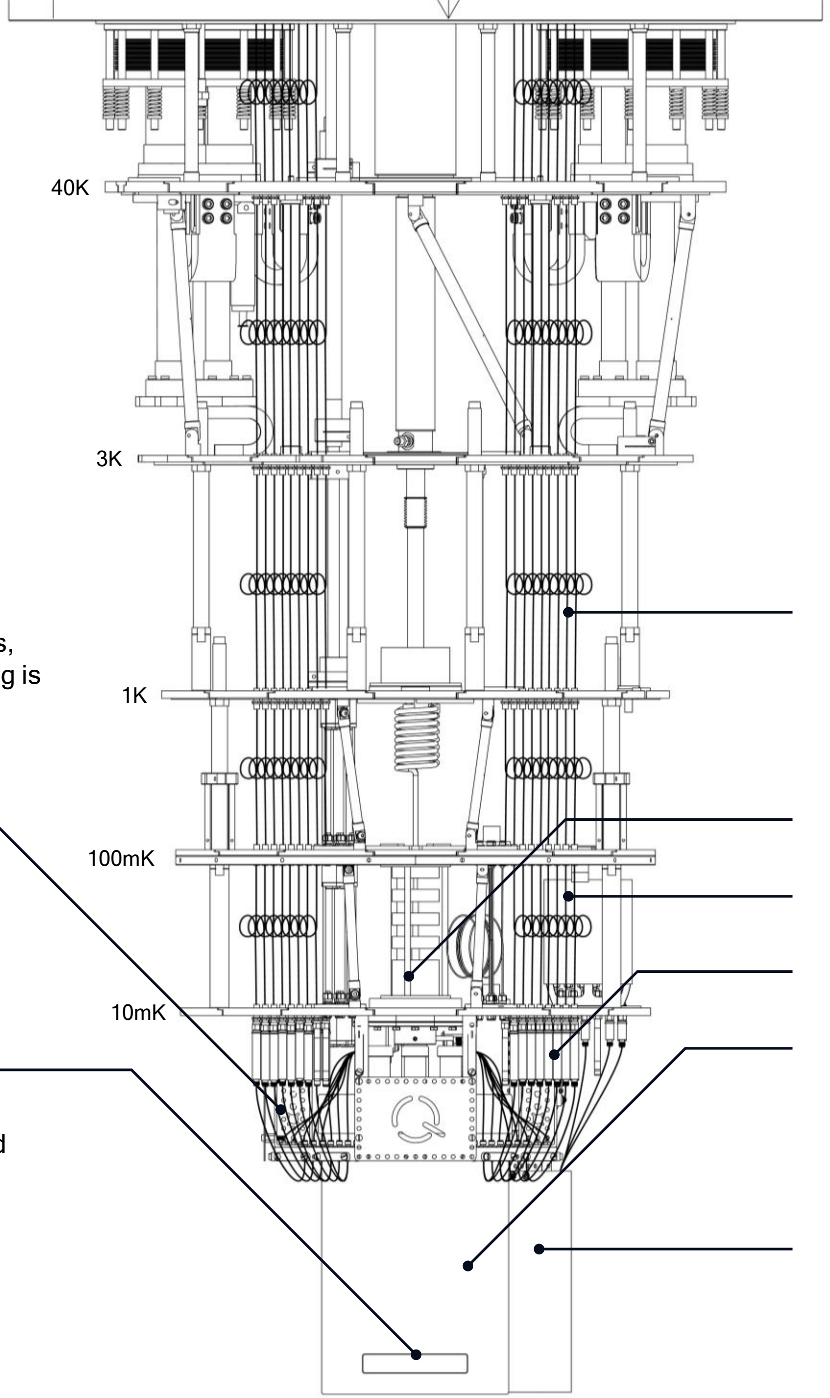


Source: La physique autrement

And after **some** years...

Superconducting quantum computers are here!

Inside look: Superconducting quantum computer



Cryogenic cooling process

Superconducting quantum computers must be kept at extremely low temperatures, typically close to absolute zero, to maintain the superconducting state. This cooling is achieved using advanced cryogenic systems, using liquid helium.

Microwave coaxial cables

These cables (some are superconducting)
direct microwave pulses to and from the QPU. These signals enable the control and readout of the states of individual qubits and turning on/off interactions between qubits for logical operations.

Quantum Processing Unit (QPU)

This is the ‘heart’ of the quantum computer. Here the chip contains interconnected quantum bits that perform calculations based on the laws of quantum mechanics. Fundamentally, the qubits utilize superposition and entanglement as computing resources for information processing.

Microwave signal lines

Mixing chamber

Shielded microwave isolators

Filters

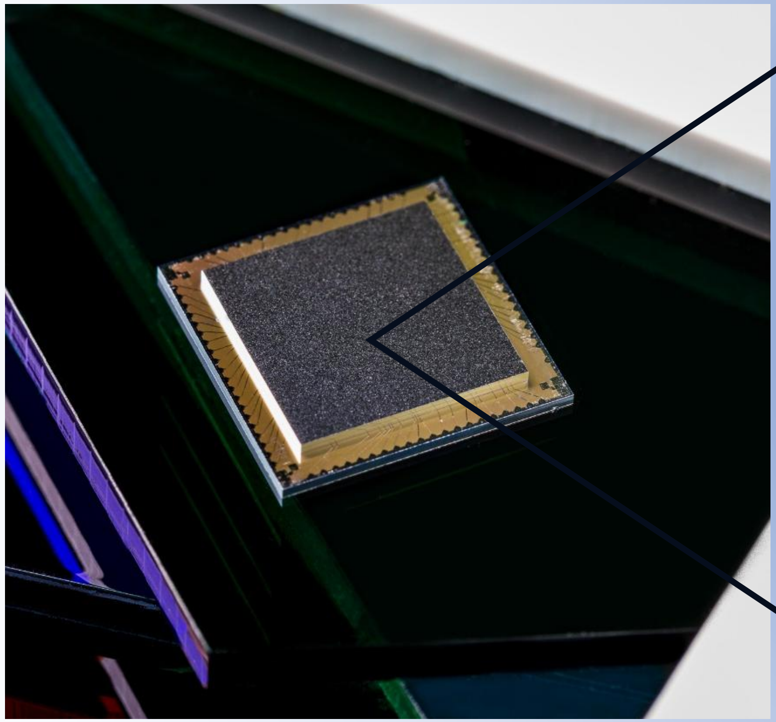
Magnetic shields

Magnetic fluctuations interfere with the qubits. Shielding is necessary to maintain the quality of the quantum processor.

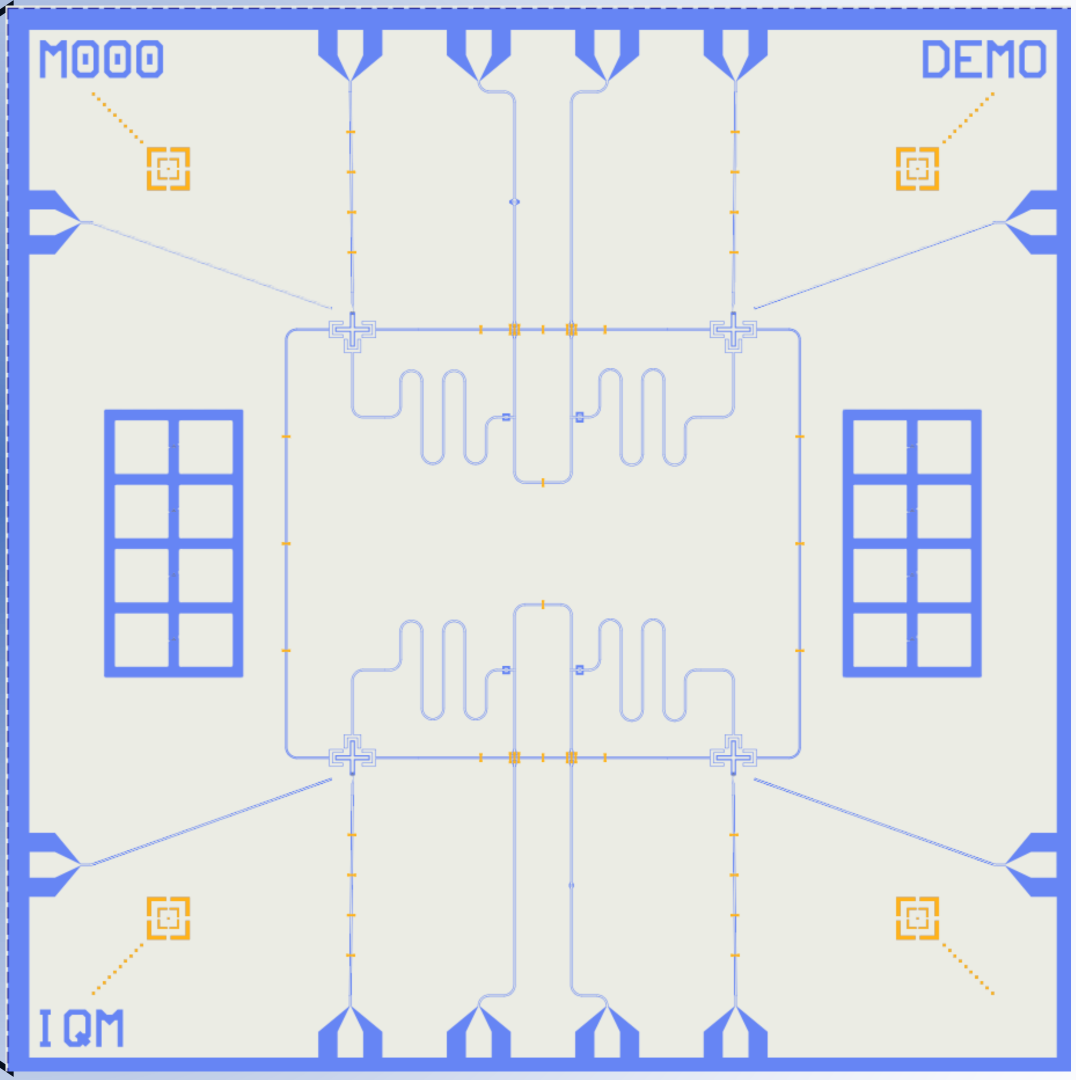
Magnetic shields for the quantum limited amplifier

IQM Quantum Computers, Built for Real Impact

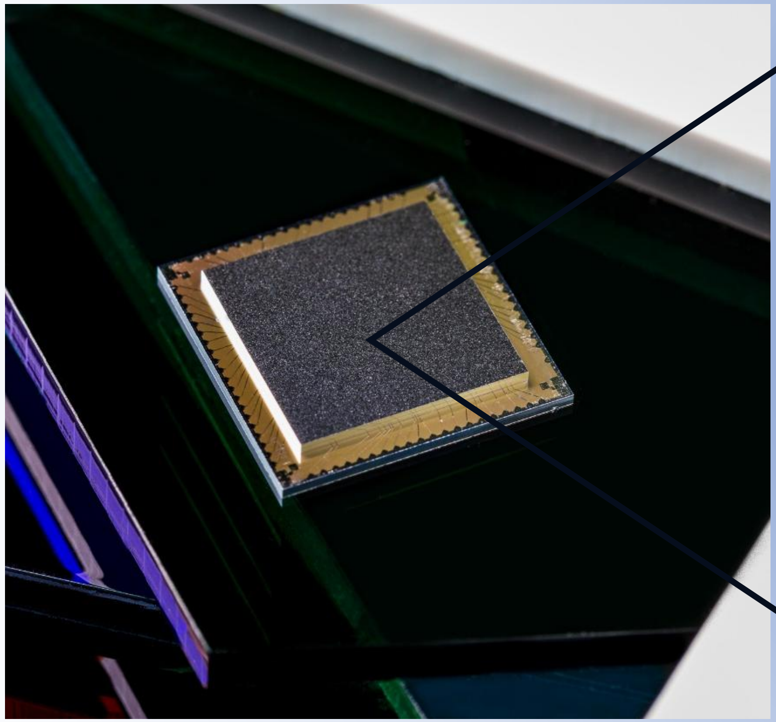
Superconducting QPU



Quantum Processing Unit



Superconducting QPU



Quantum Processing Unit

https://tinyurl.com/iqm-demo-chip

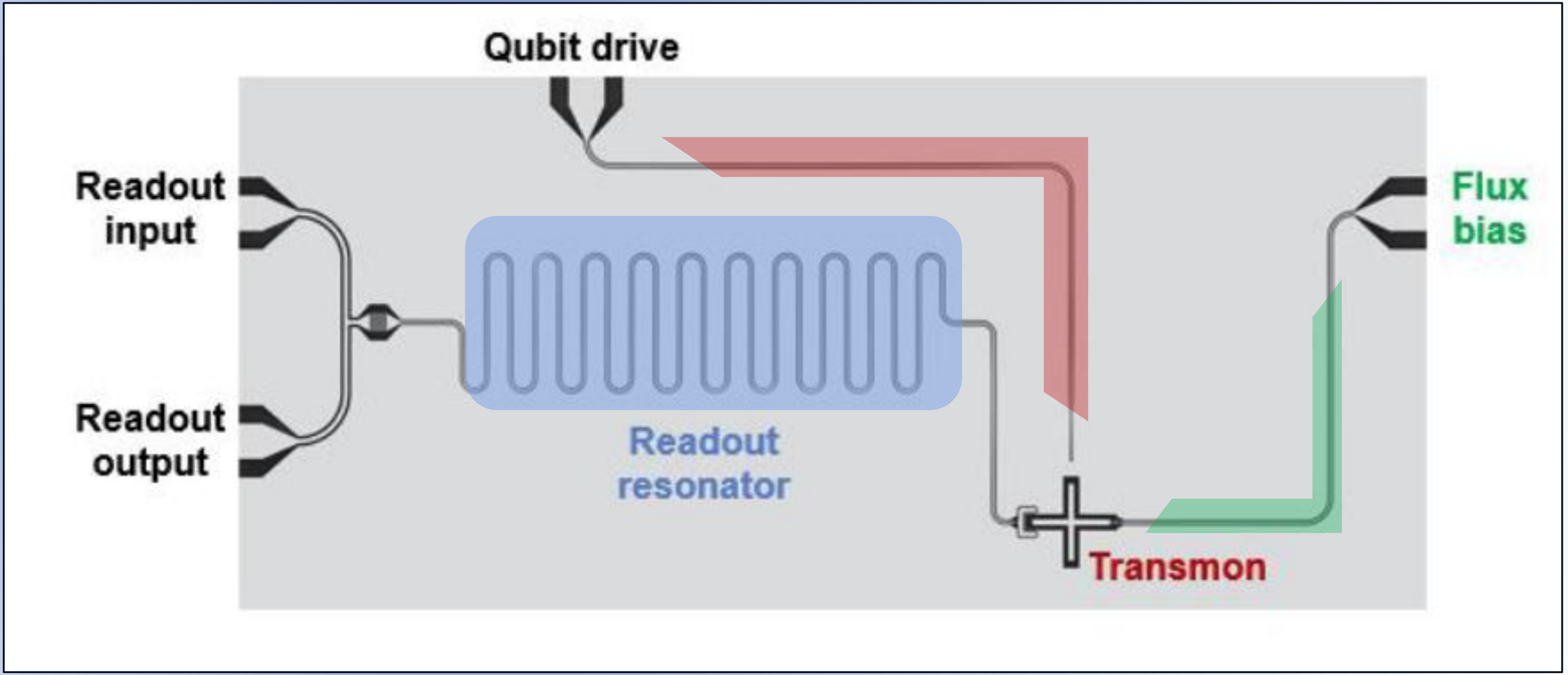
What did we discover about the QPU?

Each qubit has the following controls:

Readout resonators
(Infer qubit state)

Drive line
(Single-qubit gates)

Flux lines
(Controlling qubit and coupler frequency)

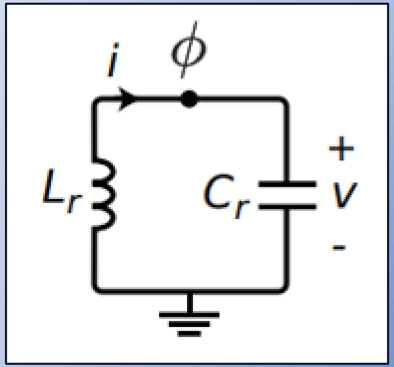


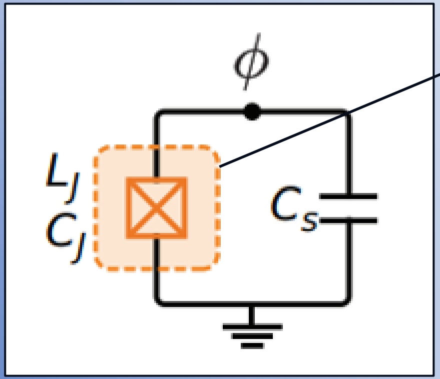
Source: *T. E. Roth et al., The Transmon Qubit for Electromagnetics Engineers: An introduction, in IEEE Antennas and Propagation Magazine, vol. 65, no. 2, pp. 8-20, April 2023*

Source: *P Krantz et al, A quantum engineer's guide to superconducting qubits, Applied Physics Reviews 6, 021318 (2019)*

Superconducting qubits

Superconducting electronic circuits



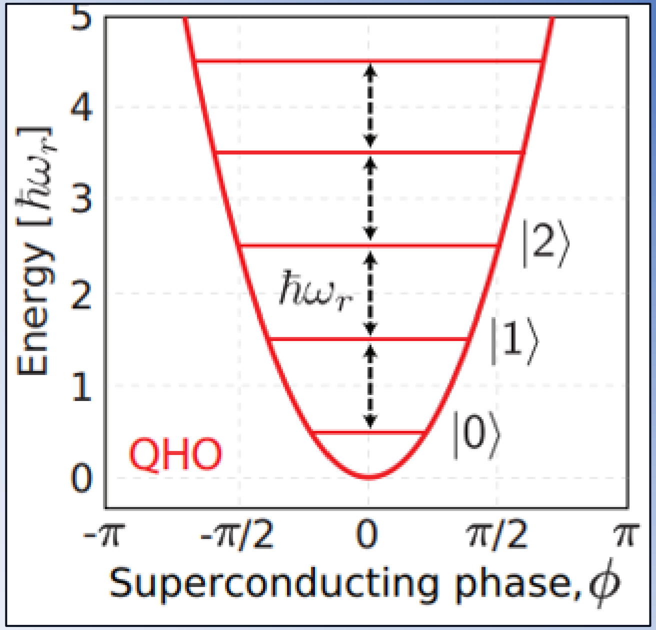


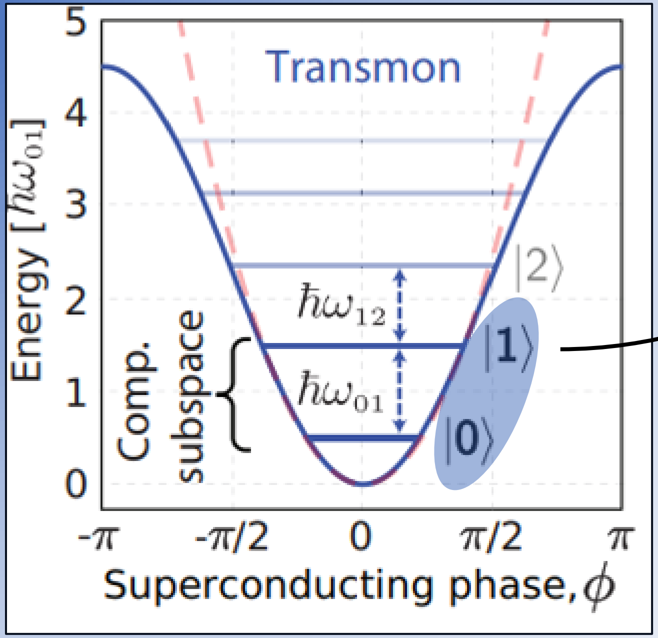
Josephson junction

(creates **nonlinear** inductance)

Anharmonic oscillator: **nonuniform** spacing between energy levels

Energy spectra of corresponding Hamiltonian





2-LEVEL SYSTEM

How to manipulate superconducting qubits?

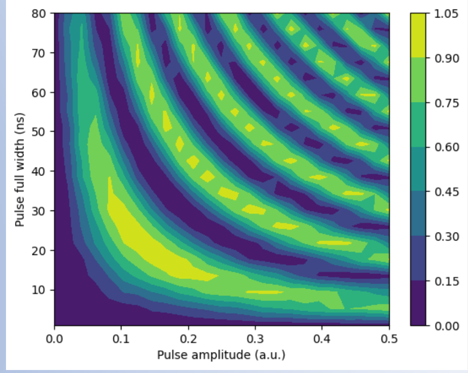
Interacting through pulses

Control of superconducting transmon qubits → **driven by microwave pulses**

$$\hat{H}(t) = -\frac{\omega}{2}\hat{\sigma}_z + \Omega(t)\sin(\nu t + \phi)\,\hat{\sigma}_y$$

constant precession around the Z-axis on the Bloch sphere

Rabi oscillation between |0⟩ and |1⟩



Hamiltonian describing the interaction between the transmon and the pulse (lab frame)

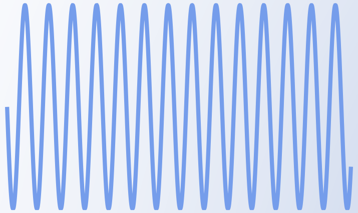
$\omega = \nu$ →

$$\hat{H}(t) = -\frac{1}{2}\Omega(t)\left(\cos(\phi)\,\hat{\sigma}_x + \sin(\phi)\,\hat{\sigma}_y\right)$$

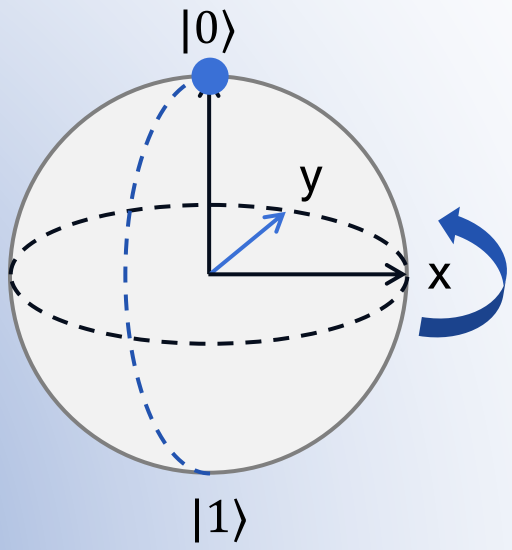
$\phi = 0$ leads to a rotation around the X-axis
$\phi = \pi/2$ leads to a rotation around the Y-axis

Hamiltonian describing the interaction between the transmon and the pulse (qubit frame)

Single qubit gates



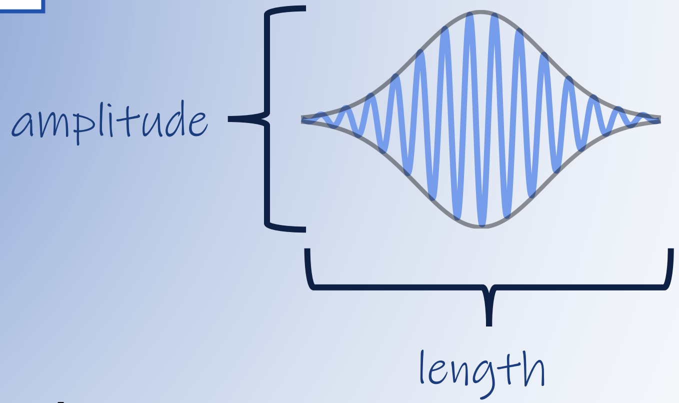
$V\cos(2\pi \nu t)$



Applying AC drive makes qubit state rotate around an axis in XY plane

Example
the **X** gate is an analog of the classical NOT gate, it **flips** the qubit state

We can realize the X gate by applying AC pulse of fixed amplitude and length (***π*** **pulse**)



The angle of rotation on the Bloch sphere is:

$$\theta(\mathrm{t}) = -\mathrm{C}\int_0^t s(t')dt'$$

Superconducting circuit constants

Pulse envelope

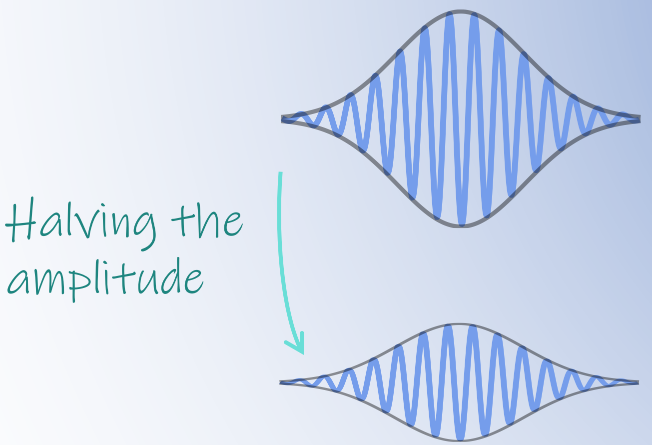
Question: if we have implemented an X gate, how can we get a $\sqrt{X}$ gate?

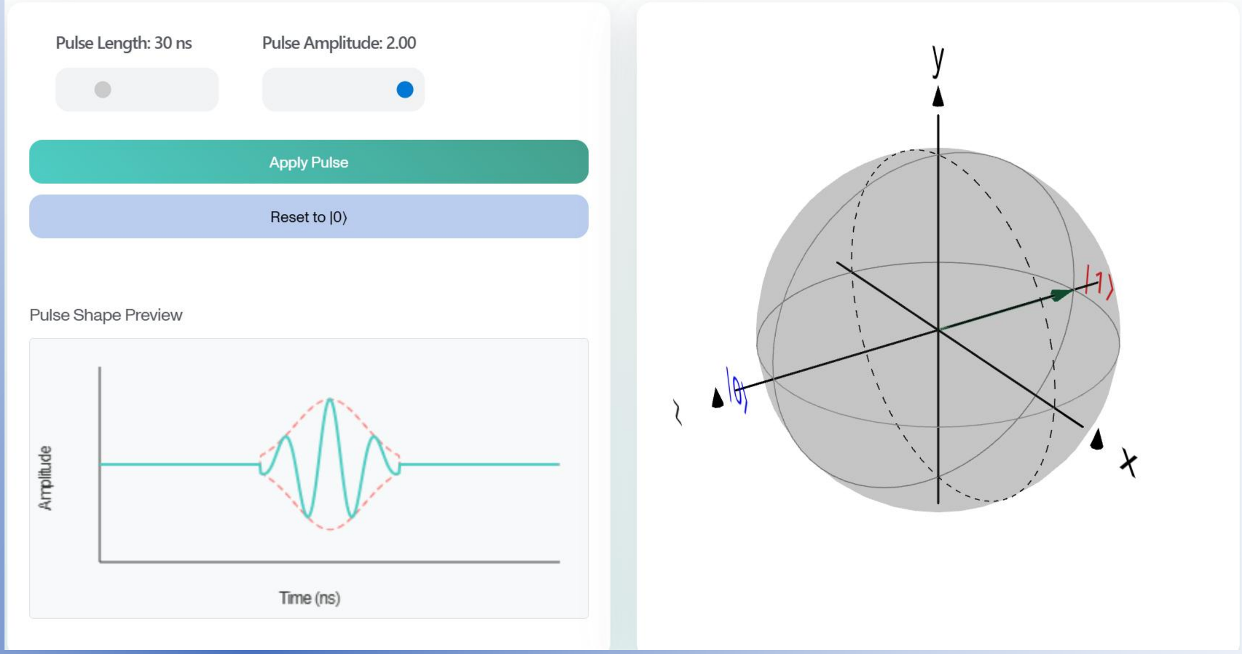
Find your answer playing with pulse amplitude and length here!

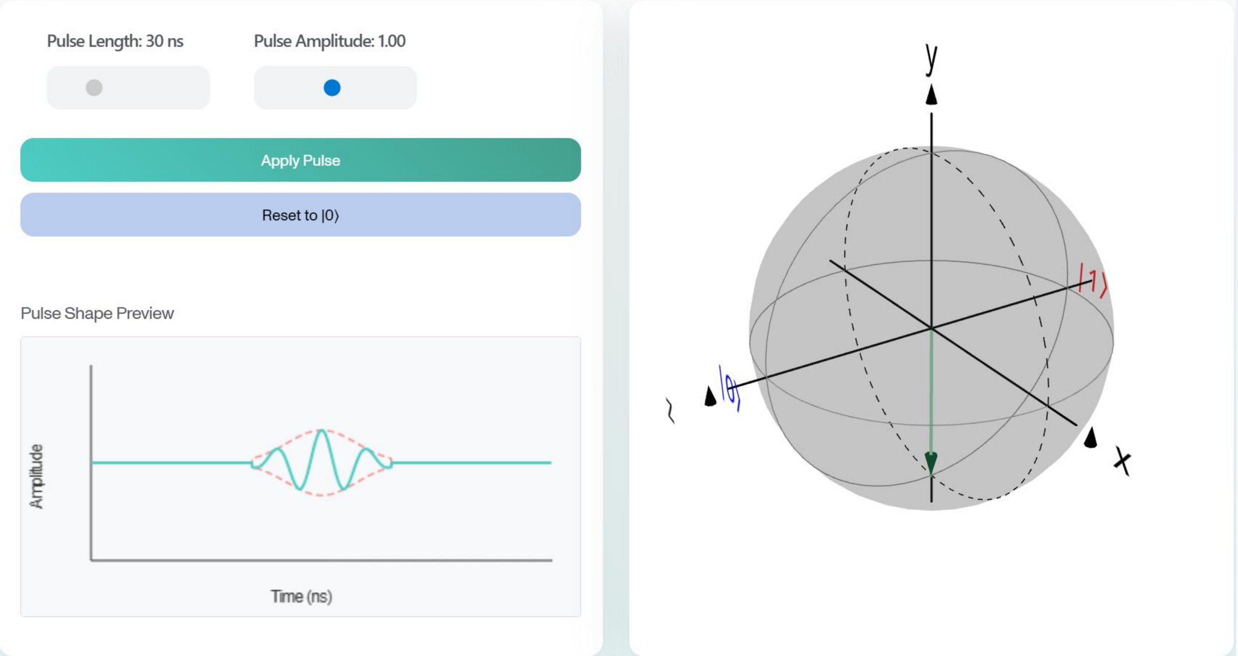
https://tinyurl.com/iqm-bloch-pulse

X gate: rotation of an angle π around the x-axis

$\sqrt{X}$ gate: rotation of an angle $^{\pi}/_{2}$ around the x-axis



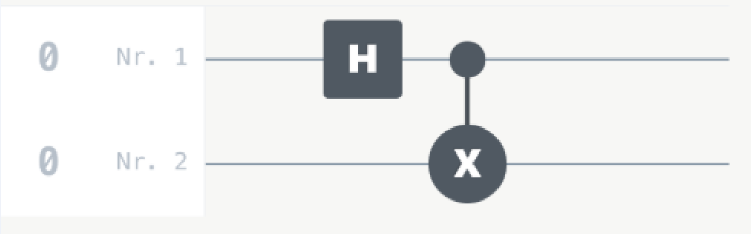




How to do pulse control on IQM quantum computers?

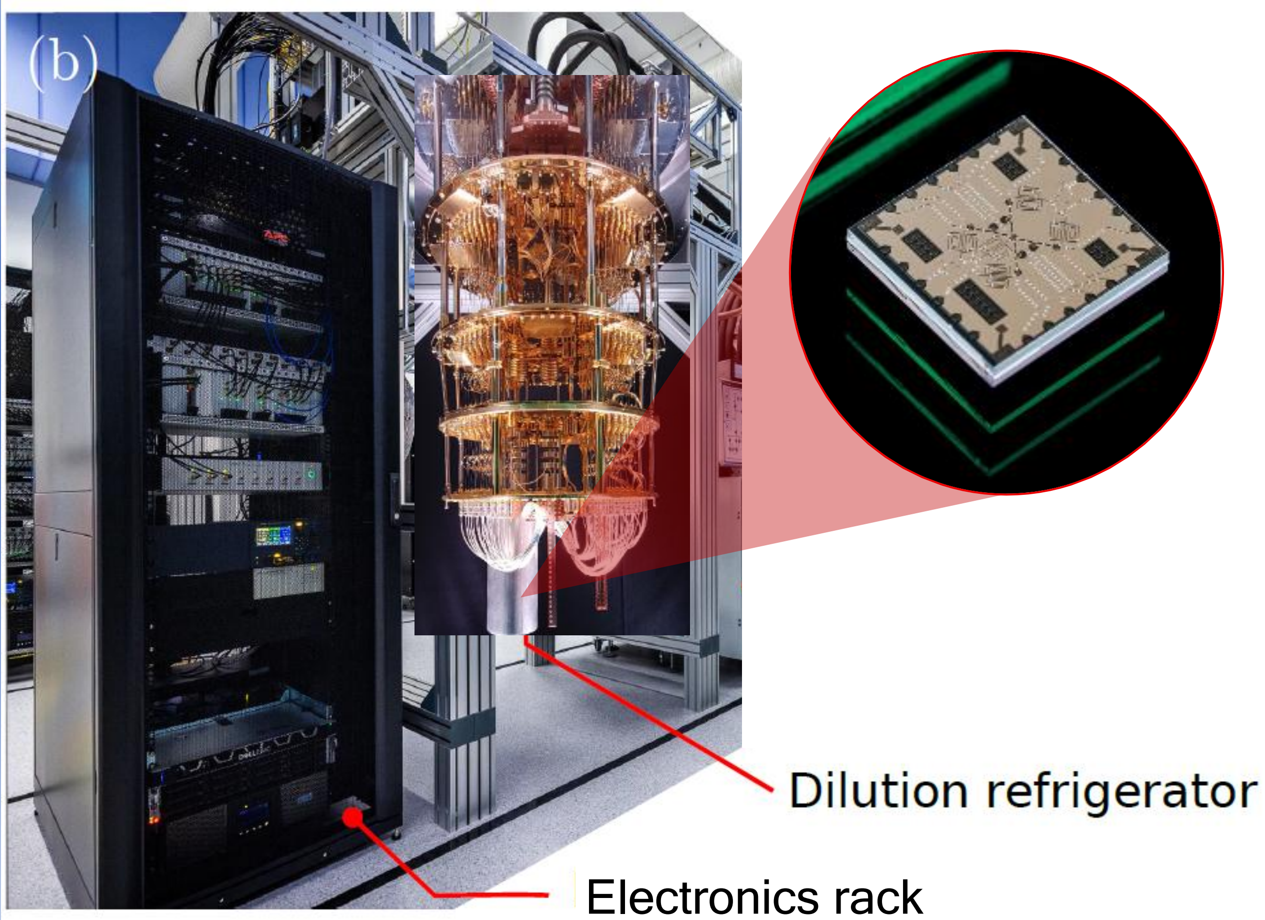
What happened when you pressed the button

Whenever you constructed and ran a circuit...

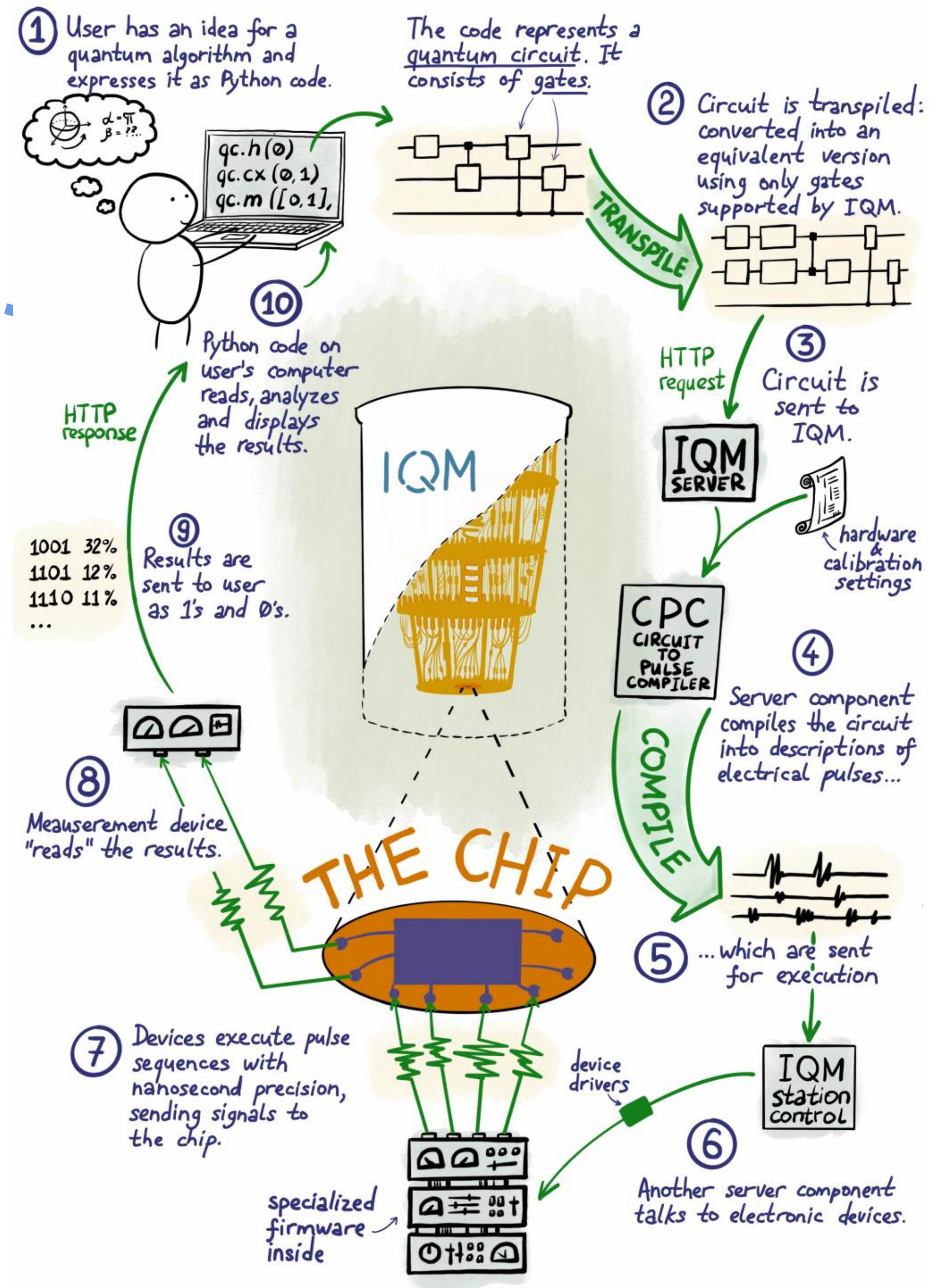


- Your request was compiled by a server into a sequence of pulses
- Control and readout pulses were generated in the electronics rack and sent into the refrigerator
- The pulses interacted with QPU

After that, the measurement device "reads" the results, and you can analyze them on your PC.



From Gates



To Pulses

PulLA package: Pulse Level Access

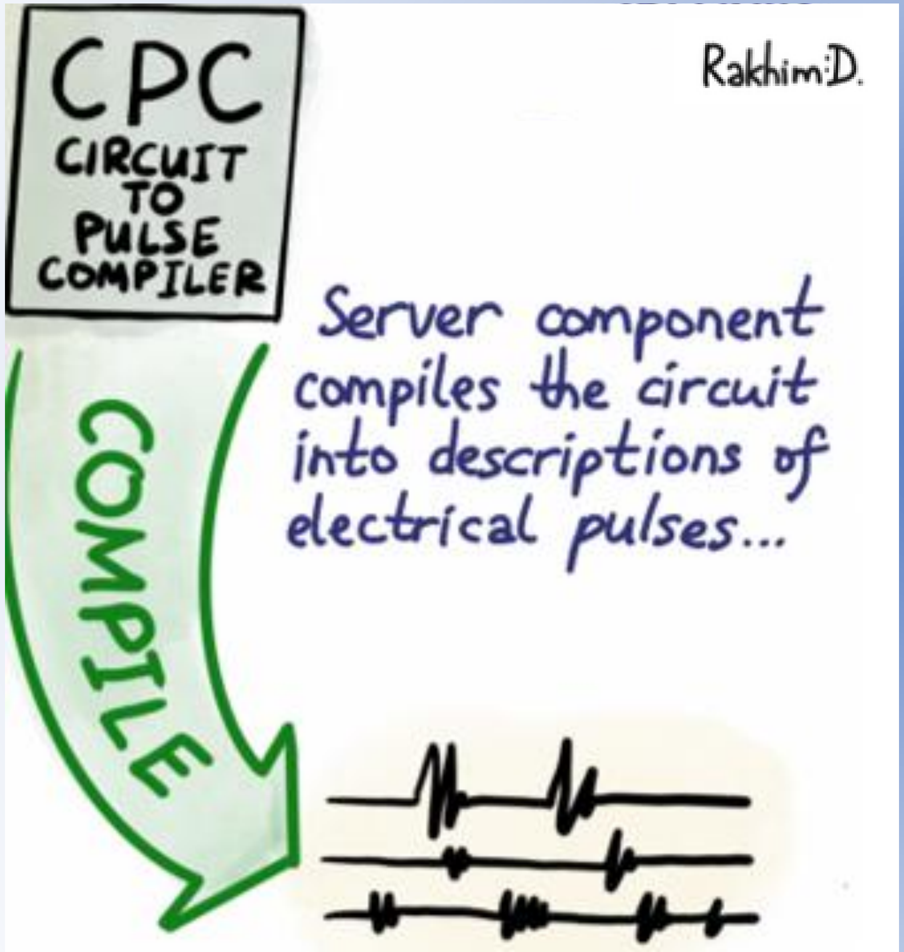
What you can do with it

- Compile a quantum circuit into an instruction schedule on the client side
- Define custom implementations of quantum gates
- Access and modify the calibration data to be used for the circuit-to-schedule compilation
- View and modify the default implementations of quantum gates, using e.g. custom pulse shapes
- Define new composite gates out of native gates and set their calibration data
- Control the multi-step compilation procedure, and edit the intermediate data
- Construct instruction schedules manually

And why you might need it

IQM Quantum Computers, Built for Real Impact

Compilation



A **quantum compiler** translates high-level quantum programs into operation that a quantum processor can execute at the lower level of the **physical** qubits.

Lab time!

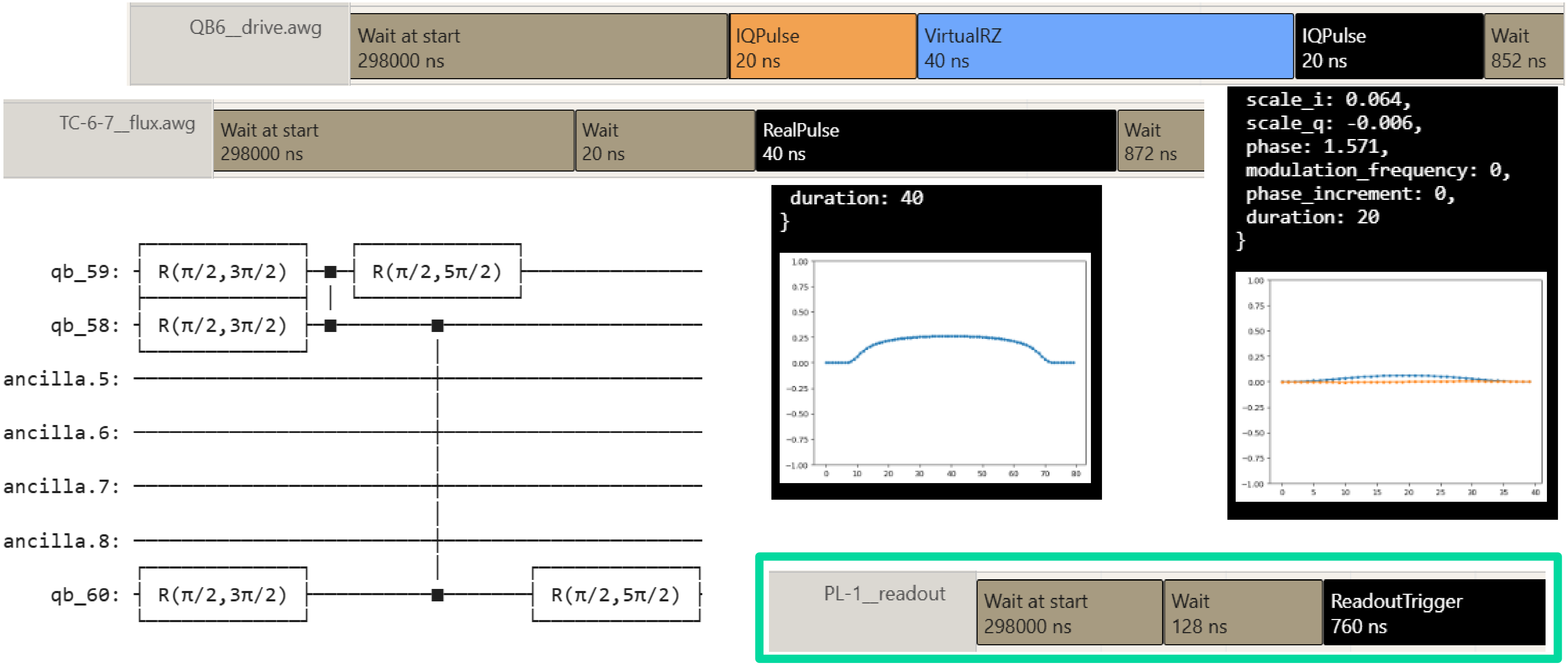
https://tinyurl.com/QS2026Day3-Lab2-participant

Pulse viewer

1. Take the GHZ state preparation seen in the previous labs and **compile it into pulses**!

2. Use the **playlist viewer** from PulLA to visualize the sequence of pulses and inspect the details

Pulse viewer



Readout of superconducting qubits

Calibration

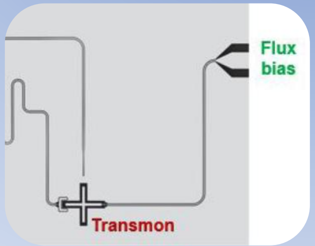
Find the parameters for the QPU control signals that **maximize the performance** of the QPU

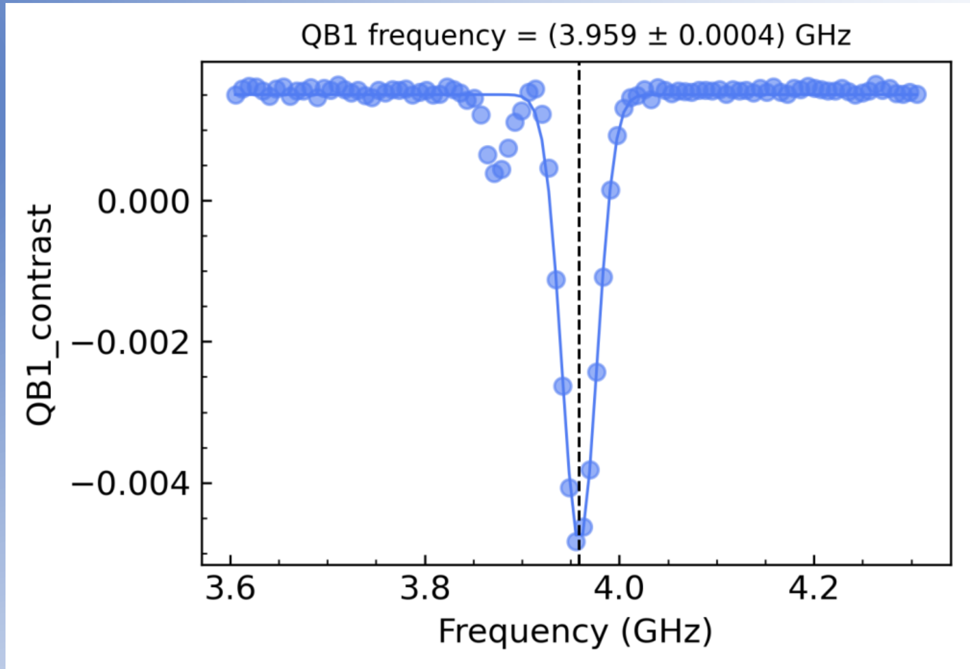
Re-calibration is a (small) subset of the full calibration which we run **periodically** to combat unwanted effects

Example: Find qubit frequency

- We drive the qubit at different frequencies
- We see a signal if we drive at the qubit frequency
- Normally, you don't need that for recalibration!

- Run this experiment, for example, if you have changed the **qubit flux**





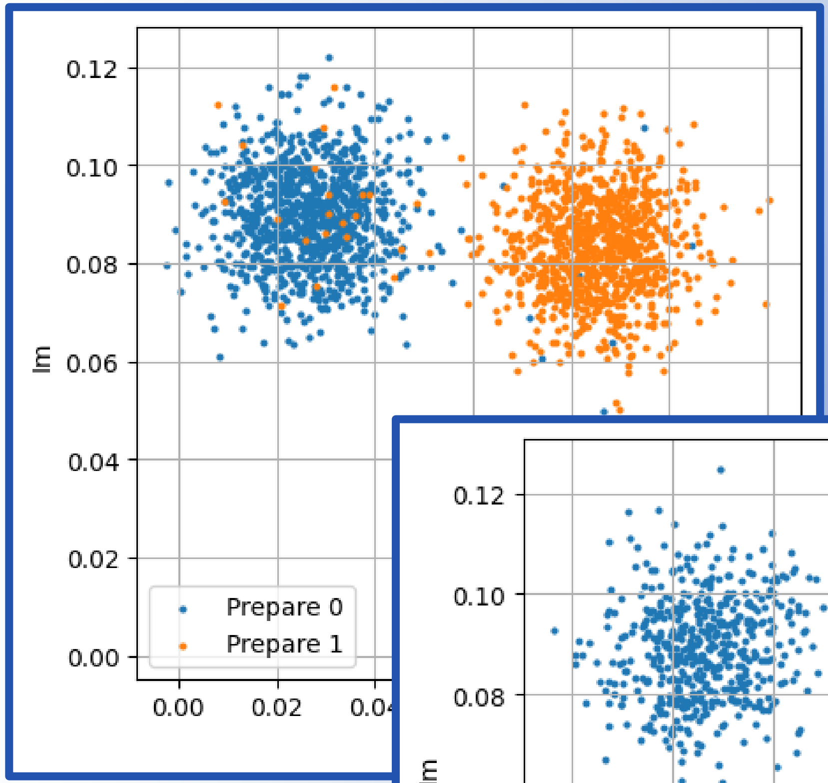
Parameters you care about

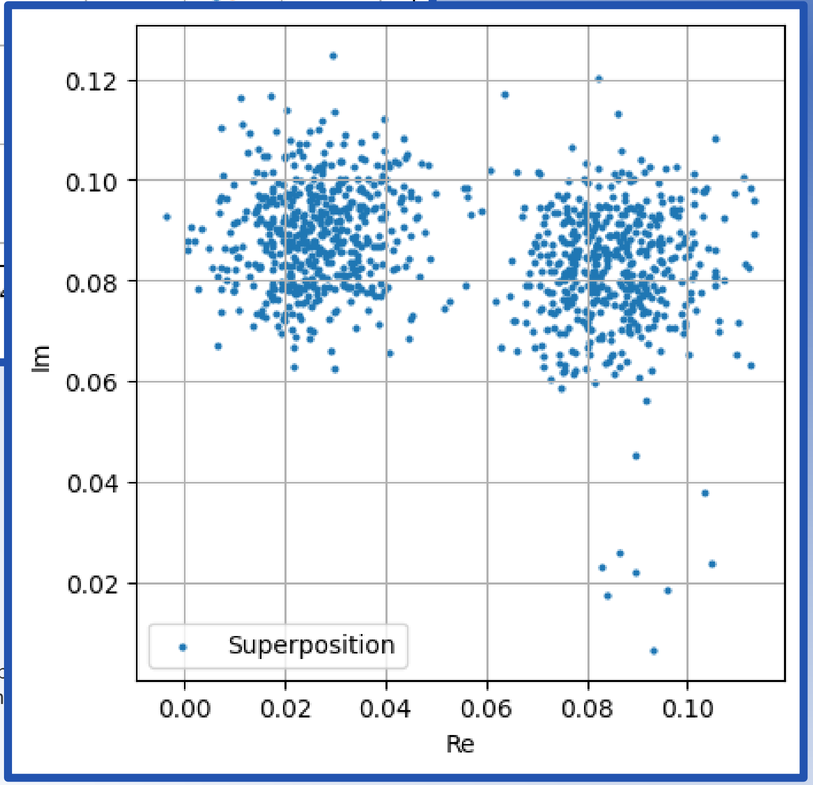
Single-qubit gates	Readout	Two-qubit gates
	Calibration	
Qubit frequency	Readout frequency & amplitude	Coupler pulse amplitude
Drive amplitude	Readout phase	Qubit pulse amplitude
	Readout threshold	VZ phases

Lab time!

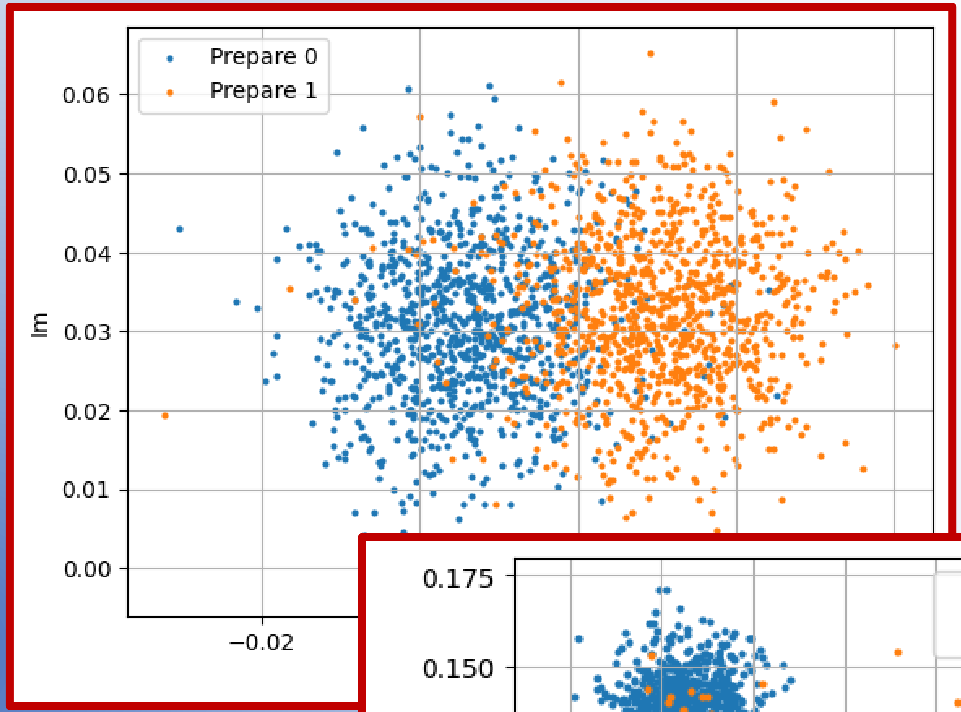
https://tinyurl.com/QS2026Day3-Lab3-4-participant

Results summary

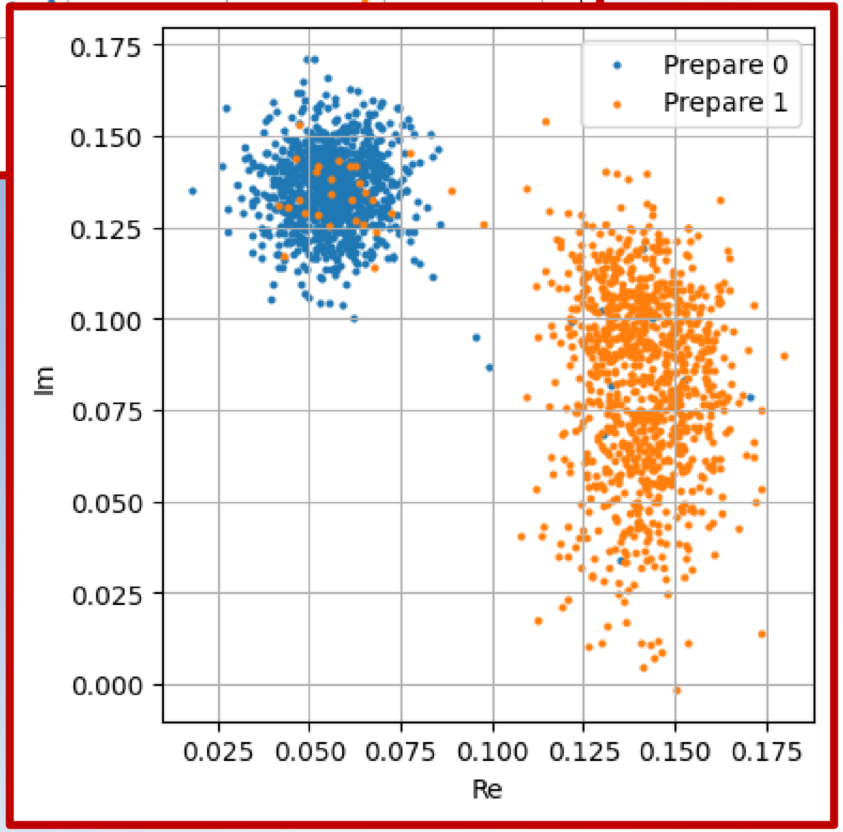




Good calibration



Bad calibration



Homework

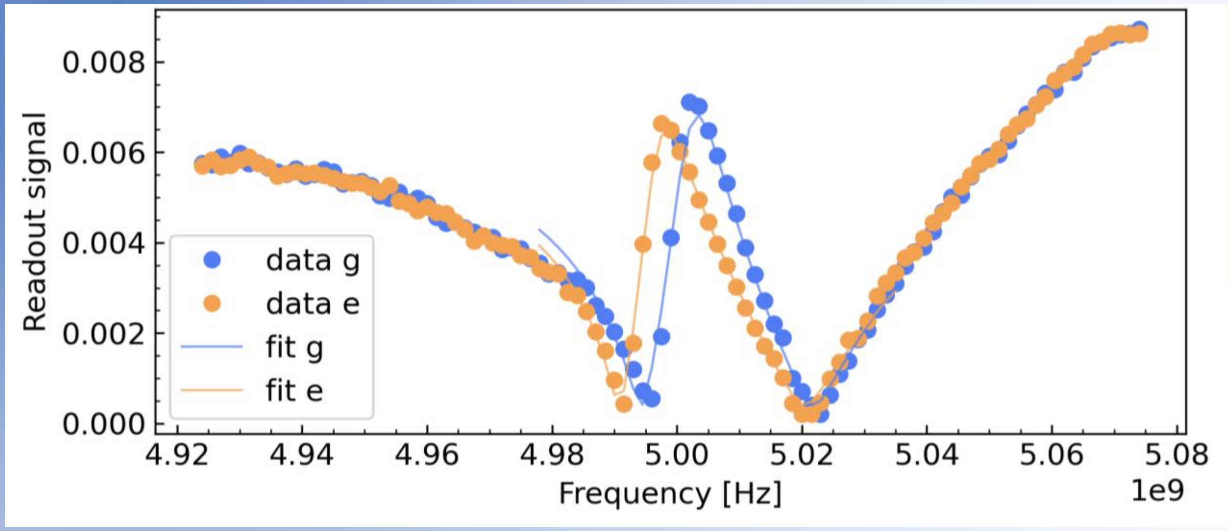
https://tinyurl.com/QS2026Day3-Lab3-4-participant

Dispersive shift

1. Prepare the qubit in the $|0\rangle$ and $|1\rangle$ state and measure

2. Repeat the state preparation and measurement protocol for different frequencies

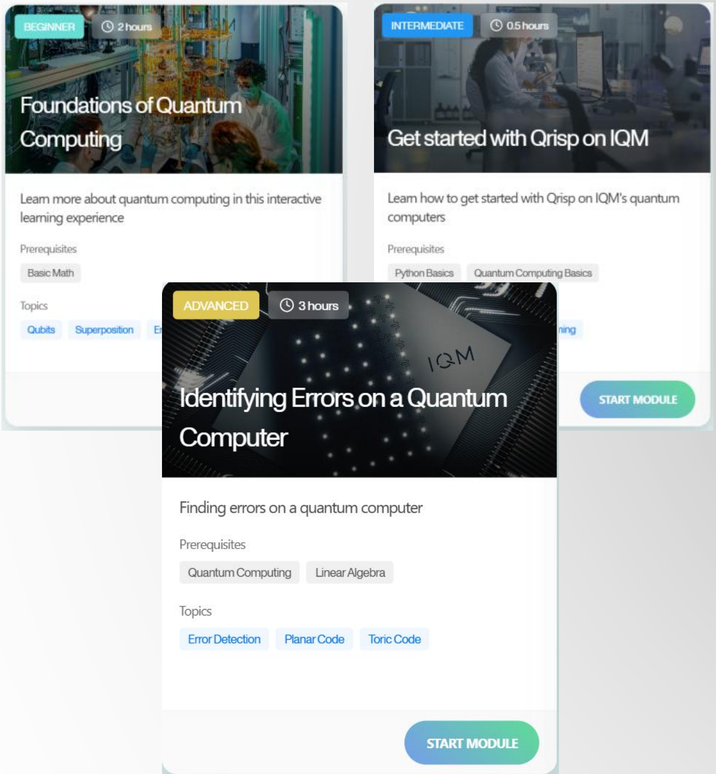
Your results should look similar to this!



What next?

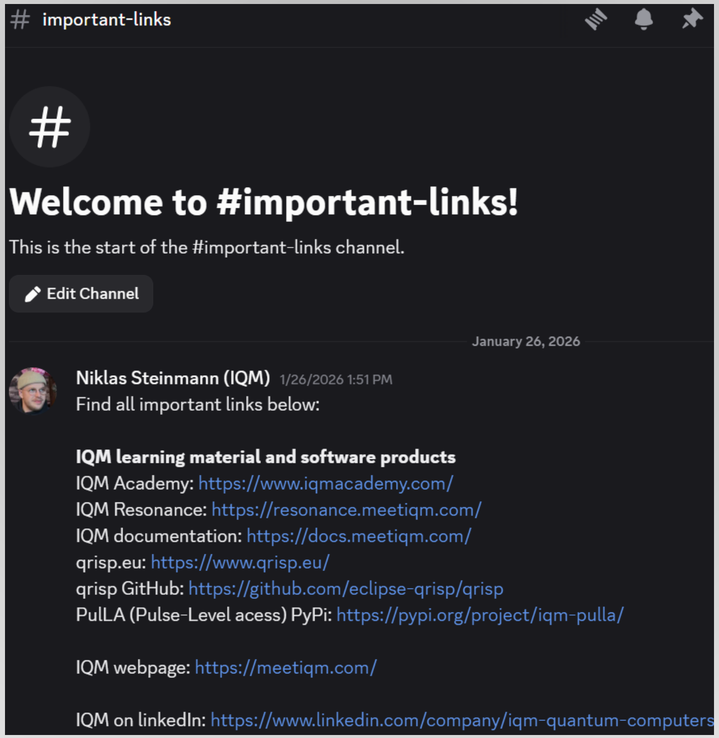
Here are some ideas!

Continue learning on **IQM Academy**



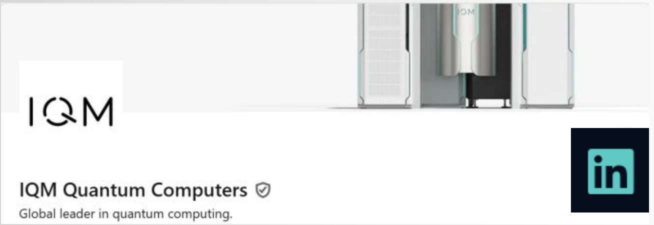
iqmacademy.com

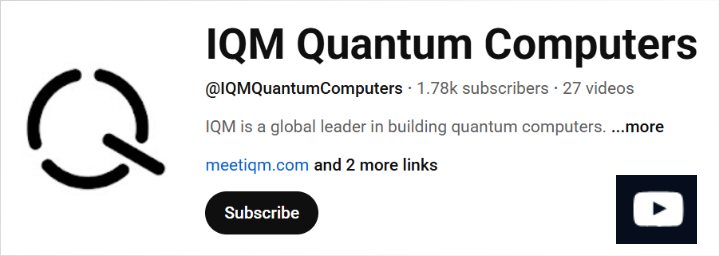
Join the IQM **Discord**



https://discord.gg/F38bwqPYJ4

Follow us on social media for **next events**





Thank you everyone for participating to IQM Quantum School!

Final wrap-up

- Give us a shout-out on LinkedIn!
  - Please tag IQM and us (Daniel Bulmash, Nadia Milazzo, and Niklas Steinmann)
- Recordings will be uploaded to the IQM Youtube channel in the next few days
- Materials (slides, lab links) will be posted to schools.iqmacademy.com in the next few days
- Certificates will hopefully be emailed out next week and shareable directly to LinkedIn.
  - They will either come from academy@iqm.tech or no-reply@certifier.io – both of these are legitimate emails!

We’d love your feedback!

https://tinyurl.com/QS2026Day3-feedback