Universität Basel

NCCR SPIN

Distinguishing the False from the Reasonable Promises of Quantum Computing.

By Pierre Fromholz

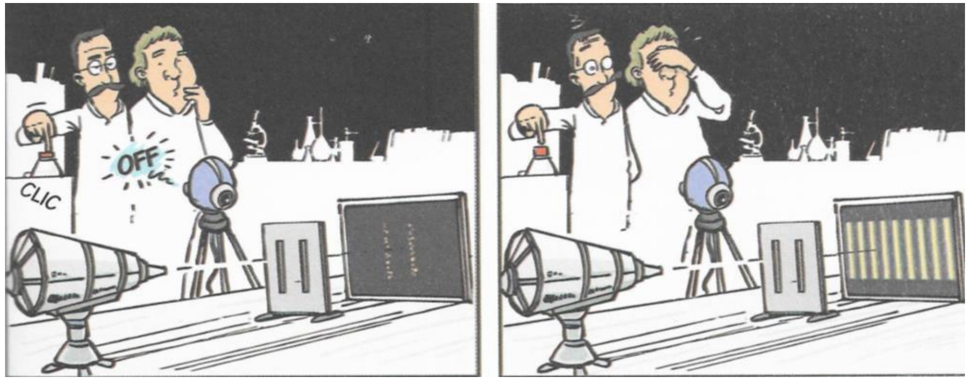
What is quantum mechanics?

A mathematical theory based on physical principles used to successfully explain observed phenomenon

- No religion
- No philosophy
- No ideology
- Not perfect

1st Quantum Revolution

Noisy particle-wave duality



Technological advances

2nd Quantum Revolution

Sharp superposition and entanglement

Quantix, Laurent Schafer

1st revolution achievements

Diodes
1873

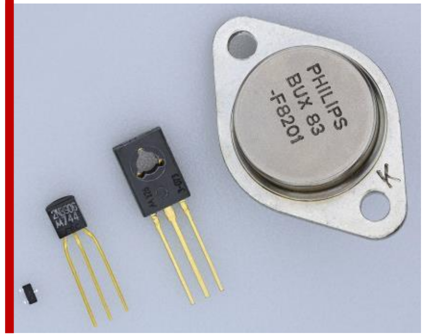
LEDs
1927

Wikipedia

Electron microscope
ca. 1928

Wikipedia

Transistors
1947
Building blocks of computers



Wikipedia

Lasers
1960
Telecom, electronics fabrication and use

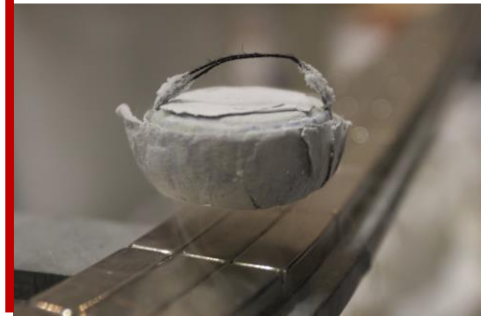
Magnetic resonance imaging (MRI)
1971

Modern chemistry

More research

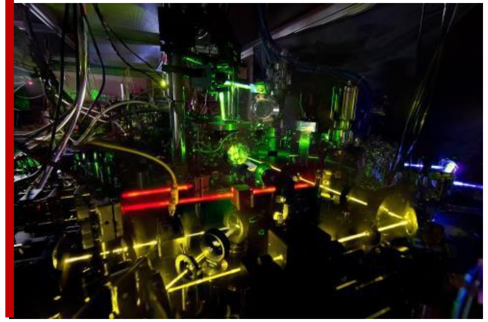
2nd revolution achievements

Quantum materials
1911
Ex. *superconductors*



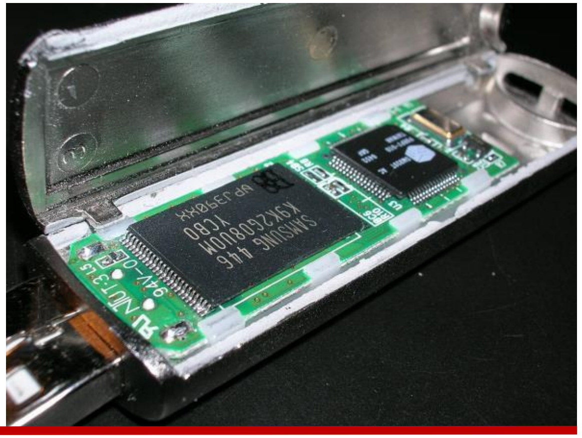
Wikipedia

Atomic clocks
1945
In GPS



Wikipedia

Flash memory
1967



Wikipedia

Metrology

Quantum key exchange and cryptography
1991

More research

Quantum computers?

Quantum ABC: quantum state & the qubit

Coin	Heads 	Tails 
Qubit	$\|0\rangle$	$\|1\rangle$

+ quantum properties

Quantum ABC: superposition & measurements

Superposition

$$a|0\rangle + b|1\rangle \approx$$

Question

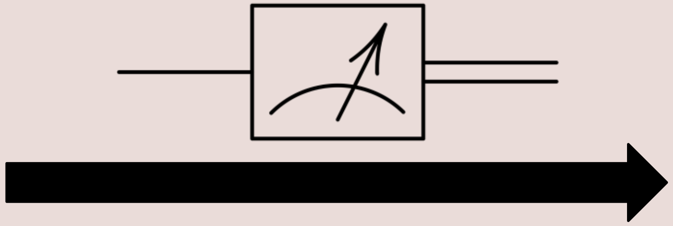
~~**What is the qubit state?**~~

Is the qubit state 0 or 1?

Measurement process

Superposition

$$a|0\rangle + b|1\rangle$$

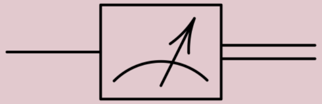


Measurement
(probabilistic)

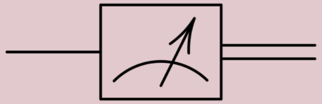
Collapse

$$|0\rangle$$

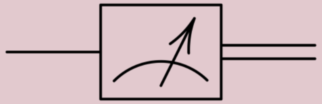
Quantum ABC: information



Is it 0 or 1? → **1 "bit" of information = yes/no**



Is b positive? → **yes/no**

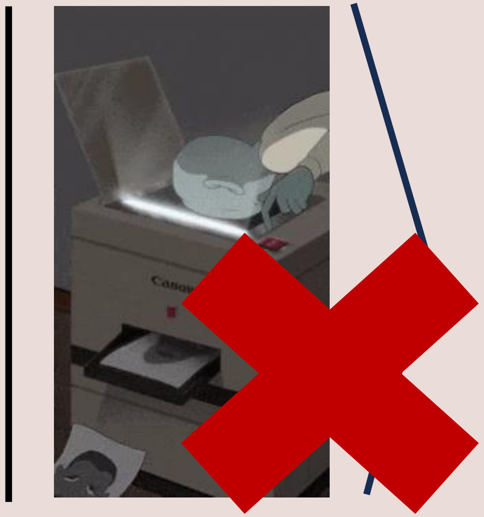


Is a >0.3? → (**destroy**) **yes/no**

…

Infinite copies? → (**deduce**) $a|0\rangle + b|1\rangle$

One copy? → **?**



False promises

Infinite storage

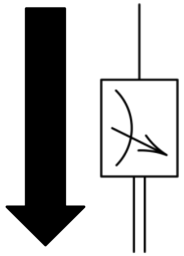
Inputing big data

Replace regular computers

Quantum ABC: entanglements

Superposition between **two** qubits: $$|0\,0\rangle + |1\,1\rangle$$

Measurement of only **one** qubit:



Collapse of **both** qubits: $$|0\,0\rangle$$

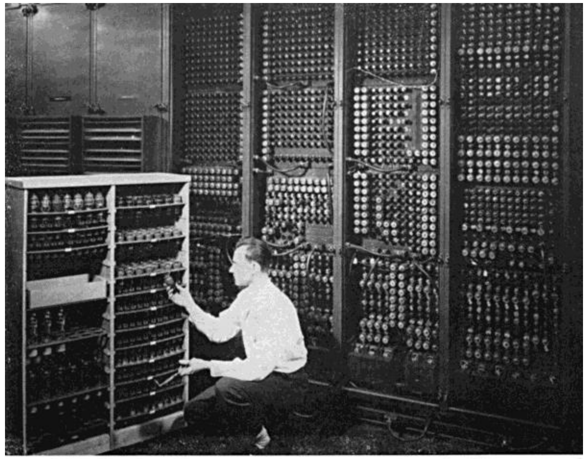
Quantum ABC: coherence and decoherence

$$a|0\rangle + b|1\rangle$$

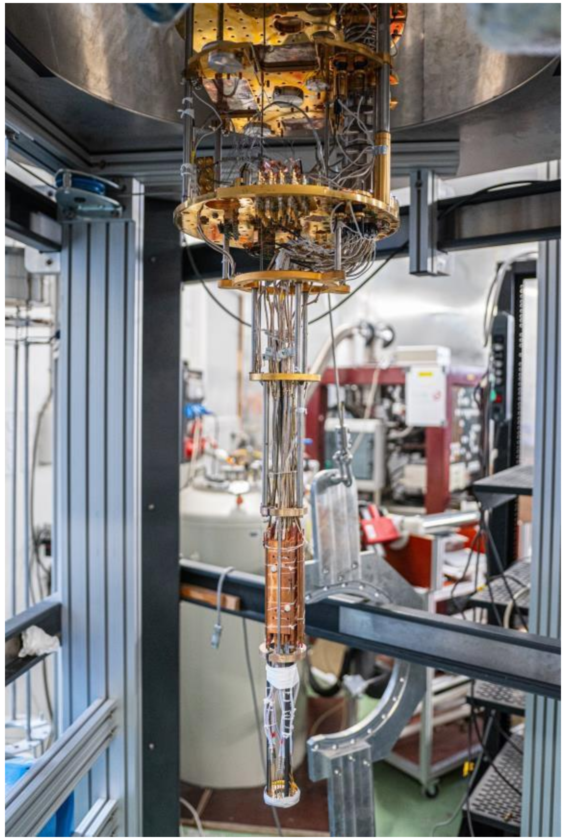
No information

Decoherence
= noise…

Recipe for a quantum computer

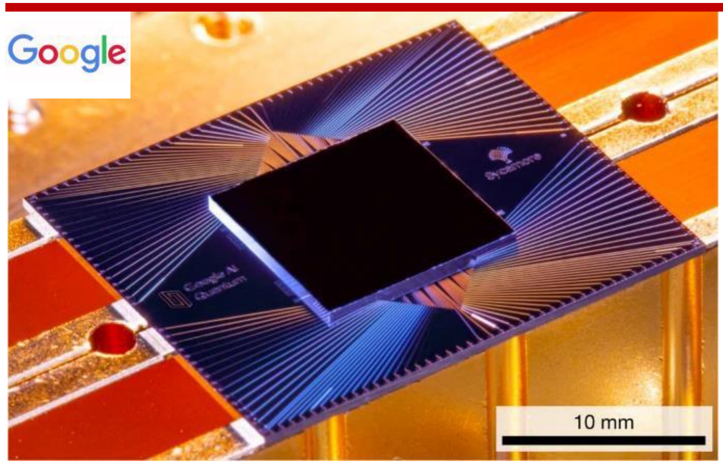

Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.

Standard computer	Quantum computer
Bits	Qubits
+	+
	Entanglement
	+
Transformations (called gates)	More transformations (quantum gates)
+	+
Measurement	Measurement
+	+
Little noise	"No noise"



(Controversial) examples of quantum advantage

Generating random numbers



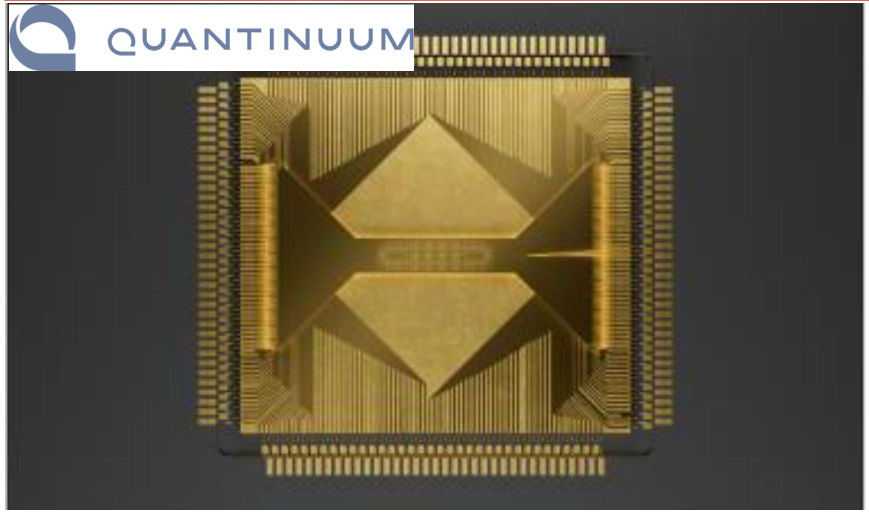
Arute F. et al, *Nature* **574** 505 (2019)
53 qubits
10^{10} times faster

Han-Sen Zhong et al., *Science* **370**, 6523pp. 1460-1463 (2020)
30 qubits
10^{14} times faster

Yulin Wu et al. *Phys. Rev. Lett.* **127**, 180501 (2021)
30 qubits
10^{13} times faster

Other examples

Simulation of small quantum systems



W.J. Huggins et al., *Nature* **603**, 416–420 (2022)
53 qubits (google)
?

I. Shapoval et al., *Quantum* **7**, 1138 (2023).
~ 20 qubits
?

Google Quantum AI *Nature* **614**, 676–681 (2023).
72 > 49 qubits (google)
-

Art and multimedia?

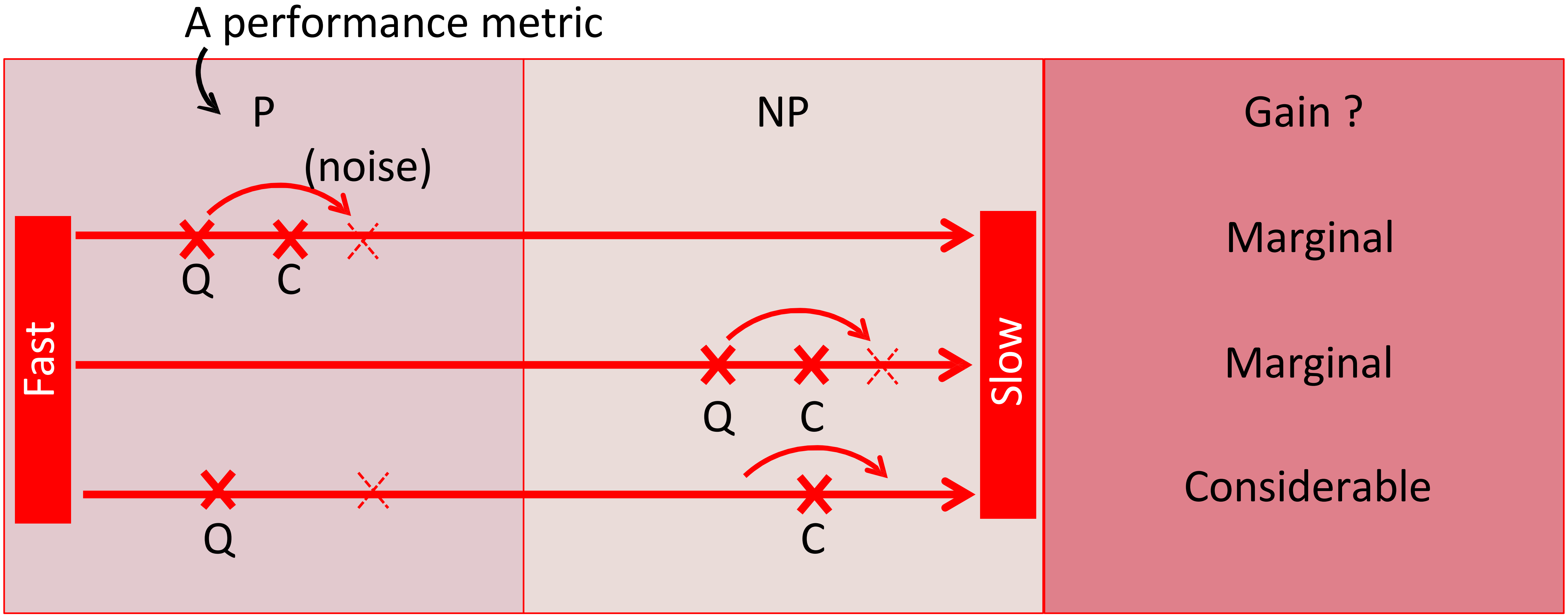
Random generation and AI

James Wootton

Quantum creativity

Libby Heaney

Reasonable promises



Important algorithms (= solution recipe)

Deutsch-Josza
Simon (Deutsch-Josza + errors)

→

Academic problems
Guessing black boxes

Shor

→

Factorizes into prime numbers

- Cracks regular cryptography (RSA in particular)

Solution: quantum cryptography

Grover

→

Find elements in a list
Crucial when using big data

Important algorithms (= solution recipe)

Adiabatic

Optimization and chemistry

- Many-body simulation
- Modeling of quantum systems

<u>Applications:</u> new materials, new/cheaper drugs/chemicals, high energy physics

Variational

Finding minimum

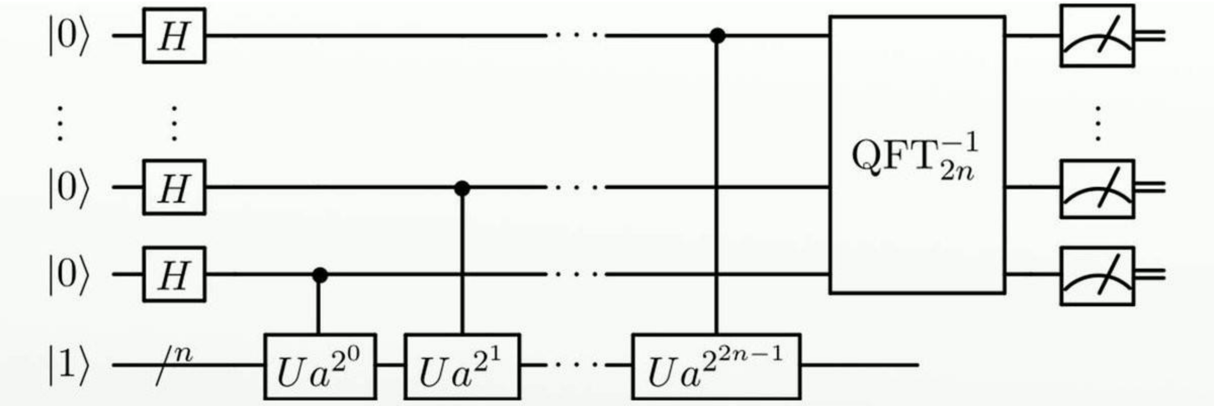
- Find the best path
- Train AI faster
- Solving equations (ex. Water/air flows)
- Inspiring classical algorithm: Netflix recommendations

What does an algorithm look like?

Using an SDK

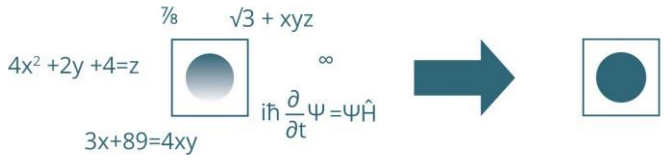
```
from qiskit_ibm_runtime import SamplerV2 as Sampler

# If using qiskit-ibm-runtime<0.24.0, change `mode=` to `backend=`
sampler = Sampler(mode=backend)
sampler.options.default_shots = 10000

# Set simple error suppression/mitigation options
sampler.options.dynamical_decoupling.enable = True
sampler.options.dynamical_decoupling.sequence_type = "XY4"
sampler.options.twirling.enable_gates = True
sampler.options.twirling.num_randomizations = "auto"

pub= (optimized_circuit, )
job = sampler.run([pub], shots=int(1e4))
counts_int = job.result()[0].data.meas.get_int_counts()
counts_bin = job.result()[0].data.meas.get_counts()
shots = sum(counts_int.values())
final_distribution_int = {key: val/shots for key, val in counts_int.items()}
final_distribution_bin = {key: val/shots for key, val in counts_bin.items()}
print(final_distribution_int)
```

Conceptual representation



What makes a good qubit?

Computational ability

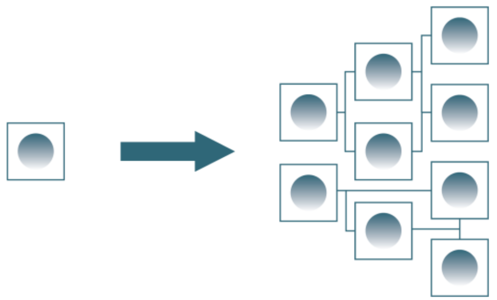


- perform as many calculations as possible on the qubits before their superposition and entanglement are lost.

Operability

- reliable control on the preparation, manipulation, and measure of the qubit

Scalability



- We need to interconnect thousands – probably millions – of qubits to make a useful quantum computer.

Leading technologies

Superconducting circuits
- Qubit: excitation of an electronic mode
- Two types: transmons & Fluxmons

Trapped ions
- Qubit: 2 internal states of ions
- Long coherence time, high gate fidelity
- Hardly scalable

Neutral atoms (+Rydberg)
- Qubit: excitation of the atoms

Colour centers
- Qubit: point defect in crystal
- Very clean
- Difficult to make

Spin qubits / quantum dots
- Qubit: up or down spin of a particle (electron or hole)
- Uses the semiconductor industry

Photons
- Mainly used as information carrier (travel at the sped of light)
- Difficult to make gates

Honorable mentions

Nuclear Magnetic Resonance
- Qubit: nuclear spin
- Scales poorly

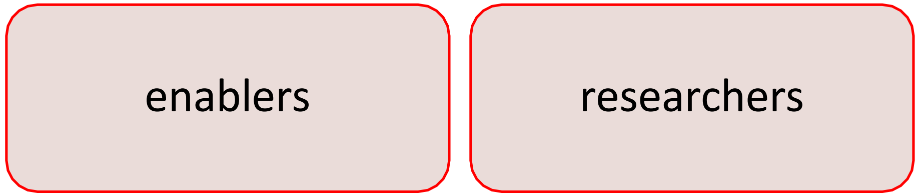
Topological Majorana and anyons
- Qubit: braiding of anyons
- No realization…

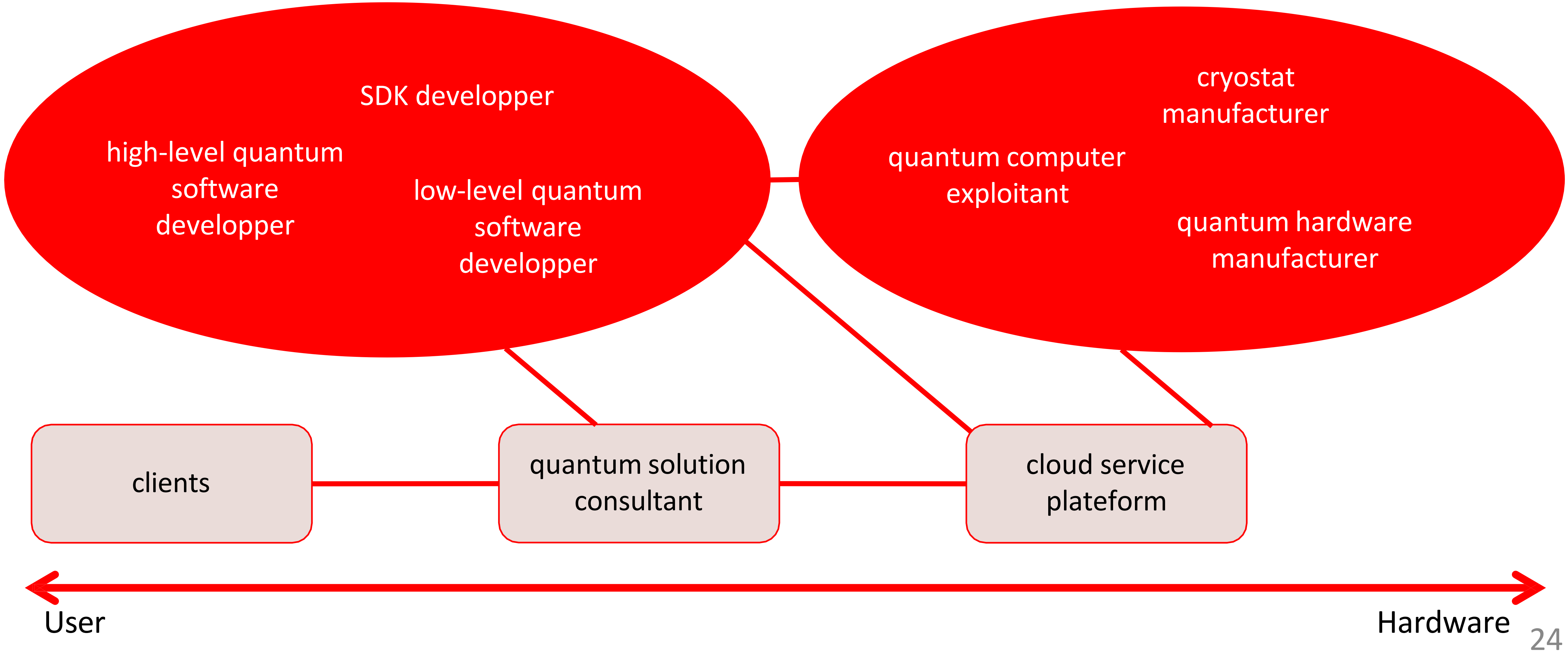
And more !

Quantum annealer
- Restricted to a certain kind of problems and algorithms

Measurement-based
- Using measurement to do the algorithm
- Requires to start with many entangled qubits

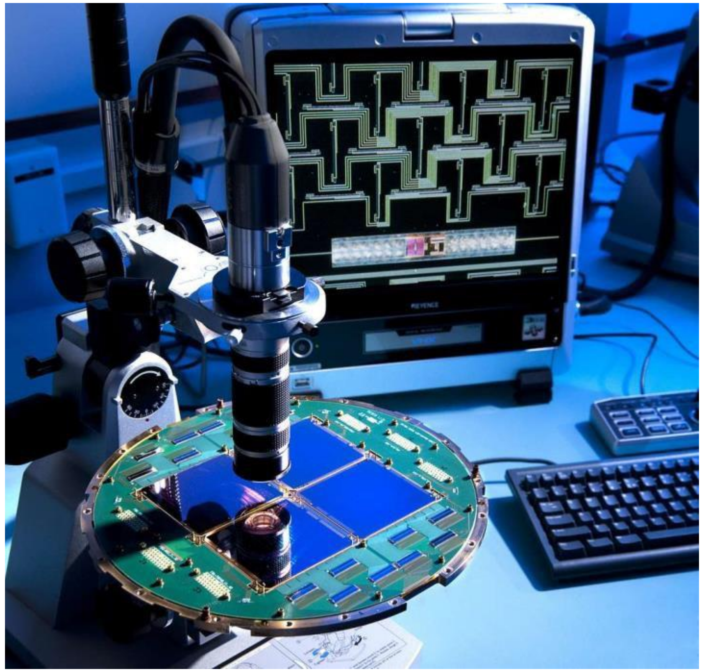
Quantum ecosystem



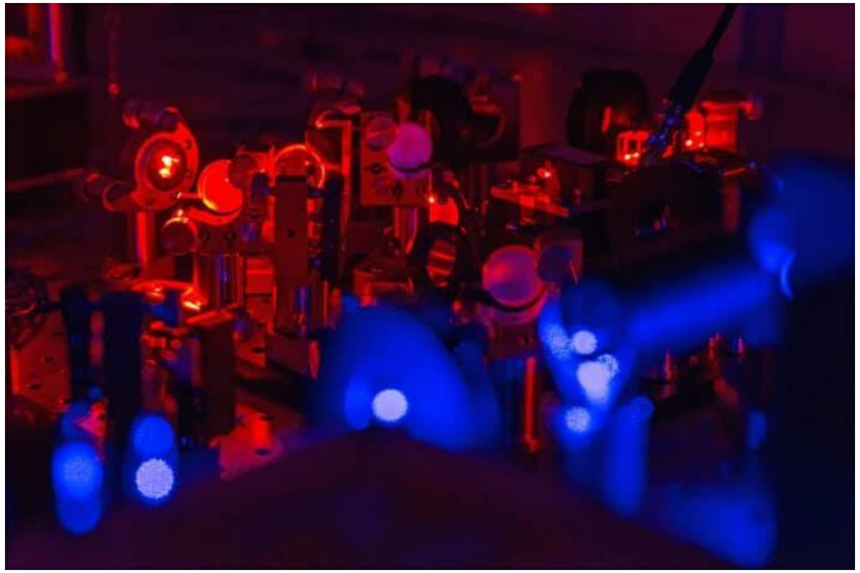


Other utility of quantum?

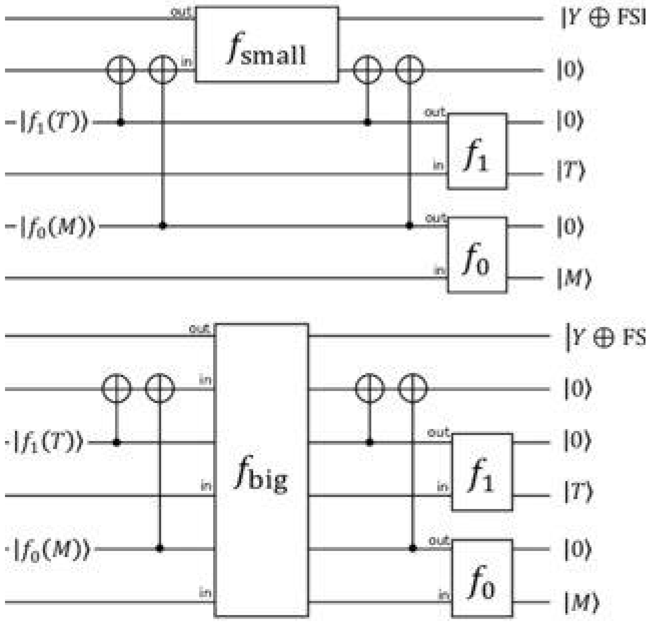
Quantum sensors



Quantum simulators



Quantum-inspired algorithms



Where we stand

- Classical computers struggle to simulate > 30 perfect qubits... in general
- Almost all technologies have proof-of-concept on 10-100 imperfect qubits
- Too many errors everywhere to see the benefit
- Other issues:

Large circuits | Always some noise | Far advantage