JOURNÉES RECHERCHE & TECHNOLOGIE- IP2I - LYON

cnrs IN2P3

iP2i LES 2 INFINIS LYON

Université Claude Bernard Lyon 1

Du 17 au 19 octobre 2022

Campus LyonTech – La Doua

4, rue Enrico Fermi

69622 Villeurbanne Cedex

Journées R&T 2022

Programmation des processeurs quantiques

Bogdan VULPESCU (Laboratoire de Physique de Clermont)

pour le projet QC2I (Quantum Computing pour les Deux Infinis)

L'abstraction RAM (Random Access Machine)

problème ⇒ algorithme ⇒ programme ⇒ exécution + I/O sur une machine

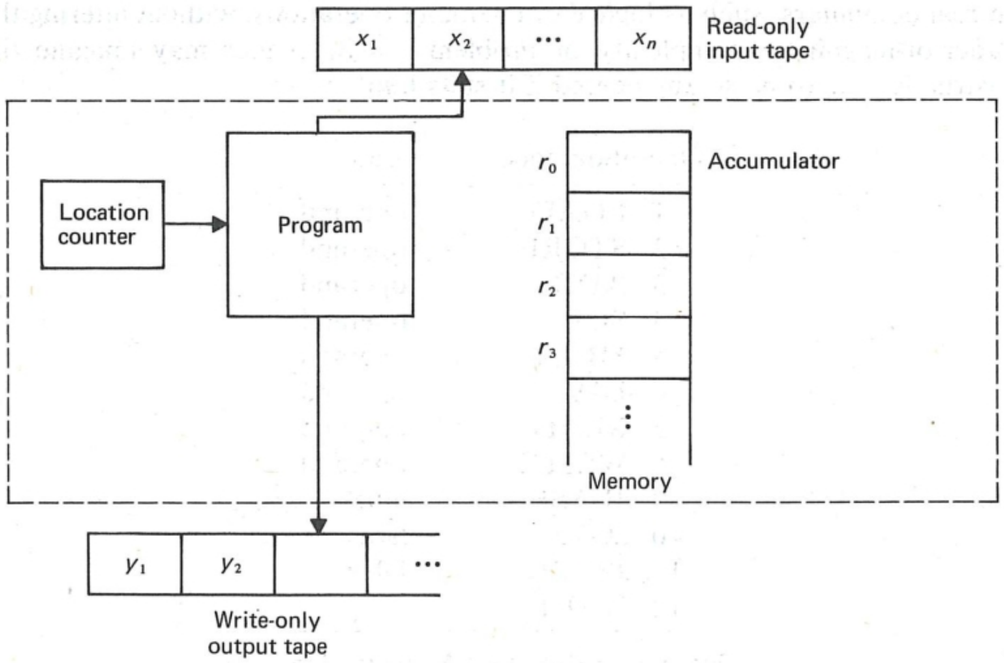


Fig. 1.3 A random access machine.

Instruction	Meaning
1. LOAD *a*	$c(0) \leftarrow v(a)$
2. STORE *i*	$c(i) \leftarrow c(0)$
STORE $*i$	$c(c(i)) \leftarrow c(0)$
3. ADD *a*	$c(0) \leftarrow c(0) + v(a)$
4. SUB *a*	$c(0) \leftarrow c(0) - v(a)$
5. MULT *a*	$c(0) \leftarrow c(0) \times v(a)$
6. DIV *a*	$c(0) \leftarrow \lfloor c(0)/v(a) \rfloor$†
7. READ *i*	$c(i) \leftarrow$ current input symbol.
READ $*i$	$c(c(i)) \leftarrow$ current input symbol. The input tape head moves one square right in either case.
8. WRITE *a*	$v(a)$ is printed on the square of the output tape currently under the output tape head. Then the tape head is moved one square right.
9. JUMP *b*	The location counter is set to the instruction labeled *b*.
10. JGTZ *b*	The location counter is set to the instruction labeled *b* if $c(0) > 0$; otherwise, the location counter is set to the next instruction.
11. JZERO *b*	The location counter is set to the instruction labeled *b* if $c(0) = 0$; otherwise, the location counter is set to the next instruction.
12. HALT	Execution ceases.

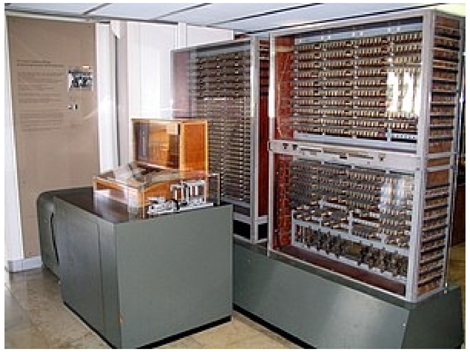
† Throughout this book, $\lceil x \rceil$ (*ceiling* of *x*) denotes the least integer equal to or greater than *x*, and $\lfloor x \rfloor$ (*floor*, or *integer part* of *x*) denotes the greatest integer equal to or less than *x*.

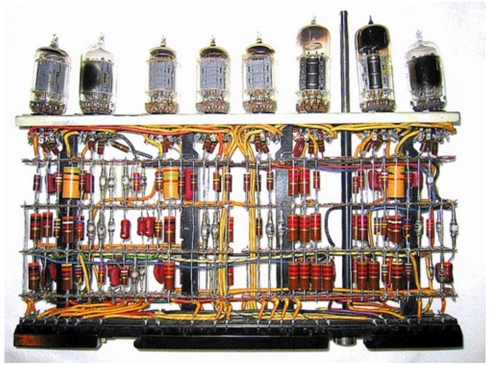
Fig. 1.5. Meaning of RAM instructions. The operand *a* is either $=i$, *i*, or $*i$.

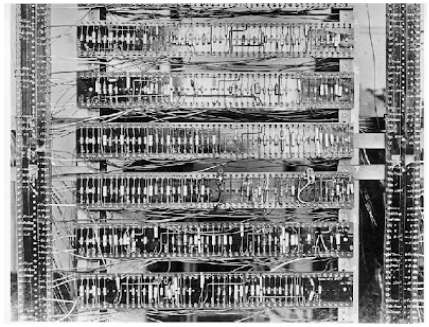
The design and analysis of computer algorithms

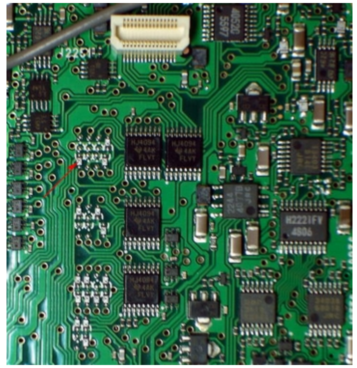
Aho, Hopcroft, Ullman, 1974

Le processeur classique


électro-mécanique


tubes


transistors


circuits intégrés

Set universel de portes : AND, OR, NOT, FANOUT (ou COPY)

$f:\{0,1\}^m \rightarrow \{0,1\}^n$ equivalent à $f_i:\{0,1\}^m \rightarrow \{0,1\}$ $(i=1,2,\ldots,n)$

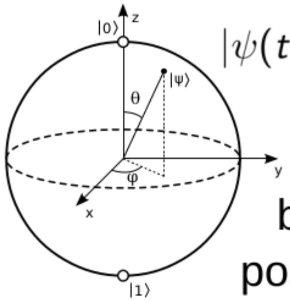
pour l'argument: $a=(a_{m-1}, a_{m-2}, \ldots, a_1, a_0)$ on calcule le minterms: $f_i^{(l)}(a)$

$f_i^{(l)}(a)=1$ si $a=a^{(l)}$ et 0 autrement, pour toute valeur de l'argument a du domaine de f

exemple: $a^{(l)}=110100\ldots001$ $\rightarrow$ $f_i^{(l)}(a)=a_{m-1}\wedge a_{m-2}\wedge \overline{a_{m-3}}\wedge a_{m-4}\wedge a_{m-5}\ldots\wedge \overline{a_2}\wedge \overline{a_1}\wedge a_0$

et finalement: $f_i(a)=f_i^{(1)}\vee f_i^{(2)}\vee\ldots\vee f_i^{(k)}$

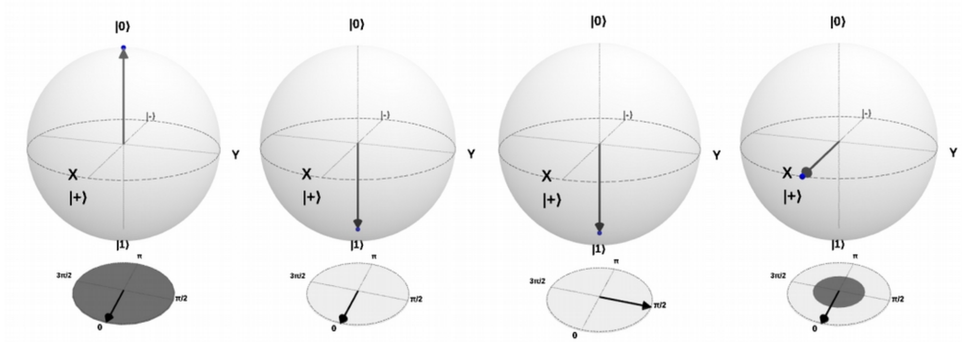
Les « opérations » quantiques



$|\psi(t)\rangle = \alpha(t)\,|0\rangle + \beta(t)\,|1\rangle$ Un qubit est décrit par une **fonction d'onde**, en général une combinaison linéaire des deux états possibles. La **sphère Bloch** offre une interprétation intuitive pour les **vecteurs d'état** situés sur sa surface

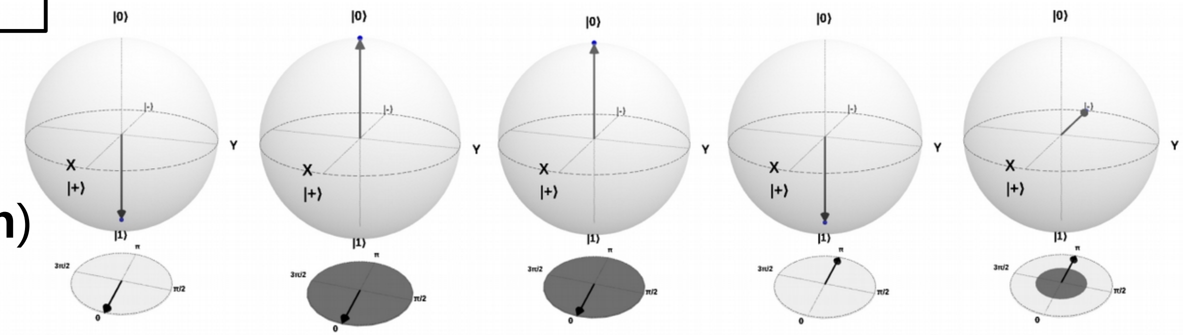
$$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle = \begin{bmatrix}\cos\frac{\theta}{2} \\ e^{i\phi}\sin\frac{\theta}{2}\end{bmatrix}$$

l'espace des états d'un seul qubit étant un espace vectoriel à 2 dimensions.



$\theta=0$
$\phi=0$

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \quad X=\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix} \quad Y=\begin{bmatrix}0 & -i\\i & 0\end{bmatrix} \quad H=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$$



$\theta=\pi$
$\phi=0$

$$|1\rangle = \begin{bmatrix}0\\1\end{bmatrix} \quad X=\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix} \quad Y=\begin{bmatrix}0 & -i\\i & 0\end{bmatrix} \quad Z=\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix} \quad H=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$$

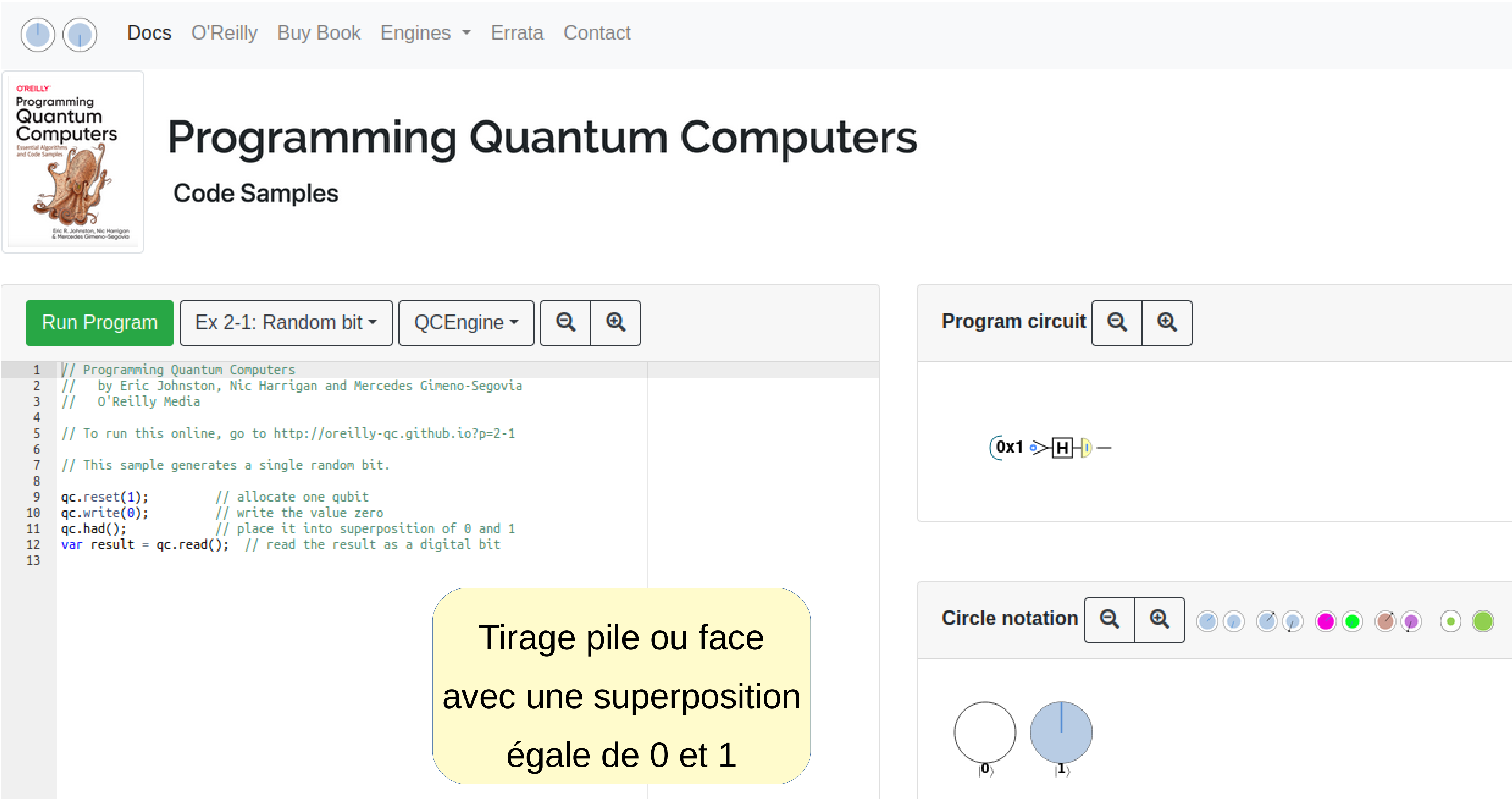
Un seul qubit :

- espace de valeurs infini (**superposition**)
- transformations unitaires

Deux qubits :

- **interférence** (phase)
- **intrication** (communication)

Quel langage ?



Tirage pile ou face avec une superposition égale de 0 et 1

https://oreilly-qc.github.io/

Qiskit https://qiskit.org/

```python
from qiskit import QuantumCircuit, QuantumRegister, ClassicalRegister, execute, Aer, IBMQ, BasicAer
import math
## Uncomment the next line to see diagrams when running in a notebook
#%matplotlib inline

## Example 2-1: Random bit
# Set up the program
reg = QuantumRegister(1, name='reg')
reg_c = ClassicalRegister(1, name='regc')
qc = QuantumCircuit(reg, reg_c)

qc.reset(reg)          # write the value 0
qc.h(reg)              # put it into a superposition of 0 and 1
qc.measure(reg, reg_c) # read the result as a digital bit

backend = BasicAer.get_backend('statevector_simulator')
job = execute(qc, backend)
result = job.result()

counts = result.get_counts(qc)
print('counts:',counts)

outputstate = result.get_statevector(qc, decimals=3)
print(outputstate)
qc.draw()        # draw the circuit
```

Q#

```
namespace QSharp.Chapter2
{
    open Microsoft.Quantum.Canon;
    open Microsoft.Quantum.Intrinsic;

    // Example 2-1: Random bit

    operation RandomBit () : Unit {
        // allocate one qubit
        use q = Qubit();
        // put it into superposition of 0 and 1
        H(q);

        // measure the qubit and store the result
        let bit = M(q);

        // make sure the qubit is back to the 0 state
        Reset(q);

        Message($"{bit}");
    }
}
```

https://learn.microsoft.com/en-us/azure/quantum/install-overview-qdk

Cirq

https://quantumai.google/cirq

https://github.com/quantumlib/cirq

```python
def main():
    qc = QPU()
    qc.reset(1)
    qc.had()  # put it into a superposition of 0 and 1
    qc.read() # read the result as a digital bit

    qc.draw() # draw the circuit
    result = qc.run() # run the circuit
    print(result)


########################################################################
## The below class is a light interface, to convert the
## book's syntax into the syntax used by Cirq.
class QPU:
    def __init__(self):
        self.circuit = cirq.Circuit()
        self.simulator = cirq.Simulator()
        self.qubits = None

    def reset(self, num_qubits):
        self.qubits = [cirq.GridQubit(i, 0) for i in range(num_qubits)]

    def mask_to_list(self, mask):
        return [q for i,q in enumerate(self.qubits) if (1 << i) & mask]

    def had(self, target_mask=~0):
        target = self.mask_to_list(target_mask)
        self.circuit.append(cirq.H.on_each(*target))

    def read(self, target_mask=~0, key=None):
        if key is None:
```

+ Amazon Braket SDK

+ etc.

OpenQASM : le standard ?

https://github.com/openqasm/openqasm

OpenQASM 3.x Live Specification

https://openqasm.com/

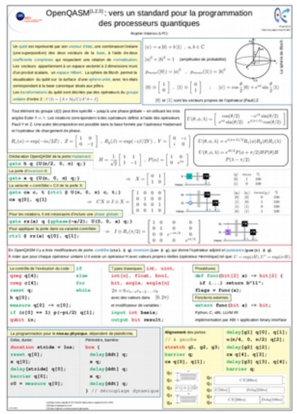
```
OPENQASM 2.0;
include "qelib1.inc";

qreg q[5];
creg c[5];

h q[0];
measure q[0] -> c[0];
```

Un langage de type IR (Intermediate Representation)

(voir Poster)



Un programme est un circuit

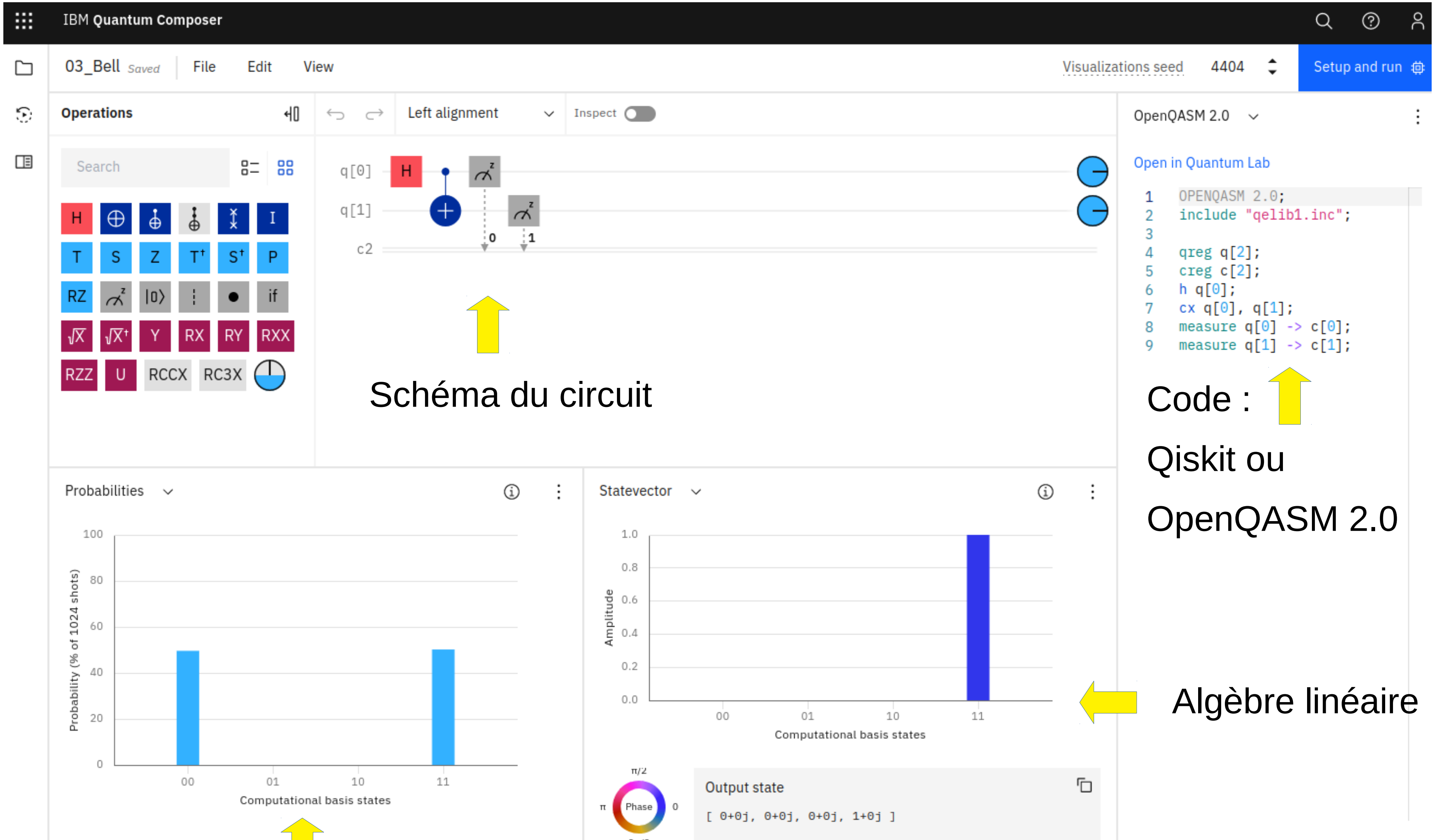


Schéma du circuit

Code :

Qiskit ou

OpenQASM 2.0

Algèbre linéaire

Mesures (probabilités)

IBM Quantum Experience

ibmq_quito

Details

5 Qubits	Status:	Online	Avg. CNOT Error:	1.053e-2
16 QV	Total pending jobs:	172 jobs	Avg. Readout Error:	4.374e-2
2.5K CLOPS	Processor type:	Falcon r4T	Avg. T1:	87.41 us
	Version:	1.1.34	Avg. T2:	82.22 us
	Basis gates:	CX, ID, RZ, SX, X	Providers with access:	1 Providers
	Your usage:	4 jobs		

Your upcoming reservations 0

Calibration data — Last calibrated: about 7 hours ago

Map view | Graph view | Table view

Qubit:

Frequency (GHz)

Avg 5.184

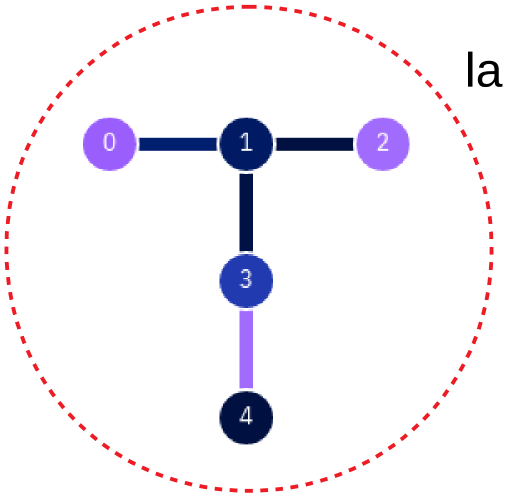
min 5.052 max 5.322

Connection:

CNOT error

Avg 1.053e-2

min 8.380e-3 max 1.581e-2



la topologie des registres de qubits (hardware), ici la configuration Falcon de IBM Quantum

Transpiler = compiler

(exemple avec le circuit pour créer l'état Bell)

$$CX=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$$, fait partie des portes natives du processeur de type Falcon

$$H=\frac{1}{\sqrt{(2)}}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$$, (porte d'Hadamard) ne fait pas partie ...

doit être obtenu à partir des portes CX, ID, RZ, SX, X:

$$U=RZ(\pi/2)\cdot SX\cdot RZ(\pi/2)$$

$$RZ(\theta)=\exp(-i\,\theta/2\,Z) \quad , \quad Z=\begin{bmatrix}1&0\\0&-1\end{bmatrix} \quad , \quad SX=\frac{1}{2}\begin{bmatrix}1+i&1-i\\1-i&1+i\end{bmatrix} \quad ,$$

$$RZ(\pi/2)=\begin{bmatrix}\exp(-i\,\pi/4)&0\\0&\exp(+i\,\pi/4)\end{bmatrix}$$

→

$$U=\exp(-i\,\pi/4)\cdot H$$

Amazon Braket (sur AWS)

QPU : Rigetti* (1, supercond.), IonQ (1, ions piégés), OQC (1, supercond.)

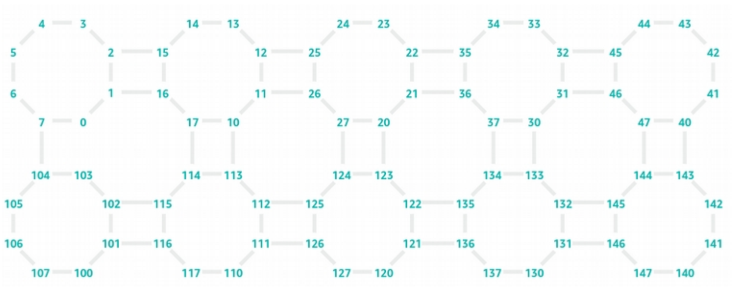
Xanadu (1, photons), D-Wave (3, supercond.)

Simulateurs : SV1, TN1, DM1

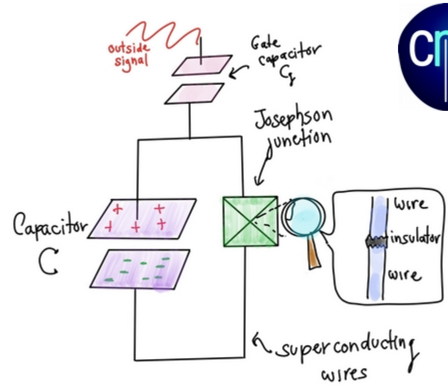
	Hardware provider ▲	Device ▽	Availability	Description
○	Amazon Web Services	SV1	AVAILABLE NOW	Amazon Braket state vector simulator
○	Amazon Web Services	TN1	AVAILABLE NOW	Amazon Braket tensor network simulator
○	Amazon Web Services	DM1	AVAILABLE NOW	Amazon Braket density matrix simulator
○	D-Wave	Advantage_system6.1	AVAILABLE NOW	Quantum Annealer based on superconducting qubits
○	D-Wave	Advantage_system4.1	AVAILABLE NOW	Quantum Annealer based on superconducting qubits
○	D-Wave	DW_2000Q_6	AVAILABLE NOW	Quantum Annealer based on superconducting qubits
○	IonQ	IonQ Device	AVAILABLE NOW	Universal gate-model QPU based on trapped ions
○	Oxford Quantum Circuits	Lucy	18:10:37	Universal gate-model QPU based on superconducting qubits
○	Rigetti	Aspen-11	OFFLINE	Universal gate-model QPU based on superconducting qubits
○	Rigetti	Aspen-M-2	00:10:38	Universal gate-model QPU based on superconducting qubits
○	Xanadu	Borealis	00:10:38	Gaussian Boson Sampling on a programmable photonic processor

*Rigetti ⇒ https://pyquil-docs.rigetti.com/en/stable/compiler.html

Rigetti Aspen-M-2



x80



Circuit with a Josephson junction and a gate capacitor

https://pennylane.ai

```
device = AwsDevice("arn:aws:braket:us-west-1::device/qpu/rigetti/Aspen-M-2")
supported_gates = device.properties.action['braket.ir.jaqcd.program'].supportedOperatio
print('Gate set supported by the Rigetti device:\n', supported_gates)
print('\n')
```

```
Gate set supported by the Rigetti device:
 ['cz', 'xy', 'ccnot', 'cnot', 'cphaseshift', 'cphaseshift00', 'cphaseshift01', 'cphaseshift10', 'cswap', 'h', 'i',
'iswap', 'phaseshift', 'pswap', 'rx', 'ry', 'rz', 's', 'si', 'swap', 't', 'ti', 'x', 'y', 'z', 'start_verbatim_box',
'end_verbatim_box']
```

Calibration

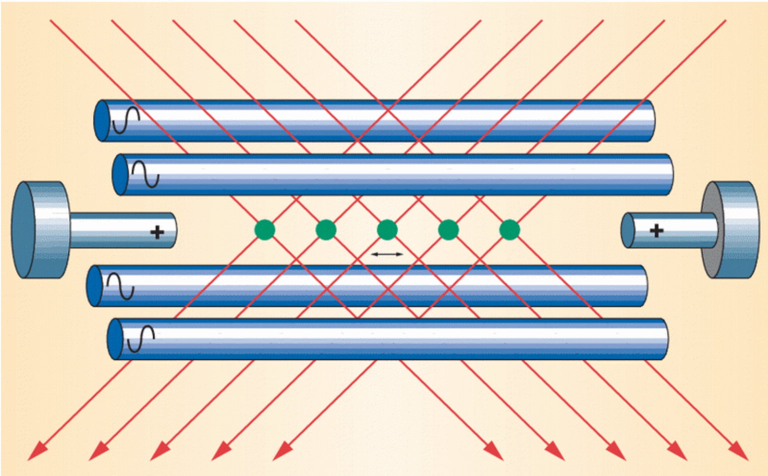
Last updated: Oct 04, 2022 15:01 (UTC) Info

Qubit specs | Edge specs | JSON

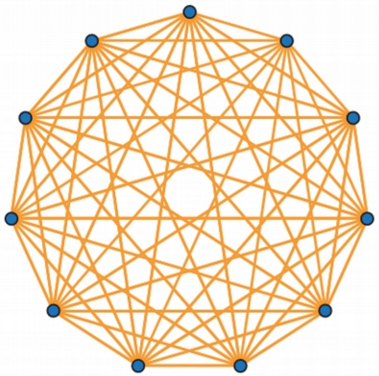
Qubit

Qubit	T1 (μs) Info	T2 (μs) Info	Fidelity (RB) (%) Info	Fidelity (simultaneous RB) (%) Info	Readout fidelity (%) Info	Active reset fidelity (%) Info
0	4.174	26.639	97.489 ± 0.363	98.366 ± 0.177	87.400	92.650
1	40.553	11.582	99.697 ± 0.018	99.599 ± 0.027	82.700	97.700
2	28.995	18.911	99.899 ± 0.007	99.792 ± 0.006	98.200	99.400
3	62.428	49.743	99.916 ± 0.020	99.855 ± 0.020	98.700	98.100
4	23.797	38.484	99.916 ± 0.011	99.780 ± 0.010	98.800	99.800
5	30.658	22.566	99.734 ± 0.034	99.788 ± 0.127	96.100	97.800
6	39.530	6.143	99.859 ± 0.027	99.684 ± 0.011	95.200	98.600
7	56.242	113.004	99.909 ± 0.011	99.854 ± 0.019	93.300	99.700

La technologie des ions piégés



Beyond Bits: The Future of Quantum Information Processing.
Andrew Steane, Eleanor G. Rieffel



11 qubits

IonQ

Calibration

Last updated: Oct 04, 2022 11:00 (UTC)


```
{
  "braketSchemaHeader": {
    "name": "braket.device_schema.ionq.ionq_provider_properties",
    "version": "1"
  },
  "fidelity": {
    "1Q": {
      "mean": 0.9954
    },
    "2Q": {
      "mean": 0.992
    },
    "spam": {
      "mean": 0.99752
    }
  },
  "timing": {
    "T1": 10000,
    "T2": 0.2,
    "1Q": 0.00001,
    "2Q": 0.0002,
    "readout": 0.00013,
    "reset": 0.00002
  }
}
```


```
device = AwsDevice("arn:aws:braket:::device/qpu/ionq/ionQdevice")
supported_gates = device.properties.action['braket.ir.jaqcd.program'].supportedOperations
print('Gate set supported by the IonQ device:\n', supported_gates)
print('\n')
```

```
Gate set supported by the IonQ device:
 ['x', 'y', 'z', 'rx', 'ry', 'rz', 'h', 'cnot', 's', 'si', 't', 'ti', 'v', 'vi', 'xx', 'yy', 'zz', 'swap', 'i']
```

Calcul mathématique versus représentation sous forme de qubits + série de circuits (évolution)

https://arxiv.org/abs/2104.08181 (Ruiz Guzman, Lacroix 2021)

are labeled as $i = 0, 1, \ldots, M-1$. This Hamiltonian is written as $H = H_J + H_U$, where H_J and H_U are the hopping and interaction terms respectively given by:

$$H_J = -J \sum_{i,\sigma} (a^\dagger_{i+1,\sigma} a_{i,\sigma} + a^\dagger_{i,\sigma} a_{i+1,\sigma}),$$
$$H_U = +U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow},$$

with $n_{i,\sigma} = a^\dagger_{i,\sigma} a_{i,\sigma}$ and $\sigma = \{\uparrow, \downarrow\}$. In order to apply the JWT mapping, it is convenient to organize the qubits as follows. Spin-up single-particle states indexed as $i = 0, \ldots, M-1$ are associated with qubits labeled with $\alpha = 0, \ldots, M-1$. Particles with spin-down indexed as $i = 0, \ldots, M-1$ are associated to qubits $\alpha = M, \ldots, 2M-1$. With this, we obtain the mapping (with proper account for the boundary conditions):

$$H_J = J \sum_{\alpha=0, \alpha \neq M-1}^{2M-2} \left[Q^+_{\alpha+1} Q_\alpha + \text{h.c.} \right],$$

together with

$$H_U = \frac{U}{4} \sum_{\alpha=0,M-1} \left[I_\alpha - Z_\alpha \right] \left[I_{\alpha+M} - Z_{\alpha+M} \right]. \quad (6)$$

The generating function evaluation with the circuits presented in Fig. 1 requires to perform the time-evolution operator. For its implementation, we simply use the Trotter-Suzuki method [25, 49]. The time interval $[0, t]$ is divided into small intervals Δt. For small enough time interval, we have:

$$U(\Delta t) = e^{-i\Delta t H} \simeq e^{-i\Delta t H_J} e^{-i\Delta t H_U} \equiv U_J(\Delta t) U_U(\Delta t).$$

The propagators U_J can be further decomposed as:

$$U_J(\Delta t) = \prod_\alpha e^{-iJ\Delta t [Q^+_{\alpha+1} Q_\alpha + \text{h.c.}]},$$
$$= \prod_\alpha \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\lambda) & -i\sin(\lambda) & 0 \\ 0 & -i\sin(\lambda) & \cos(\lambda) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}_{\alpha,\alpha+1} \quad (7)$$

with $\lambda = \Delta t J$. To obtain the matrix form, standard manipulation of Pauli matrices is used. Note that the index on the matrix indicates that the matrix acts on the two qubits α and $\alpha + 1$.

For the interaction propagator we have

$$U_U(\Delta t) = \prod_\alpha e^{-iU\Delta t [I_\alpha - Z_\alpha][I_{\alpha+M} - Z_{\alpha+M}]},$$
$$= \prod_\alpha \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{-i\Delta t U} \end{pmatrix}_{\alpha,\alpha+M}. \quad (8)$$

We recognize in the last expression the controlled phase-shift gate with phase $\phi = -\Delta t U$. The two circuits that simulate U_U and U_J are displayed in panels (a) and (b) of Fig. 2.

2. Pairing Hamiltonian

As a second illustration, we will also consider the pairing Hamiltonian [50–53] that is standardly used in the context of nuclear physics or small superconducting systems. This Hamiltonian has already been used on QC in Refs. [37, 38] and more recently in Refs. [31, 54]. We write this Hamiltonian as:

$$H = \sum_p \varepsilon_p N_p + g \sum_{pq} P^\dagger_p P_q \equiv H_\varepsilon + H_g. \quad (9)$$

Introducing the notation $(a^\dagger_p, a^\dagger_{\bar{p}})$ as the creation operators of time-reversed single-particle states. The different operators are defined as:

$$\hat{N}_p = a^\dagger_p a_p + a^\dagger_{\bar{p}} a_{\bar{p}},$$
$$\hat{P}^\dagger_p = a^\dagger_p a^\dagger_{\bar{p}}.$$

These operators correspond respectively to the pair occupation, and to the pair creation operators. In this model, time-reversed single-particle states are degenerated with

Problème de physique

↓

formulation

↓

modèle de calcul

↓

programmation

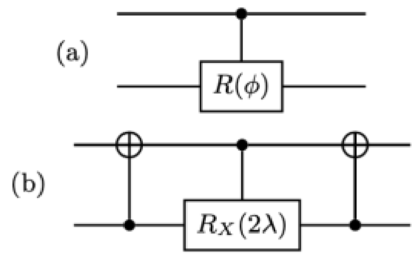
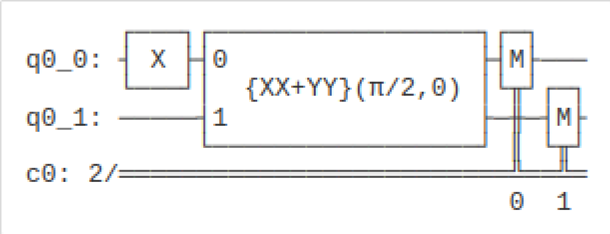


FIG. 2: Circuits used to simulate the Hubbard model. The circuit (a) simulates the interaction term H_U where $R(\phi)$ is the unitary phase operator with $\phi = -\Delta t U$. Circuit (b) simulates a short time-step evolution of the hopping term H_J where $R_X(2\lambda) = e^{-i\lambda X}$ and where $\lambda = J\Delta t$.

Simulateurs / émulateurs

Qiskit

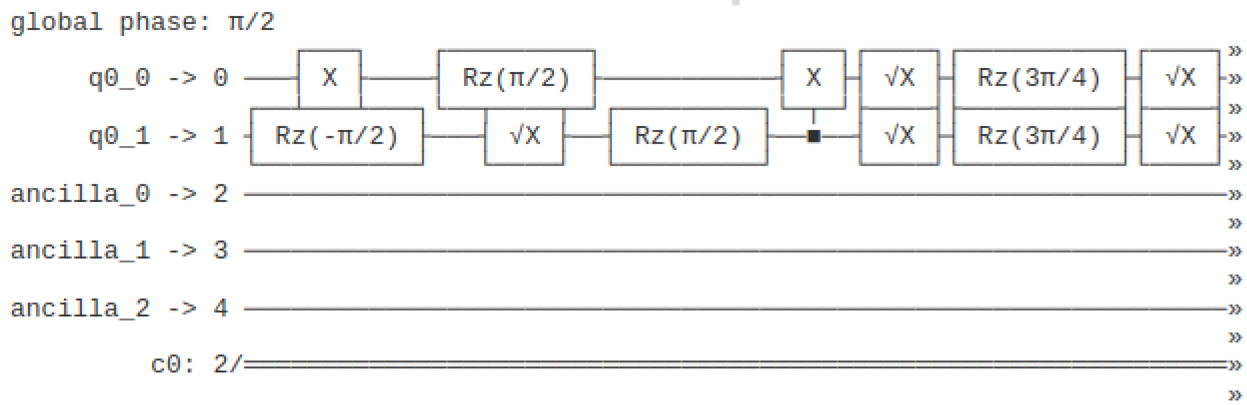


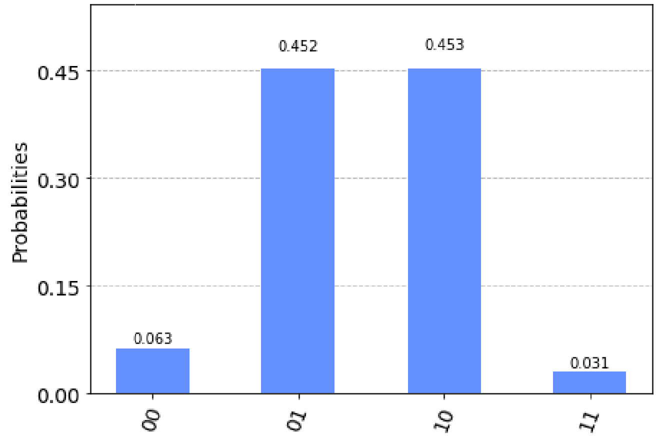
Pourquoi simuler ?

- pour comprendre la modélisation et l'optimiser
- pour adapter à une topologie spécifique de QPU
- pour essayer de mitiger les effets du bruit quantique

```
from qiskit.circuit.library import XXPlusYYGate
qr = QuantumRegister(2)
cr = ClassicalRegister(2)
qc = QuantumCircuit(qr, cr)
qc.x(qr[0])
theta = pi/2
XY = XXPlusYYGate(theta, beta)
qc.append(XY, qr)
qc.measure(qr, cr)
qc.draw()
```

```
from qiskit.providers.aer import AerSimulator
from qiskit.providers.fake_provider import FakeQuitoV2
backend = FakeQuitoV2()
backend_sim = AerSimulator.from_backend(backend)
transpiled_circuit = transpile(qc, backend_sim)
job = backend_sim.run(transpiled_circuit)
counts = job.result().get_counts()
plot_histogram(counts)
```





Simuler la théorie (pas seulement la mesure)

Amazon Braket

```
from braket.circuits import Circuit, Observable
from braket.devices import LocalSimulator
circ = Circuit().rx(0, 0.15).ry(1, 0.2).rz(2, 0.25).h(3).cnot(control=0,
        target=2).cnot(1, 3).x(4)
obs = Observable.X() @ Observable.Y()
target_qubits = [0, 1]
circ.expectation(obs, target=target_qubi
circ.variance(obs, target=target_qubits)
circ.sample(obs, target=target_qubits)
device = LocalSimulator()
task = device.run(circ, shots=100)
result = task.result()
print("Expectation value for <X0*Y1>:", result.values[0])
...
circ.state_vector()
task = device.run(circ, shots=0)
result = task.result()
print("Final state vector:\n",
result.values[0])
```

```
T  : |    0     | 1 |              Result Types                |

q0 : -Rx(0.15)-C---Expectation(X@Y)-Variance(X@Y)-Sample(X@Y)-
               |   |               |             |
q1 : -Ry(0.20)-|-C-Expectation(X@Y)-Variance(X@Y)-Sample(X@Y)-
               | |
q2 : -Rz(0.25)-X-|--------------------------------------------
                 |
q3 : -H----------X--------------------------------------------

q4 : -X-------------------------------------------------------

T  : |    0     | 1 |              Result Types                |
```

```
Final state vector:
 [-0.41050209-0.56896874j  0.        +0.j         -0.22402587-0.66486826j
  0.        +0.j          0.        +0.j          0.        +0.j
  0.        +0.j          0.        +0.j         -0.02902509-0.06413206j
  0.        +0.j         -0.00877641-0.0698452j   0.        +0.j
  0.        +0.j          0.        +0.j          0.        +0.j
  0.        +0.j          0.        +0.j          0.        +0.j
  0.        +0.j          0.        +0.j         -0.00457713+0.00265117j
  0.        +0.j         -0.00515618+0.00118012j  0.        +0.j
  0.        +0.j          0.        +0.j          0.        +0.j
  0.        +0.j         -0.04995883+0.01683351j  0.        +0.j
 -0.05270213+0.00131783j  0.        +0.j        ]
```

$(2^5 = 32 \ \text{ nombres complexes})$

Hybride : CPU + QPU (tasks et jobs)

Amazon Braket

Script Python : `script.py`

```
from braket.aws import AwsDevice
from braket.circuits import Circuit
from braket.jobs import save_job_result
device = AwsDevice(os.environ["DEVICE_ARN"])
counts_list = []
angle_list = []
for _ in range(5):
    angle = np.pi * np.random.randn()
    random_circuit = Circuit().rx(0, angle)
    task = device.run(random_circuit, shots=100)
    counts = task.result().measurement_counts
    angle_list.append(angle)
    counts_list.append(counts)
    print(counts)
save_job_result({"counts": counts_list, "angle": angle_list})
print("Test job completed!")
```

```
from braket.aws import AwsQuantumJob
job = AwsQuantumJob.create(device=
"arn:aws:braket:::device/quantum-
simulator/amazon/sv1", source_module=
"script.py", entry_point= "",
wait_until_complete= True)
```

synchrone ou asynchrone

```
results = job.result()
print("counts: ", results["counts"])
print("angles: ", results["angles"])
job.download_result()
```

S'exécute à l'intérieur d'un container Docker dans le Cloud de Calcul Élastique Amazon (EC2).

Conclusions

La programmation des processeurs quantiques aujourd'hui :

- des outils pour décrire la nature quantique des *éléments de calcul*
- des outils pour simuler (algèbre linéaire, statistique quantique)
- des commandes pour manipuler expérimentalement les qubits
- des élément *classiques* de programmation
- dépendent de l'interface vers le QPU (le fabricant) : Qiskit, Cirq, Q#, ...
- OpenQASM se profile comme un langage intermédiaire (IR) sur deux niveaux : logique et physique (voir poster)
  - initialement par IBM, récemment adopté par Amazon Braket pour les QPU mis à disposition par ses partenaires: Rigetti, IonQ, OQC

- ceci n'est pas une revue des langages existant aujourd'hui...

Merci de votre attention !

Connie Zhou for IBM (dans QuantaMagazine)