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Quantum Information Science & Technology

Quantum algorithms & error correction

Quantum Computing – Lecture 4

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Centre Européen de Science Quantiques (CESQ)
Apr.2022

Université de Strasbourg

QUSTEC
Quantum Science and Technologies at the European Campus

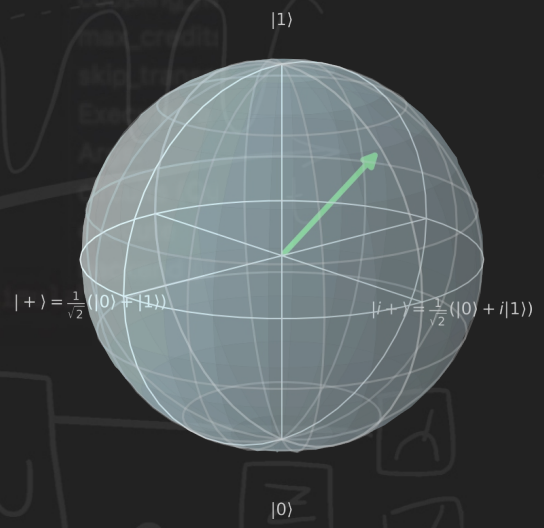
Scope of the course

- *Five lectures of 1 hour*

  1) Introduction to Quantum Science & Technology
  2) From classical logic to quantum gates
  3) Quantum circuits & implementations
  4) Quantum algorithms & error correction
  5) Quantum stack

Qubit

Bloch Sphere (Graphical representation)



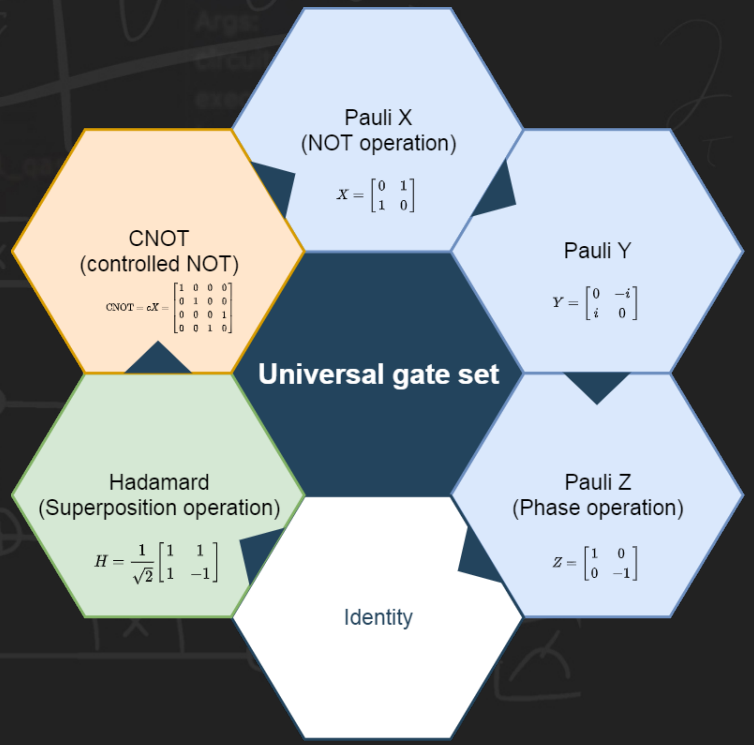
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

$$\theta, \phi \in \mathbb{R}$$

Quantum gates

From Hamiltonians to unitary transformations

$$U = e^{i\hat{\mathcal{H}}\Delta t/\hbar}$$

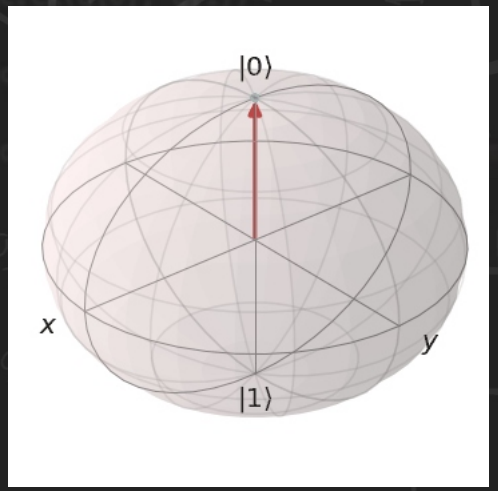


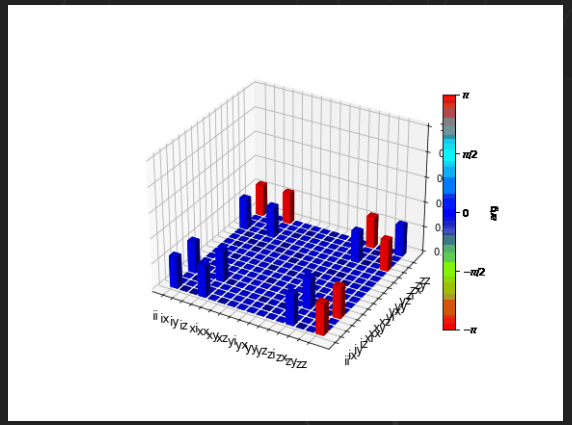
Quantum gates

Engineering 1- and 2-qubits gates

$$\hat{\mathcal{H}}_j^{ab} = \left(\frac{\Omega_j(t)}{2} e^{i\varphi_j(t)} |a_j\rangle\langle b| + \text{h.c.}\right) - \Delta_j(t)|b_j\rangle\langle b|$$

$$\hat{\mathcal{H}}_{j,k}^{abcd} = \frac{V_{j,k}}{2}|ab\rangle\langle cd| + \text{h.c.}$$





$$\mathrm{U}_{xy}(\theta,\varphi) = \begin{pmatrix} cos(\theta/2) & -isin(\theta/2)e^{i\varphi} \\ -isin(\theta/2)e^{-i\varphi} & cos(\theta/2) \end{pmatrix}$$

$$U = \exp\left(-i\hat{\mathcal{H}}_c^{r1}\tau_1\right) \times \exp\left[-i(\hat{\mathcal{H}}_t^{r1} + \hat{\mathcal{H}}_{c,t}^{rrrr})\tau_2\right] \times \exp\left(-i\hat{\mathcal{H}}_c^{r1}\tau_1\right)$$

Quantum dynamics

Schrödinger Equation

We can describe the evolution of the quantum system by solving the **Schrödinger equation**, under the *action* of a Hamiltonian:

$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle = \hat{\mathcal{H}}|\psi(t)\rangle$$

Moreover we can think in the evolution of a time-dependent Hamiltonian, that takes into account driving forces that depend on time:

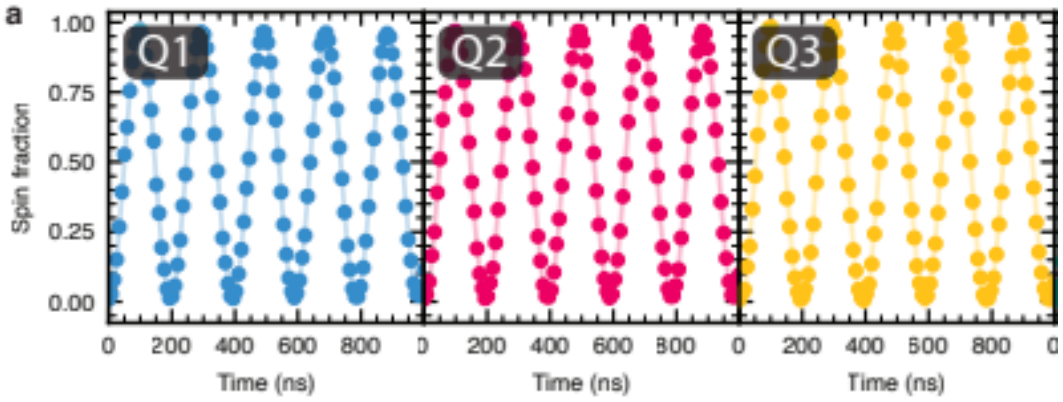
$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle = \hat{\mathcal{H}}(t)|\psi(t)\rangle$$

Quantum Resources

Rabi experiment - T_1

It is an experimental sequence composed by one long pulse that drive the probability populations of the qubit states.

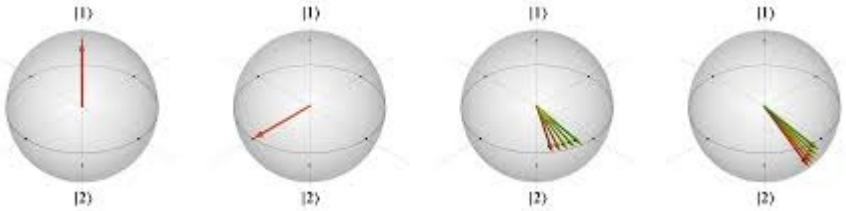
This defines the T_1 time, that relates with the operation time.

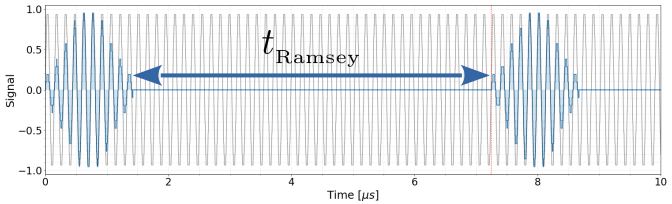


https://arxiv.org/abs/2202.09252

Quantum Resources

Ramsey experiment - T_2



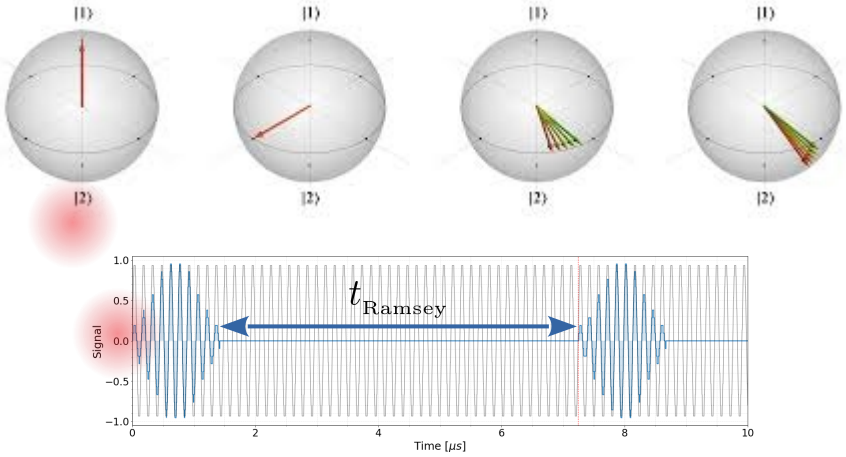


It is an experimental sequence composed by two pi/2 pulses (¼ rotation in the Bloch sphere) separated by a time called Ramsey Time, where the qubit is free to dephase.

This define the T_2 time, or coherence time.

Quantum Resources

Ramsey experiment - T_2



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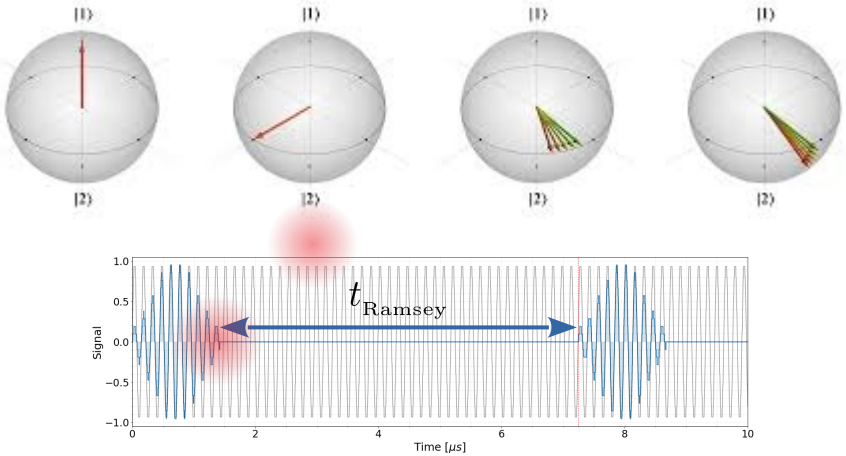

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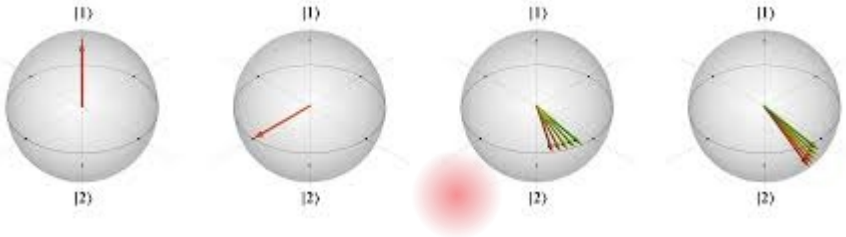

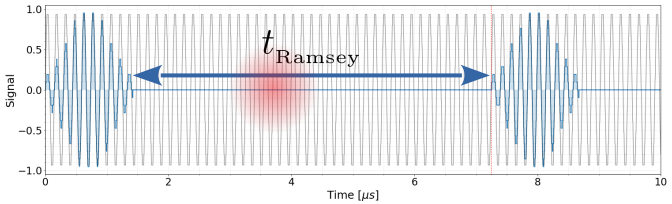

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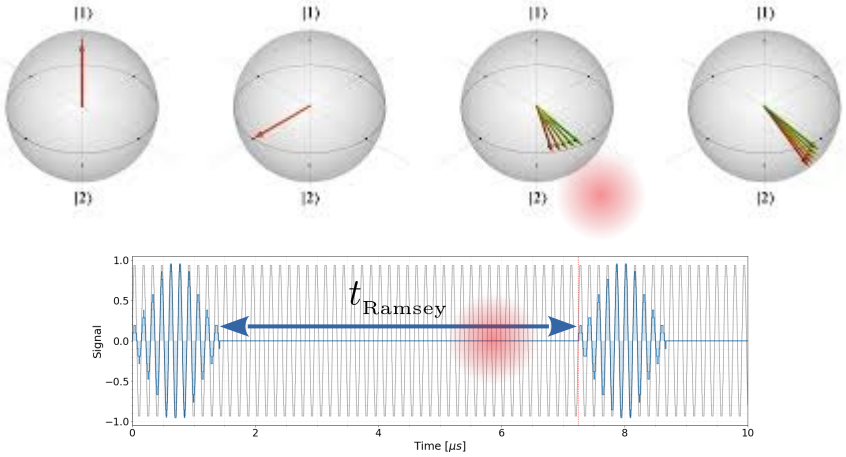

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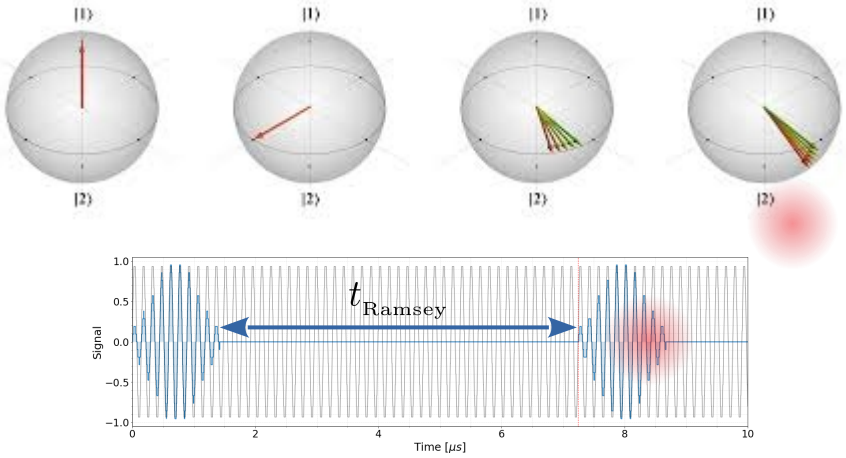

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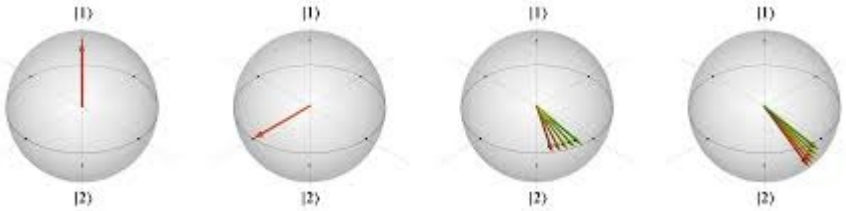

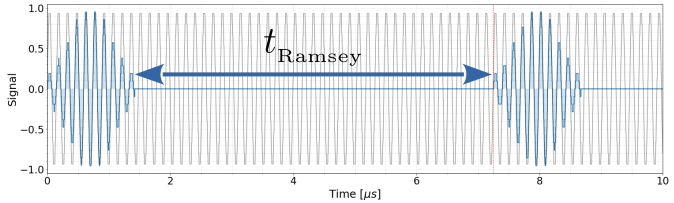

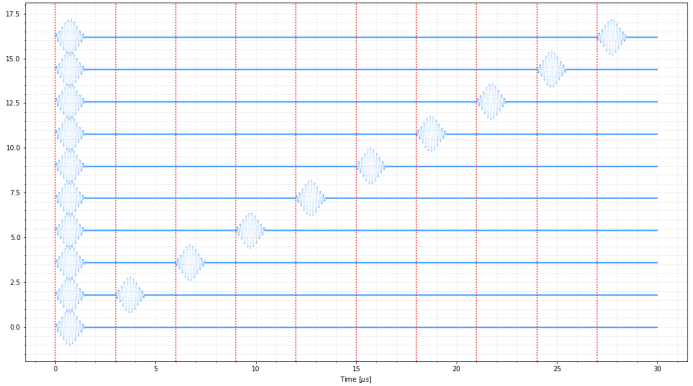

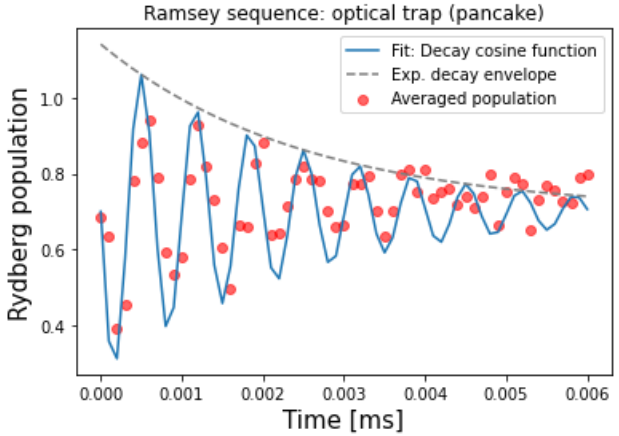

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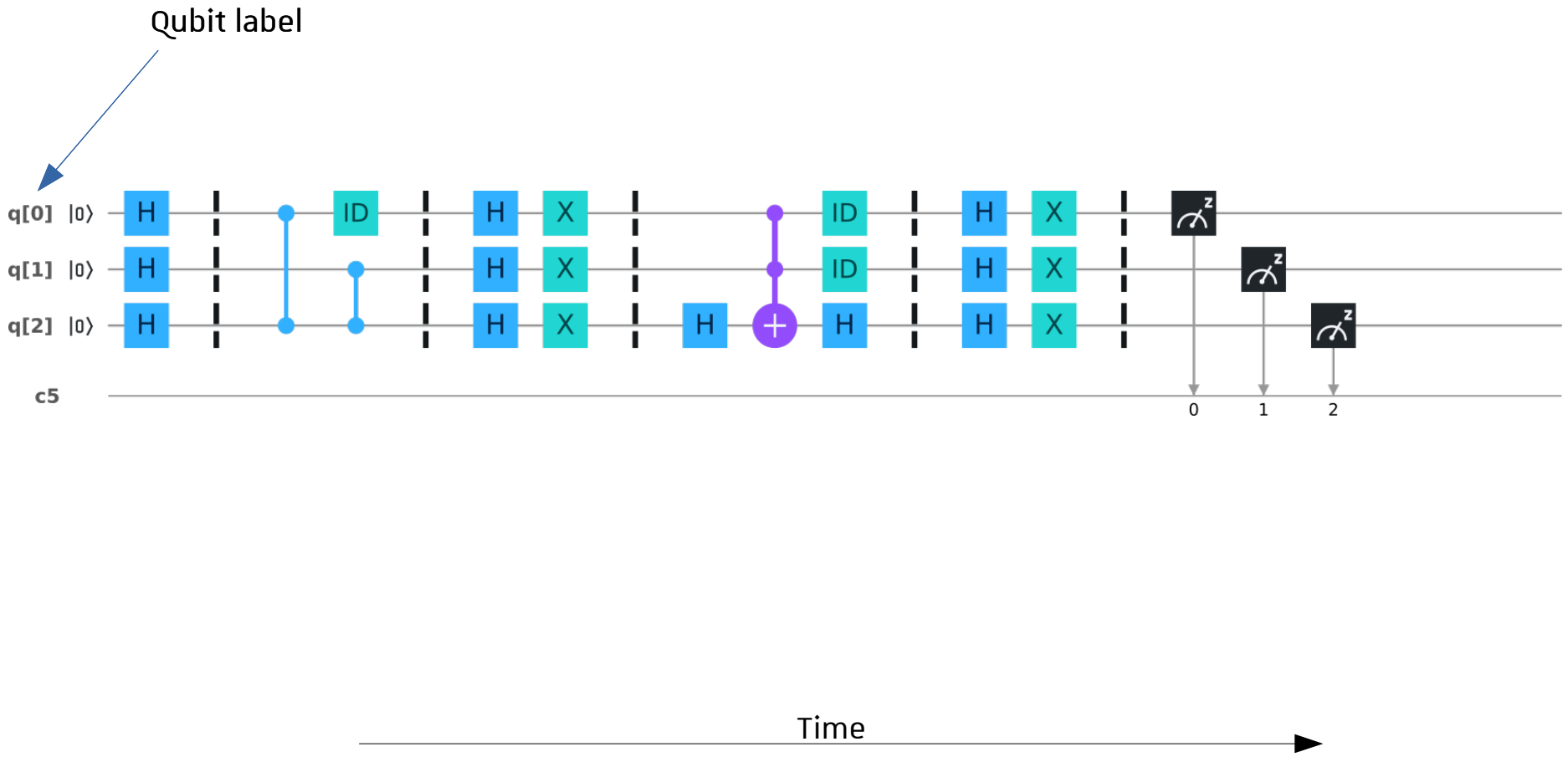
Quantum circuits

Anatomy of a quantum circuit



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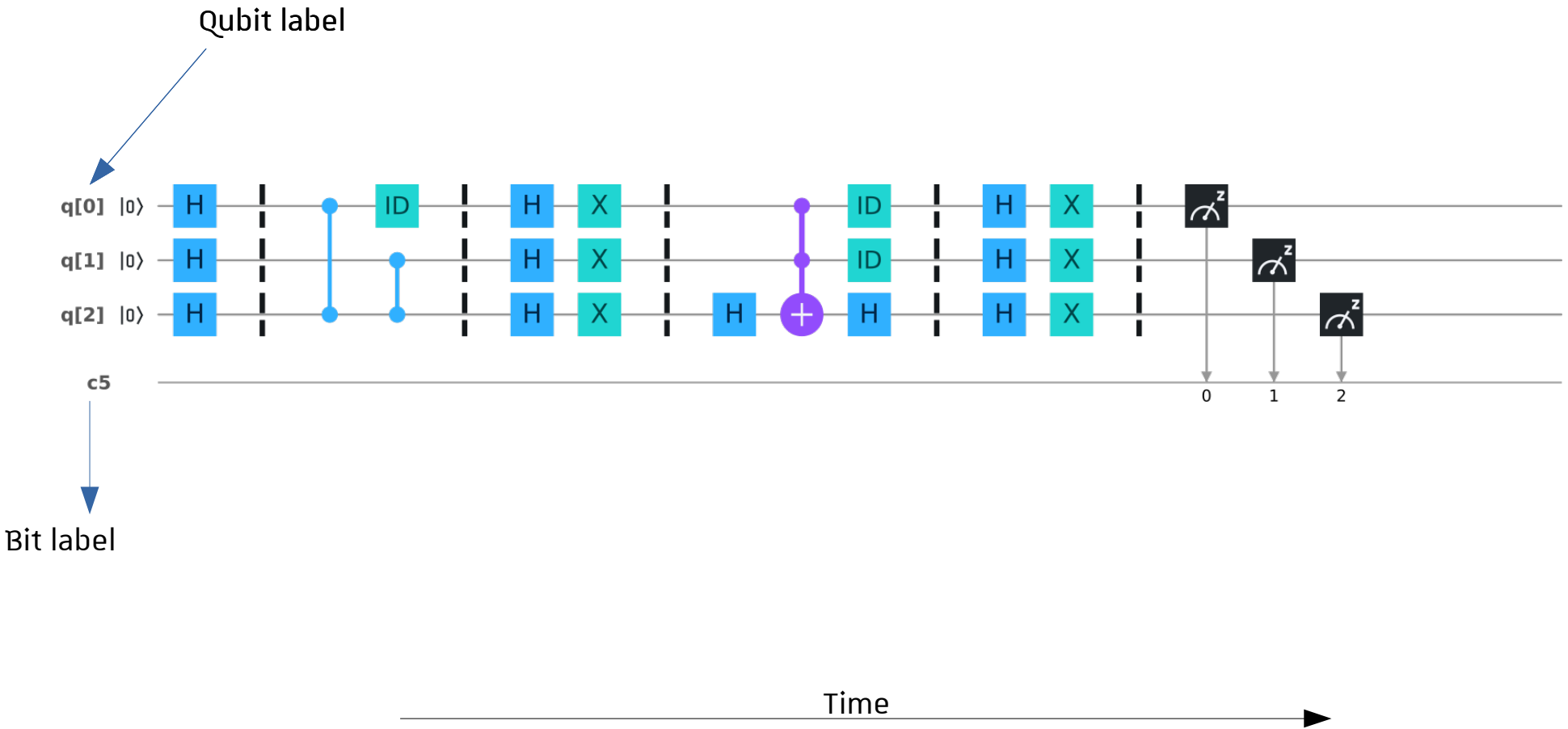

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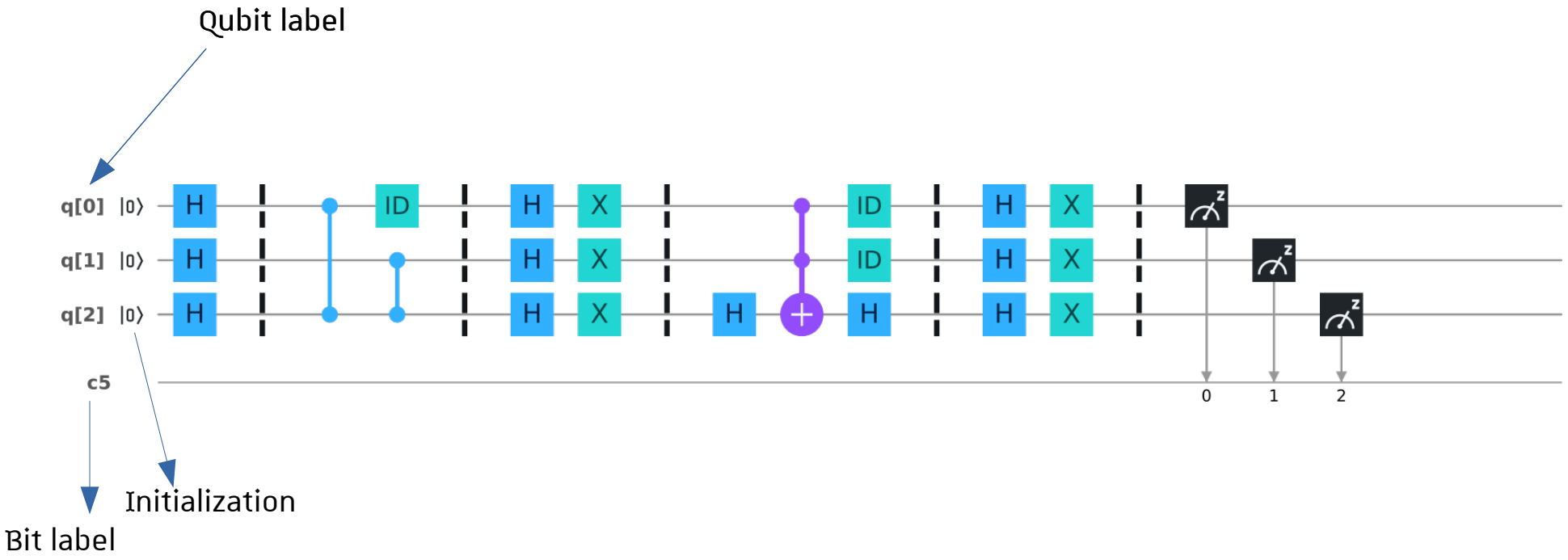
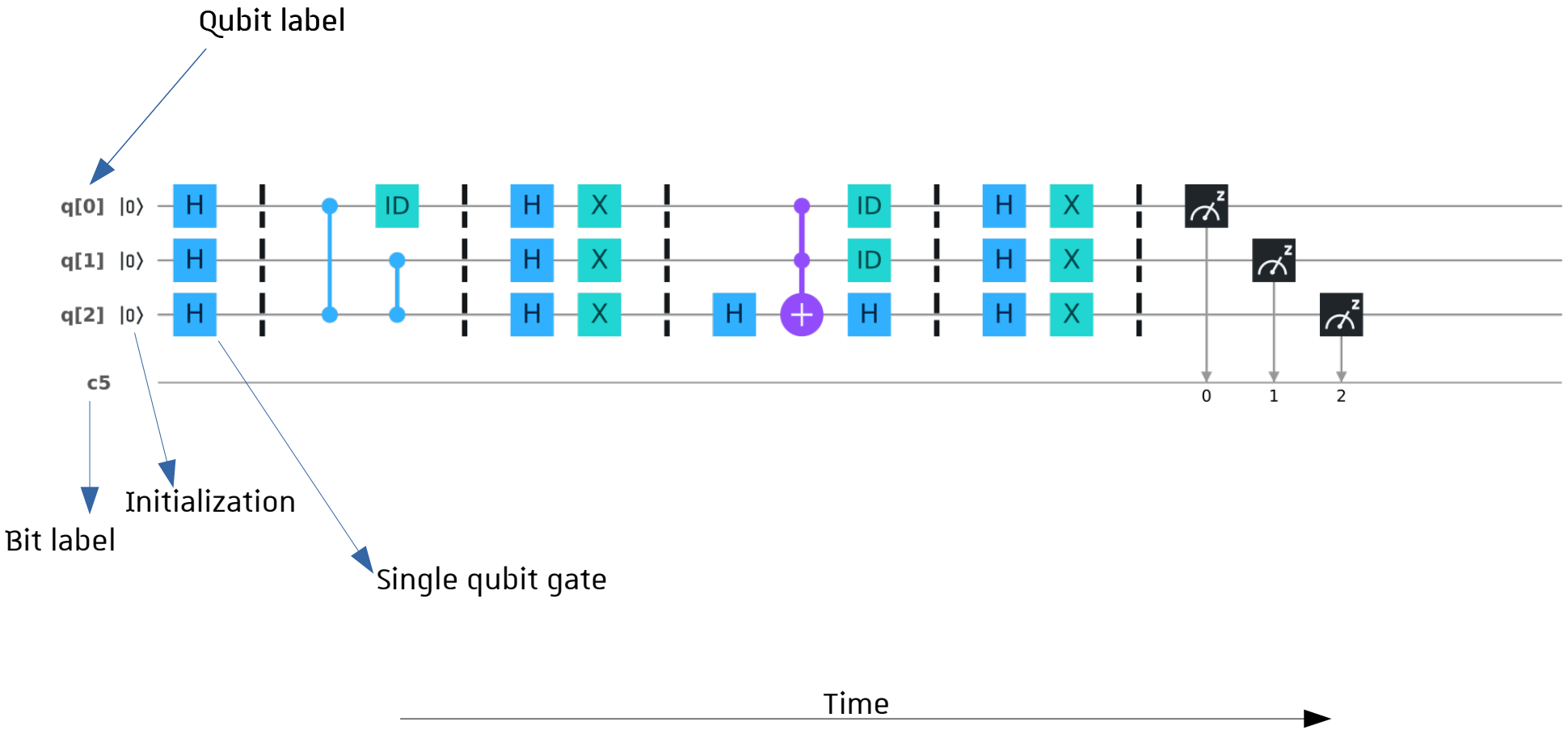


Time

Quantum circuits

Anatomy of a quantum circuit



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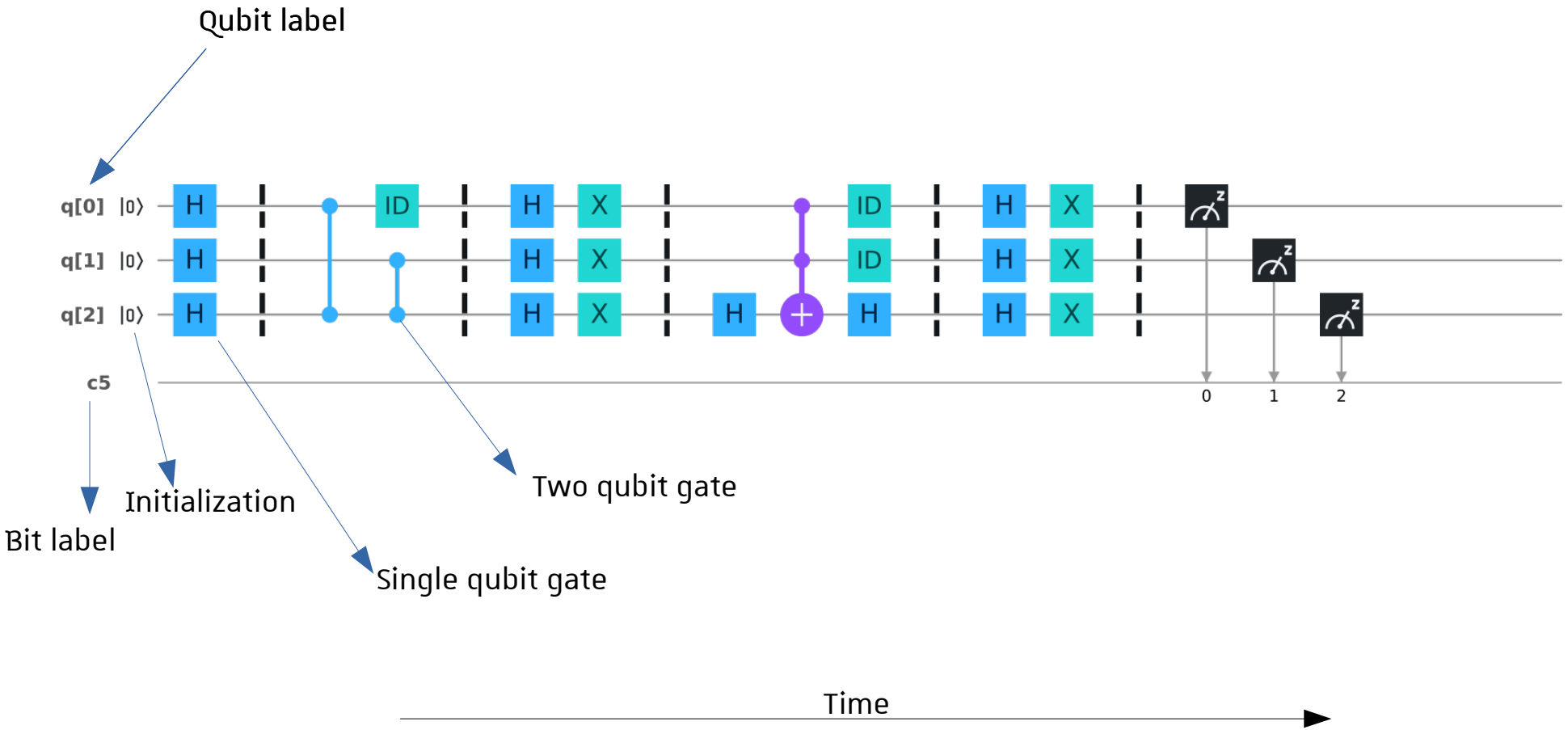

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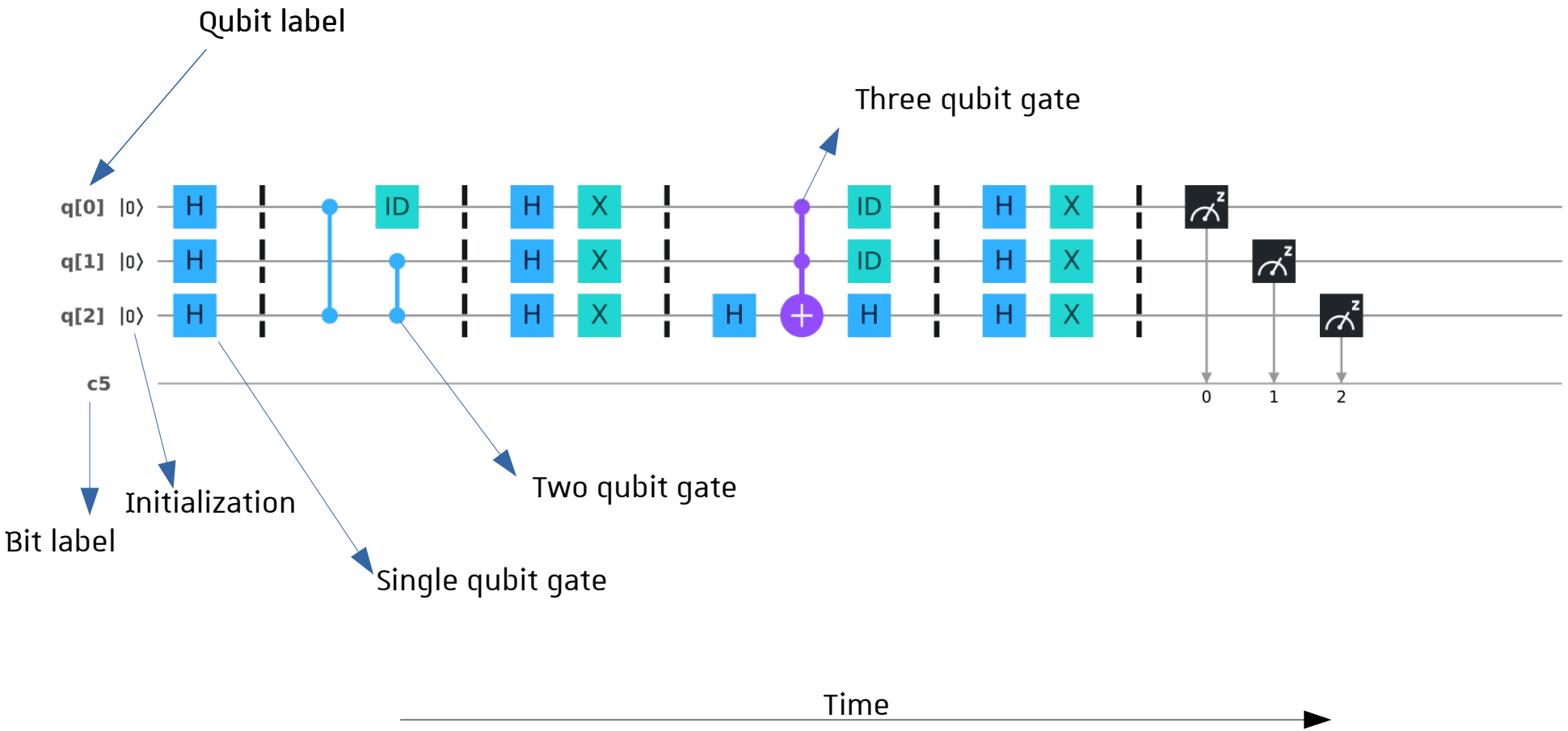

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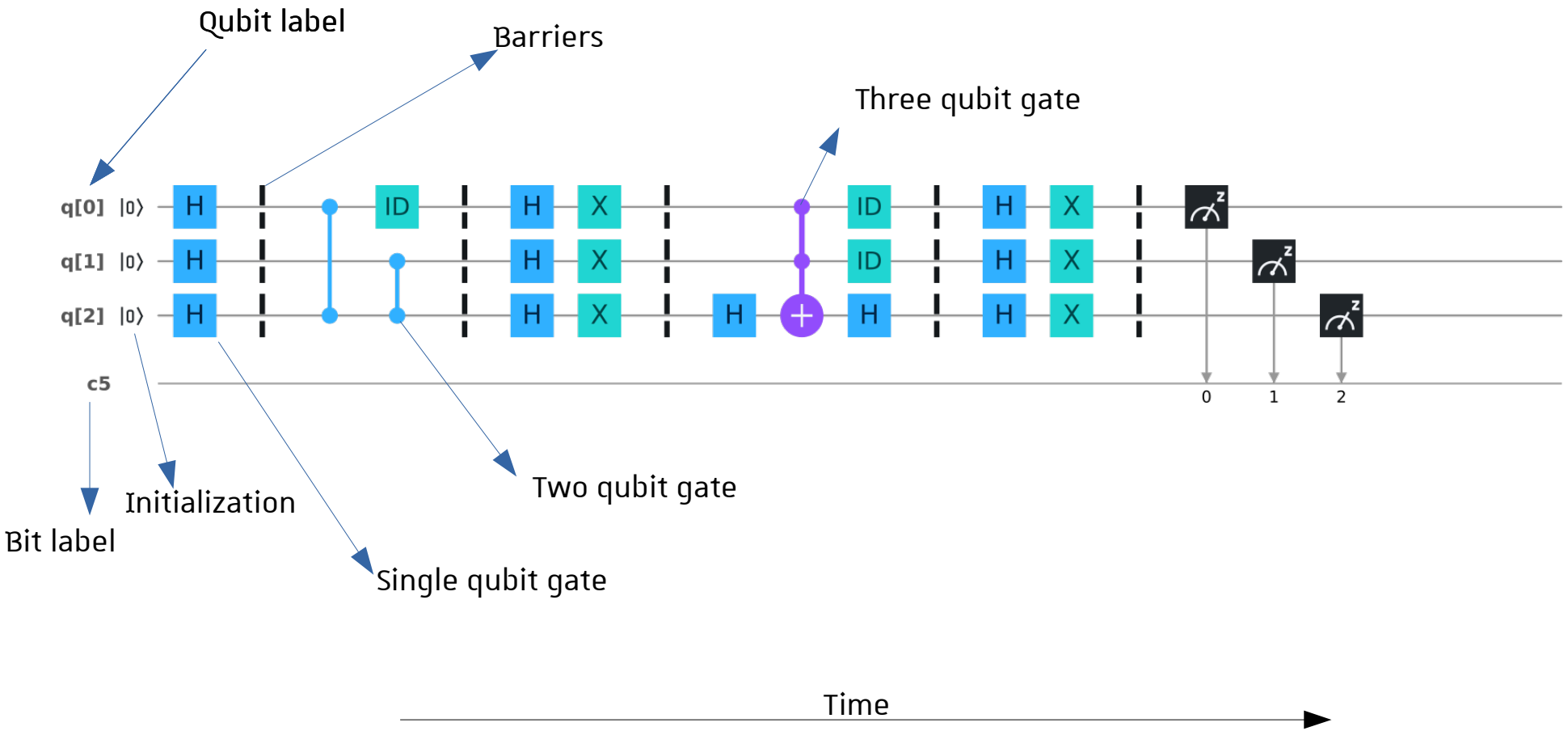

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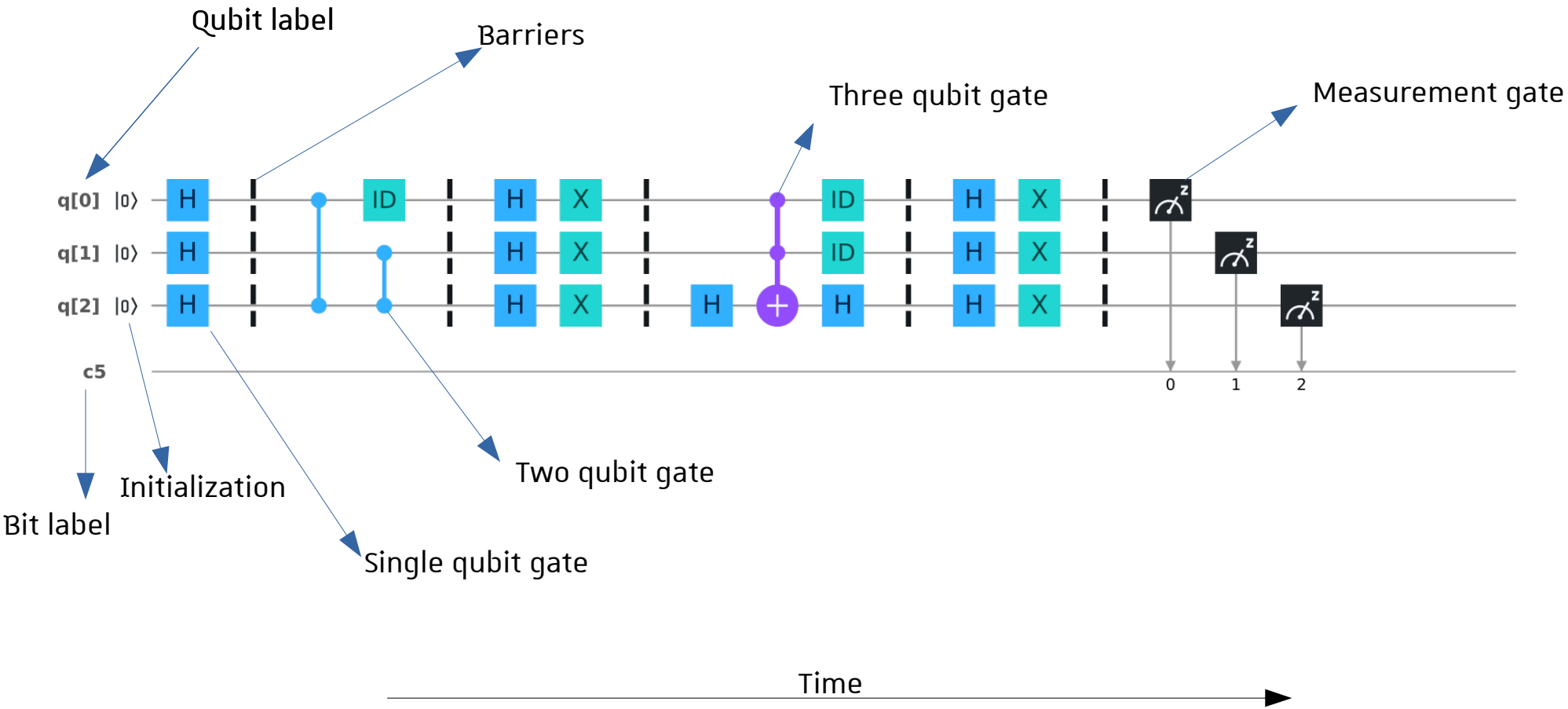

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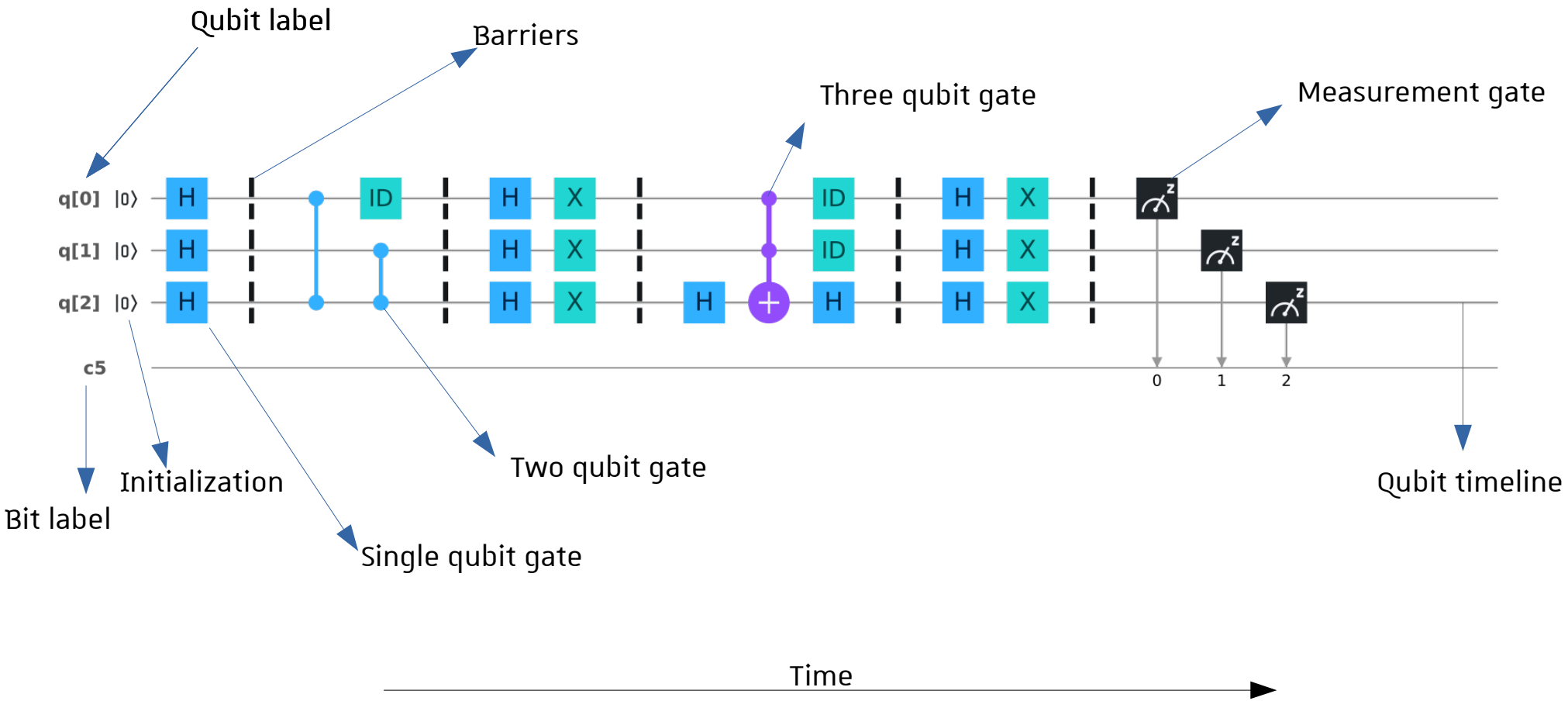

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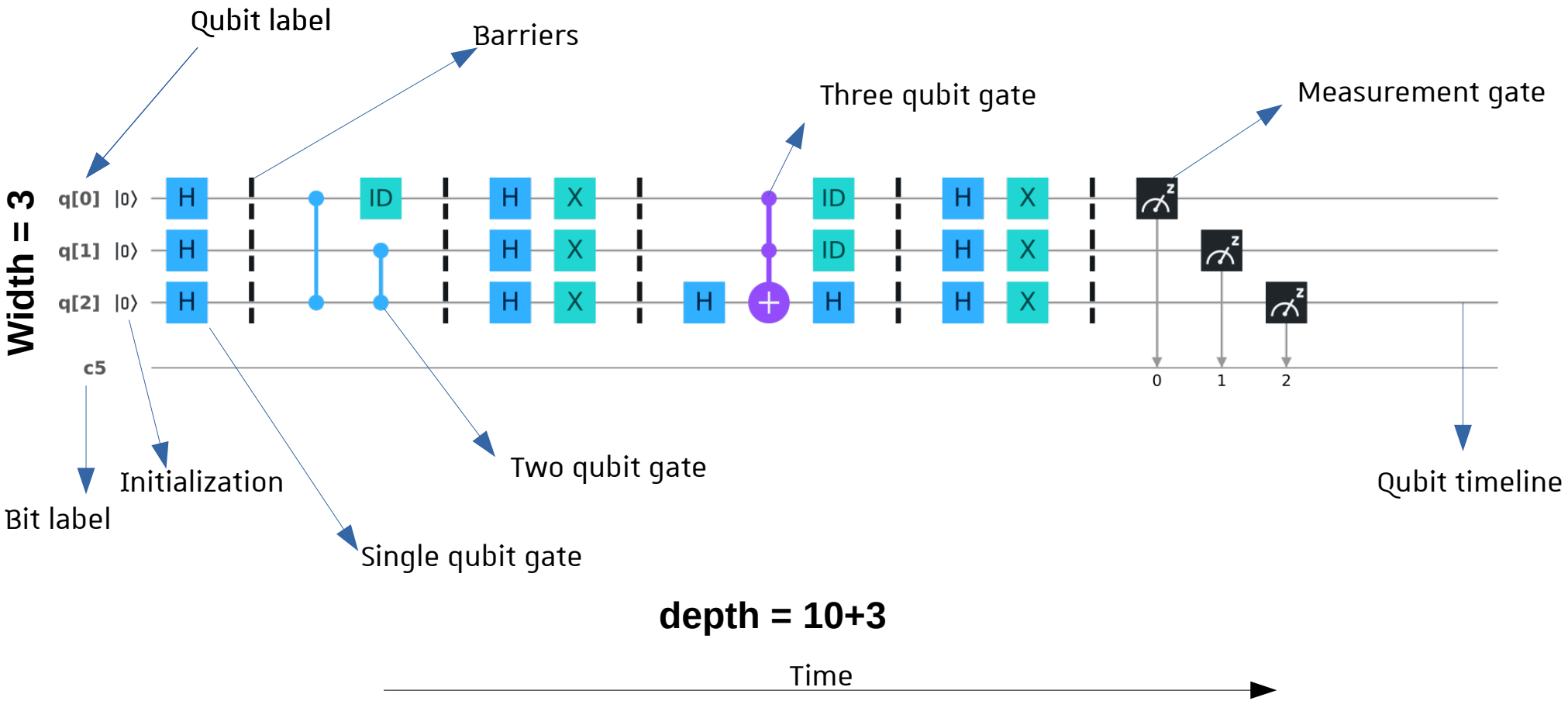

example.py

```
1
2
```

clideo.com

Line 1, Column 1 Tab Size: 4 Python

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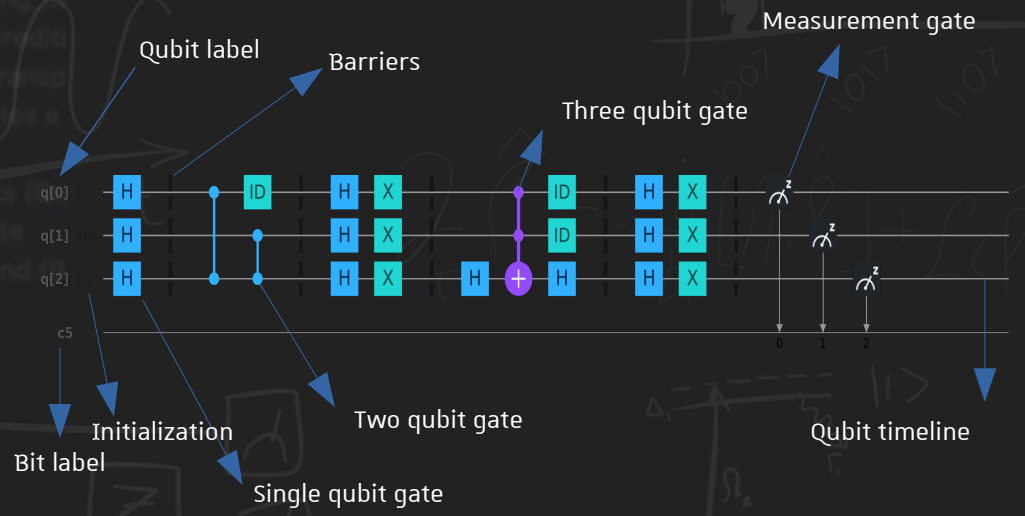
example.py

```python
import qiskit
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(3, 'q')
creg_q = ClassicalRegister(3, 'c')
circuit = QuantumCircuit(qreg_q, creg_q)

circuit.h(qreg_q[0])
circuit.h(qreg_q[1])
circuit.h(qreg_q[2])

circuit.barrier(qreg_q[0])
circuit.barrier(qreg_q[1])
circuit.barrier(qreg_q[2])

circuit.cz(qreg_q[0], qreg_q[2])
circuit.id(qreg_q[0])
circuit.cz(qreg_q[1], qreg_q[2])

circuit.barrier(qreg_q[0])
circuit.barrier(qreg_q[1])
circuit.barrier(qreg_q[2])

circuit.h(qreg_q[0])
circuit.h(qreg_q[1])
circuit.h(qreg_q[2])
circuit.x(qreg_q[0])
circuit.x(qreg_q[1])
circuit.x(qreg_q[2])

circuit.barrier(qreg_q[0])
circuit.barrier(qreg_q[1])
circuit.barrier(qreg_q[2])

circuit.h(qreg_q[2])
circuit.ccx(qreg_q[0], qreg_q[1], qreg_q[2])
circuit.id(qreg_q[0])
circuit.id(qreg_q[1])
circuit.h(qreg_q[2])

circuit.barrier(qreg_q[0])
circuit.barrier(qreg_q[1])
circuit.barrier(qreg_q[2])

circuit.h(qreg_q[0])
circuit.h(qreg_q[1])
circuit.h(qreg_q[2])
circuit.x(qreg_q[0])
circuit.x(qreg_q[1])
circuit.x(qreg_q[2])

circuit.barrier(qreg_q[0])
circuit.barrier(qreg_q[1])
circuit.barrier(qreg_q[2])

circuit.measure(qreg_q[0], creg_q[0])
circuit.measure(qreg_q[1], creg_q[1])
circuit.measure(qreg_q[2], creg_q[2])
```

Line 38, Column 22 Tab Size: 4 Python



Qiskit

Elements for building a quantum future

Gate-based Quantum Computing

Quantum Algorithms

There are many quantum algorithms that promise certain advantage over classical algorithms, using quantum computers:

- **Deutsch–Jozsa's algorithm**
  - Bernstein–Vazirani's algorithm
  - Simon's algorithm
- Grover's algorithm
- Quantum Fourier Transform algorithm
- Shor's algorithm

David Deutsch

Richard Jozsa

1992

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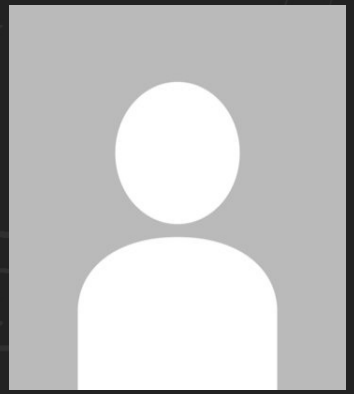

Ethan Bernstein

1992

Umesh Vazirani

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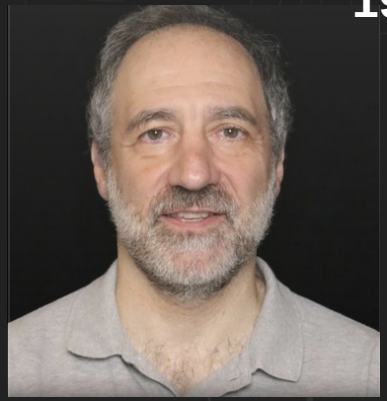

Daniel Simon

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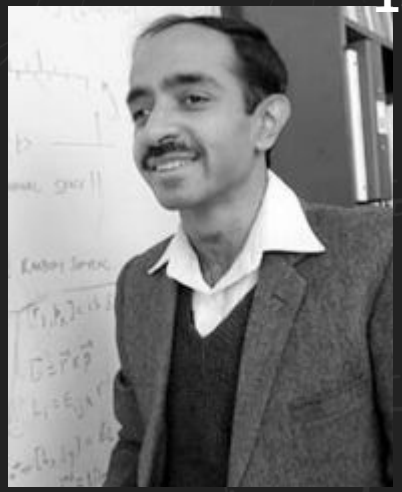
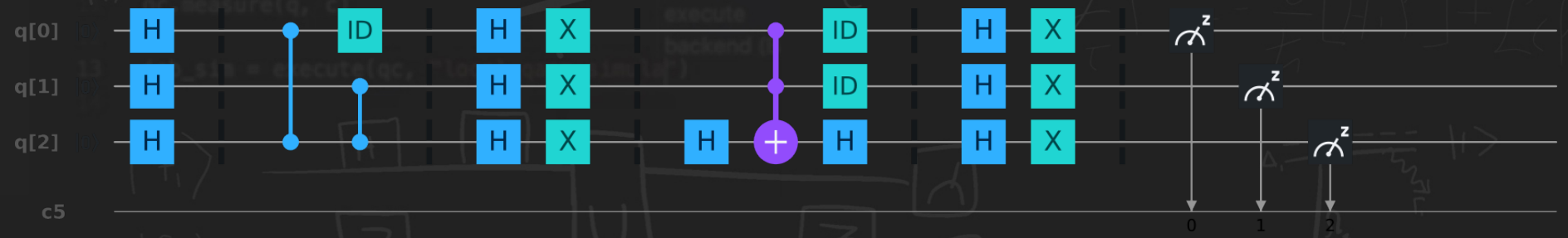


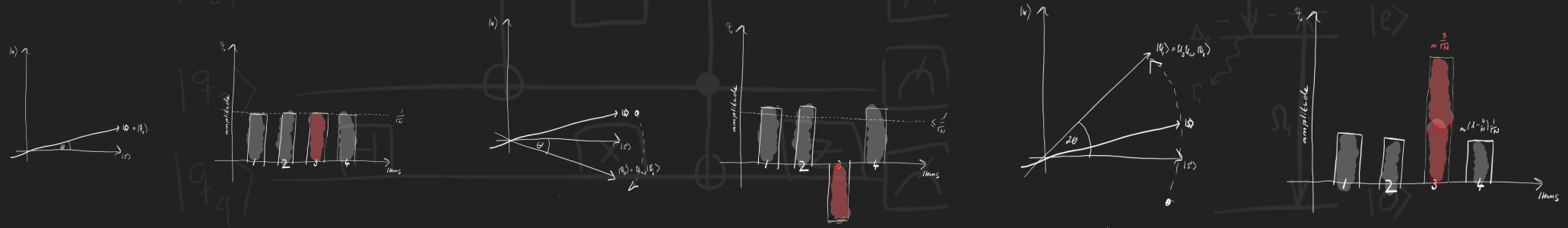
Lov Grover

Gate-based Quantum Computing

Quantum Algorithms

3-qubits Grover's algorithm





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Quantum algorithms

Quantum Fourier Transform (QFT)

Quantum algorithms

Quantum Fourier Transform (QFT)

Gate-based Quantum Computing

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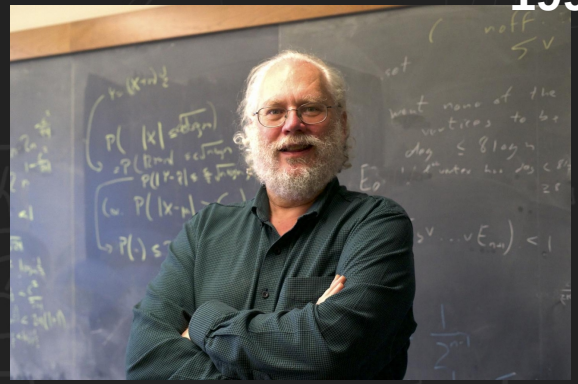


Peter Shor

Quantum error correction

Algorithmic approach

Source of **noise and decoherence** in quantum systems can lead to errors in the quantum bit and moreover in the quantum register.

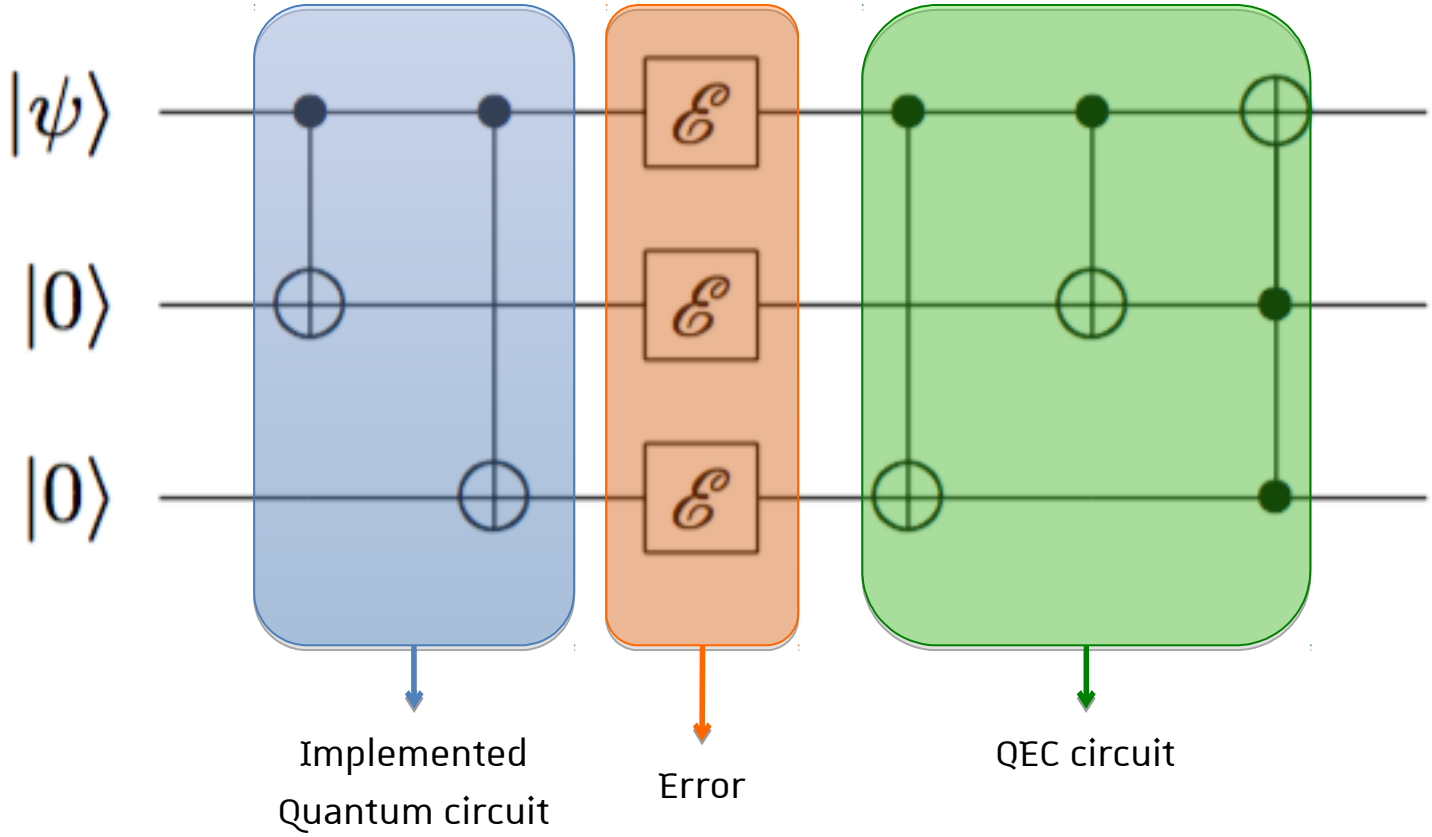
Considering an error rate of 1e-3 per single qubit gate can lead to very low state fidelities. For this reason quantum computer must present a way to make more robust computation, similar to current classical computers.

Then, the idea is to correct the state of the qubits using feedback and iterative application of quantum gates that correct properties of the state such as: bit and phase.

Ultimately, the expectation is to conserve the entanglement and other quantum properties of the system.

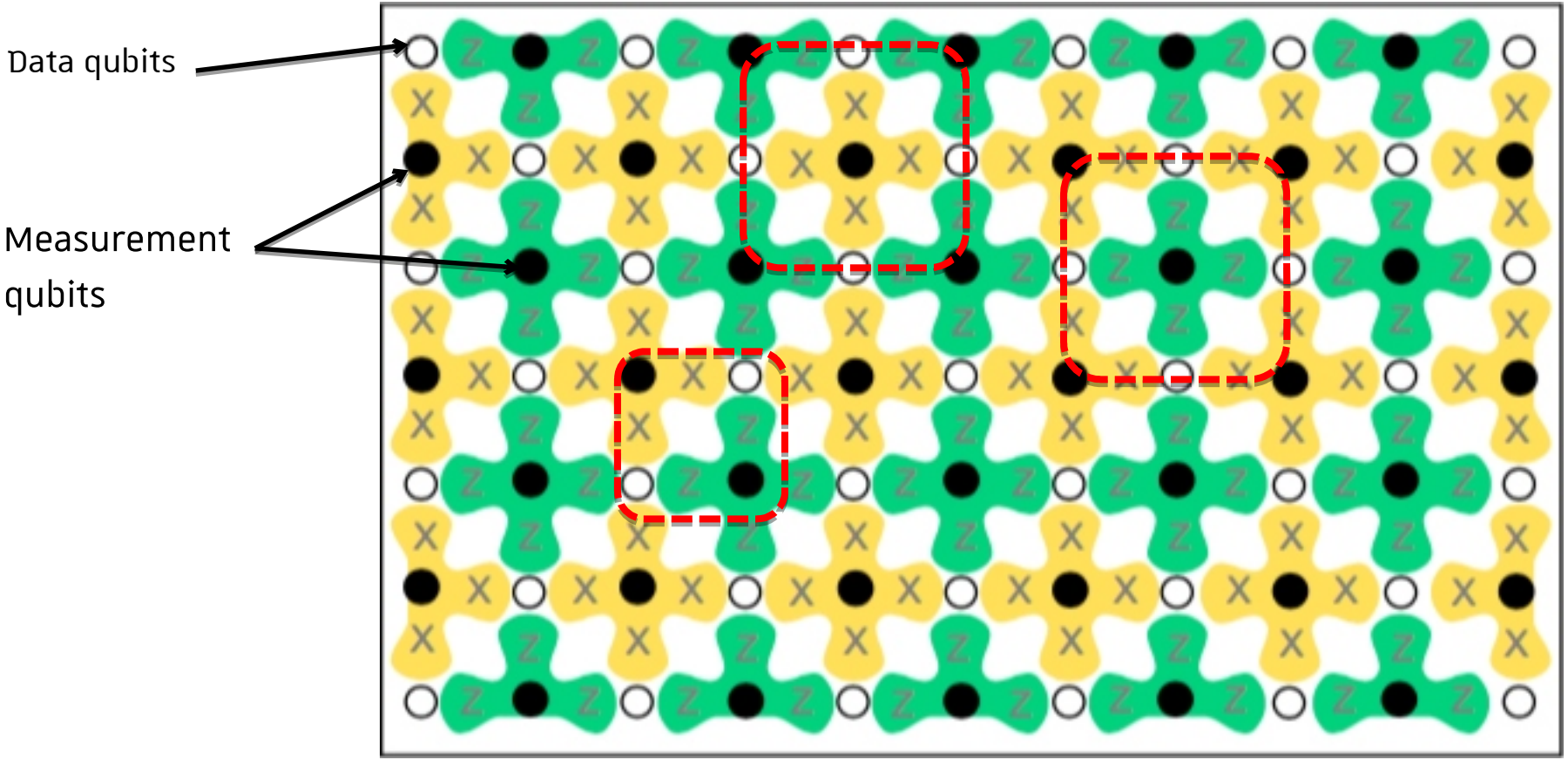
Quantum error correction

Algorithmic approach



Quantum error correction

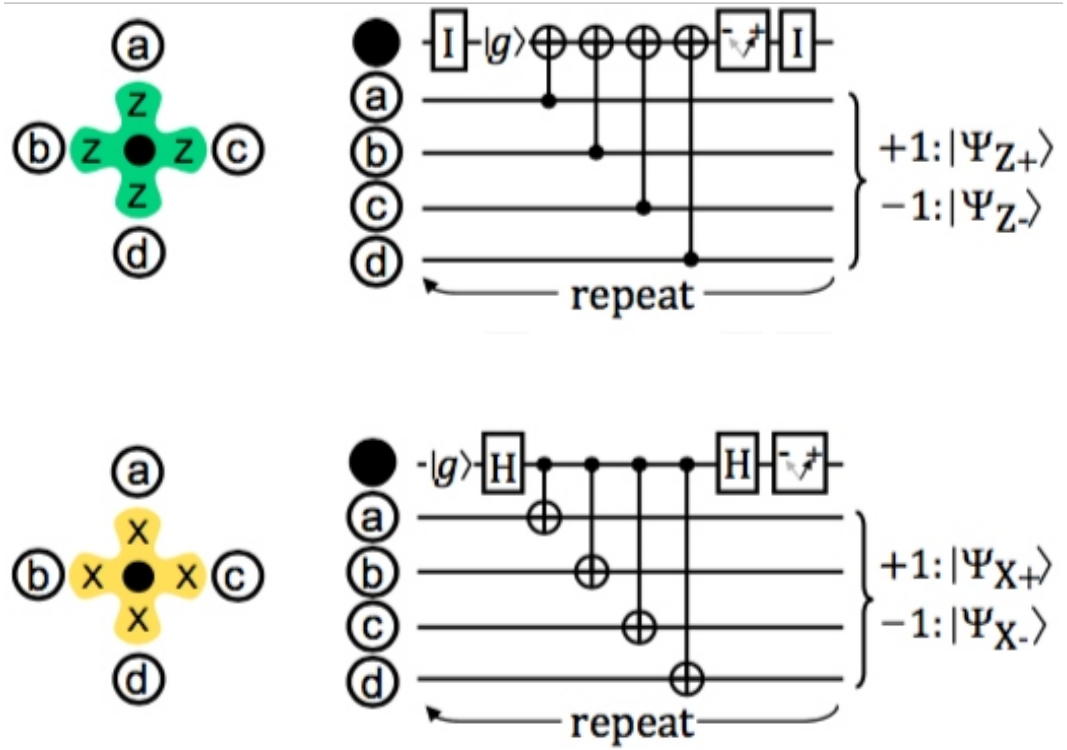
Surface Code

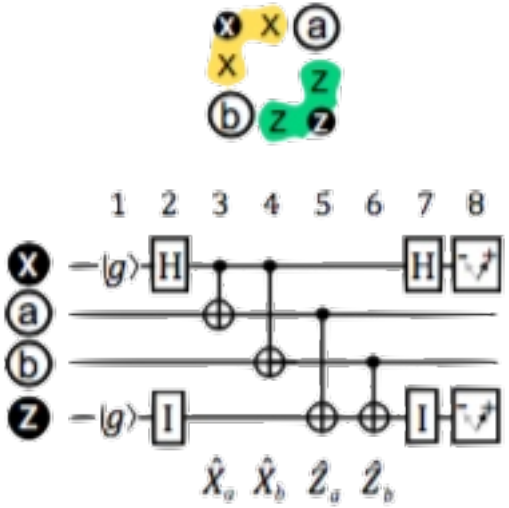


A.Fowler *et al* *Phys. Rev. A* 86, 03232 (2012).

Quantum error correction

Surface Code





A.Fowler *et al* *Phys. Rev. A* 86, 03232 (2012).

THANK YOU FOR YOUR ATTENTION ;)

$$|\text{Questions}\rangle + |\text{answers}\rangle$$

Gather

Backup slides