

(\*) IBM's quantum device. Source: Wikipedia (CC BY 4.0)

# Como Programar Computadores Quânticos Reais

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Setembro/2021

# Objetivos desta apresentação

- **O que é a CQ?**

Trata-se de usar a mecânica quântica para resolver alguns problemas mais eficientemente

- **O que a CQ não é?**

Não é mágica! Ou seja, nem todo problema fica eficiente em computadores quânticos

- **O que temos hoje?**

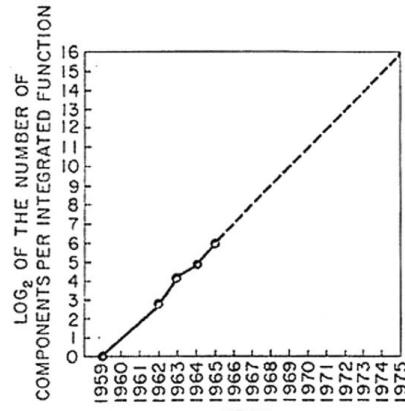
Posso MESMO programar um computador quântico real?

- **O que teremos no futuro?**

Quais setores beneficiados no curto, médio e longo prazo

# Os limites da computação clássica

## ■ Lei de Moore

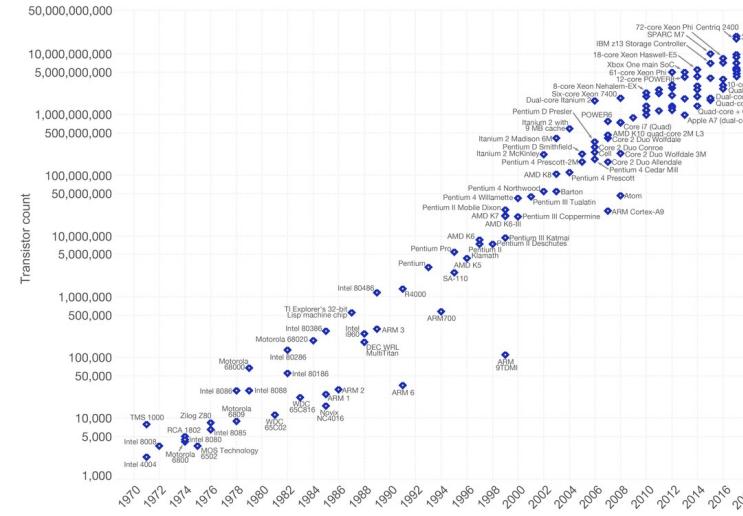


(\*) Gordon Moore's original graph, Source: Electronics, 1965



### Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.

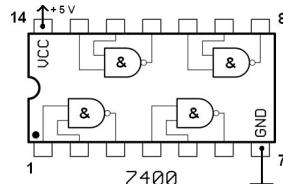


Data source: Wikipedia ([https://en.wikipedia.org/wiki/Transistor\\_count](https://en.wikipedia.org/wiki/Transistor_count))  
The data visualization is available at OurWorldInData.org. There you find more visualizations and research on this topic.

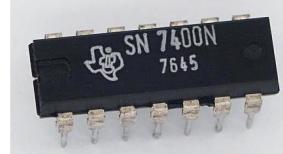
OurWorld  
in Data

Licensed under CC-BY-SA by the author Max Roser.

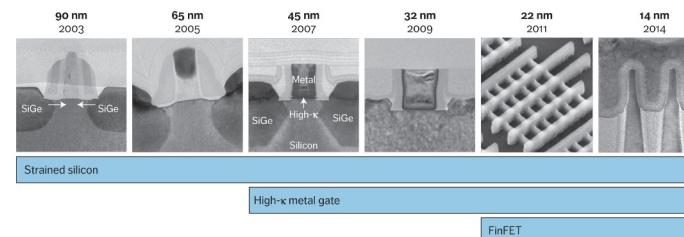
## ■ Miniaturização



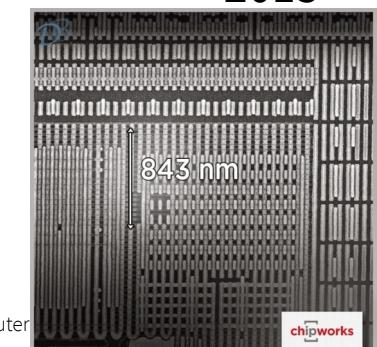
1960s



(\*) Texas IC containing 4 NAND gates. Source: Wikipedia



(\*) Source: IEEE Micro, [www.computer.org](http://www.computer.org)



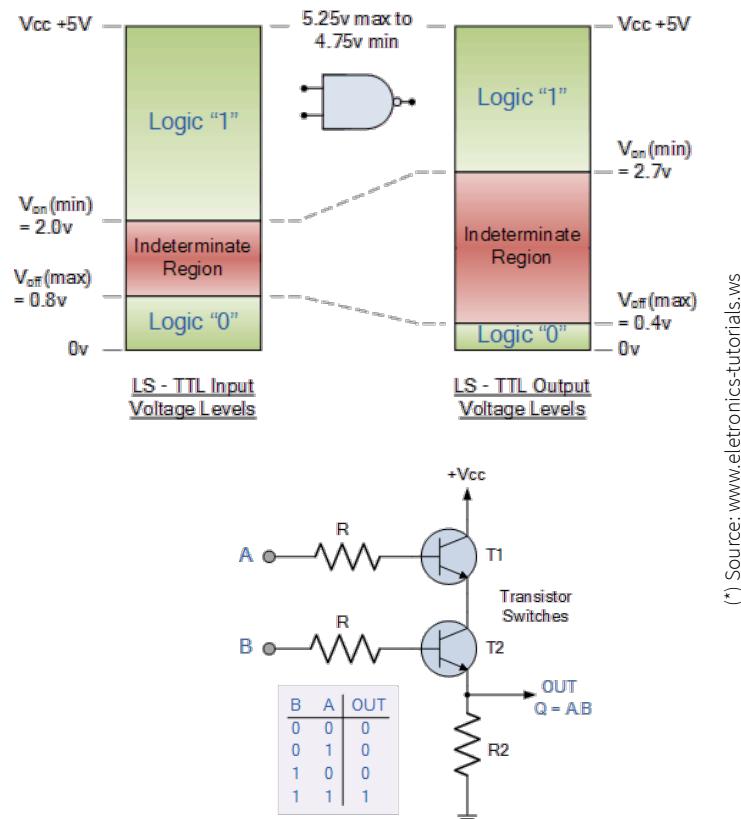
# Mecânica quântica



- **As regras do jogo, ou seja, os postulados da mecânica quântica**
  - ▷ Representação
  - ▷ Evolução
  - ▷ Medições
  - ▷ Composição
- **Conselho para estudantes:**  
**Keep Calm**  
**and**  
**Learn Linear Algebra**

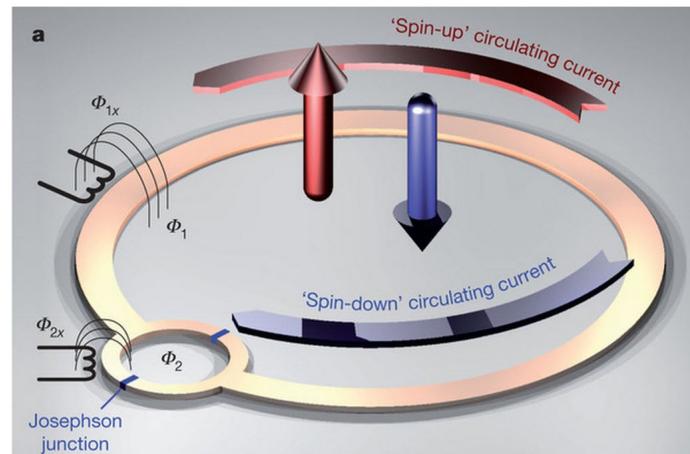
# Apresentando os bits quânticos

- Bits (clássicos) podem ser 0 ou 1



(\*) Source: [www.electronics-tutorials.ws](http://www.electronics-tutorials.ws)

- Bits quânticos (qubits) pode ser um vetor (1,0) ou um vetor (0,1) ou qualquer combinação deles



(\*) Superconducting qubit. Source: "Quantum annealing with manufactured spins", Nature, 2011

# Aplicações de computadores quânticos

## ▪ Simulação

- ▷ Química quântica
- ▷ Design de materiais
- ▷ Design de fármacos

## ▪ Otimização

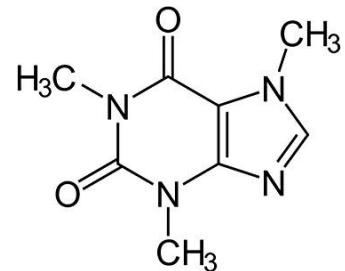
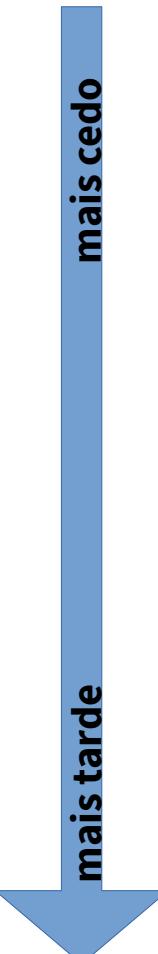
- ▷ Finanças
- ▷ Óleo & gás

## ▪ Machine learning

## ▪ Buscas

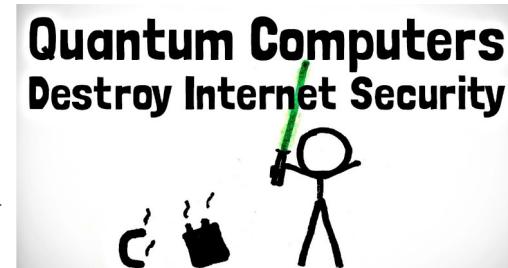
## ▪ Fatoração

## ▪ etc.



Simulação clássica,  $10^{48}$  bits  
(Mais que o número de átomos de nosso planeta!)

Simulação quântica, 160 qubits



(\*) minutephysics, Youtube

Requer muitos qubits e tolerância a falhas

# Supremacia quântica

- Usar um computador quântico para resolver um problema que não seja “possível” em um computador clássico
- Não precisa ser problema útil
- Candidatos
  - ▷ Fatoração
  - ▷ Amostragem de circuitos quânticos aleatórios
  - ▷ Amostragem de bosons

# Supremacia quântica

- Usar um computador quântico para resolver um problema que não seja “possível” em um computador clássico

- Não precisa ser problema útil

- Candidatos

- ▷ Fatoração

- ▷ Amostragem de circuitos quânticos aleatórios

- ▷ Amostragem de bosons

- Supremacia quântica já foi demonstrada! (Mesmo?)

- ▷ Simulações usando computadores clássicos só vão até 56 qubits até hoje

- ▷ 9 PB para simular 50 qubits, cada qubit adicional dobra o requisito



# Supremacia quântica

- Usar um computador quântico para resolver

um problema  
computador

- Não precisa

- Candidato

- ▷ Fatoração
- ▷ Amostragem
- ▷ Amostragem

- Supremacia

- ▷ Simulações
- qubits até h
- ▷ 9 PB para s
- requisito

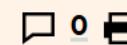
Quantum technologies

+ Add to myFT

## Google claims to have reached quantum supremacy

Researchers say their quantum computer has calculated an impossible problem for ordinary machines

Madhumita Murgia and Richard Waters SEPTEMBER 20 2019



0



Google claims to have built the first [quantum computer](#) that can carry out calculations beyond the ability of today's most powerful supercomputers, a landmark moment that has been hotly anticipated by researchers.

A paper by Google's researchers seen by the FT, that was briefly posted earlier this week on a Nasa website before being removed, claimed that their processor

28-qubit quantum computer based on an equivalent quantum processor that leverages emerging hybrid computing algorithms used to test programs and potential applications.

# Supremacia quântica

**nature**

Article | Published: 23 October 2019

## Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis 

*Nature* 574, 505–510(2019) | Cite this article

728k Accesses | 155 Citations | 6059 Altmetric | Metrics

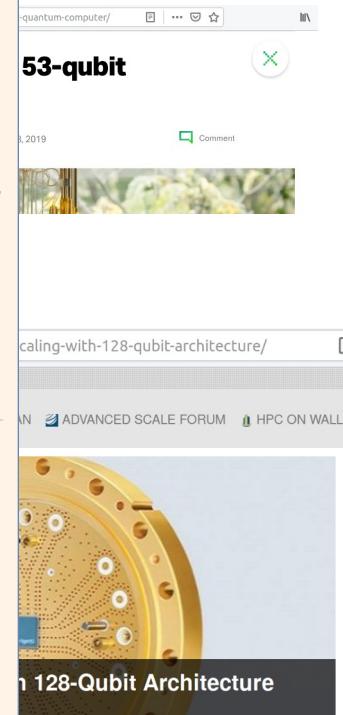
computer that can carry out calculations beyond the ability of today's most powerful supercomputers, a landmark moment that has been hotly anticipated by researchers.

- ▶ Simulações de qubits até 53 qubits
- ▶ 9 PB para superar o requisito

A paper by Google's researchers seen by the FT, that was briefly posted earlier this week on a Nasa website before being removed, claimed that their processor

 Resource Library  
 Papers

28-qubit quantum computer based on an equivalent quantum processor that leverages emerging hybrid computing algorithms used to test programs and potential applications.



# Supremacia quântica

nature

Article | Published: 23 October 2019

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qubits até h

► 9 PB para s

requisito

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Sign up to our daily email newsletter

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## It's official: Google has achieved quantum supremacy



PHYSICS 23 October 2019

By Daniel Cossins

A paper by Google's researchers seen by the FT, that was briefly posted earlier this week on a Nasa website before being removed, claimed that their processor

28-qubit quantum computer based on an equivalent quantum processor that leverages emerging hybrid computing algorithms used to test programs and potential applications.

# Supremacia quântica

**nature**

Article | Published: 23 October 2019

## Quantum program processes

Frank Arute, I

Nature 574,

728k Access

Supremacy

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## It's official: Google's quantum supremacy



PHYSICS 23 October 2019

By Daniel Cossins

► Simula

qubits até h

► 9 PB para s

requisito

A paper by Google's researchers is available [this week on a Nasa website](#)

The New York Times

Opinion

## Why Google's Quantum Supremacy Milestone Matters

The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?

By Scott Aaronson

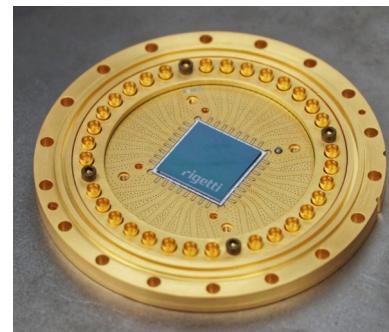
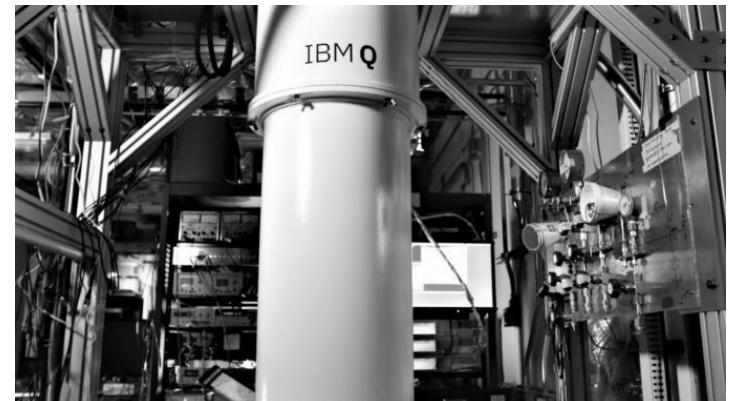
Dr. Aaronson is the founding director of the Quantum Information Center at the University of Texas at Austin.

Oct. 30, 2019



# Computadores quânticos atuais

- Para rodar um programa quântico, você vai precisar de um computador quântico!
- Já existem alguns computadores QREI disponíveis (poucos qubits, ruidosos)
  - ▷ IBM Q Experience
  - ▷ Rigetti (precisa de convite)
  - ▷ Dwave Leap (não no Brasil)
  - ▷ Xanadu Cloud (precisa de convite)
- Vários outros já foram anunciados



# Empresas

Software e consultoria



Zapata Computing



Q Branch



QILIMANJARO

|EeroQ>

Hardware quântico



... e muitas outras

# Empresas

## THE EUROPEAN QUANTUM COMPUTING STARTUP LANDSCAPE

**Hardware**

**Computing**

OQC Alice & Bob QAQT IQM  
ORCA Computing OXFORD IONICS Universal Quantum eleQtron  
the nnn project QUANTUM MOTION NextGenQ

**Components & Materials**

AegiQ QBLOX kiutra qnami  
nu QUANTUM MIRAEK Delft Circuits TORIDION  
QDevil QUANDELA TORIDION

**Software**

**Operating Systems**

QBaltic QUANTASTICA RIVERLANE ParityQC

**Applications**

QUSIDE PHASECRAFT QuBalt  
(InfiniQuant) Quantumz.io QUANTUM IMPENETRABLE  
Crypto Labs KRONUS ArQit  
Dawn Data Technologies QuantiCor QUANTUM SHIELD  
CRYPTO QUANTIQUE KETS CRYPTONEXT SECURITY QUANTOPTICON

**Security & Encryption**

**Chemistry & Pharma**

HQS QUANTUM SIMULATIONS KUANO rahko CQC |Ketita| APEXQUANTUM ChemAlive QU&Co Pharmaceleta CreativeQuantum

**Others**

(b) e³ AVANETIX QuantFi MULTIVERSE QUANTUM TerraQuantum shyn

VC UNTERNEHMERTUM VENTURE CAPITAL

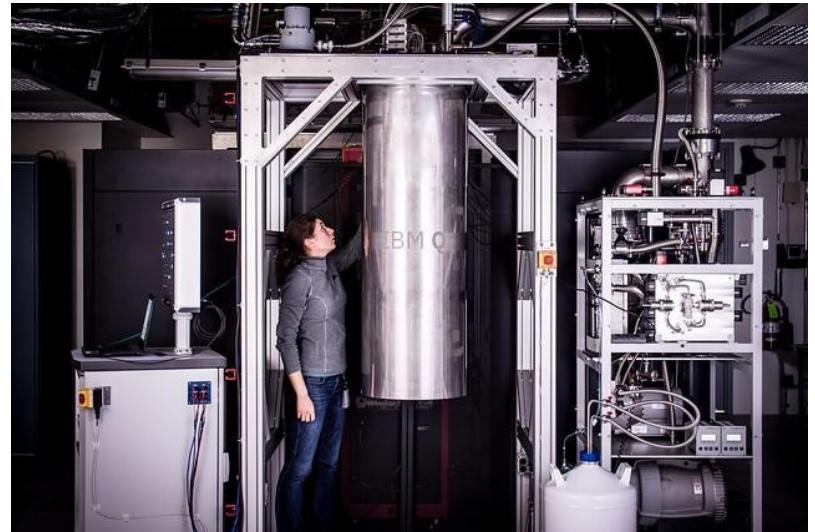
@alex\_kiltz

# Programando um computador quântico

- IBM: circuit composer, Qasm, Qiskit (Python)
- Rigetti: Forest (Python)
- Xanadu: PennyLane (Python)
- Dwave: Ocean (Python)
- Microsoft: Q#
- Outros: ProjectQ, Qubiter, etc

# IBM Quantum Experience

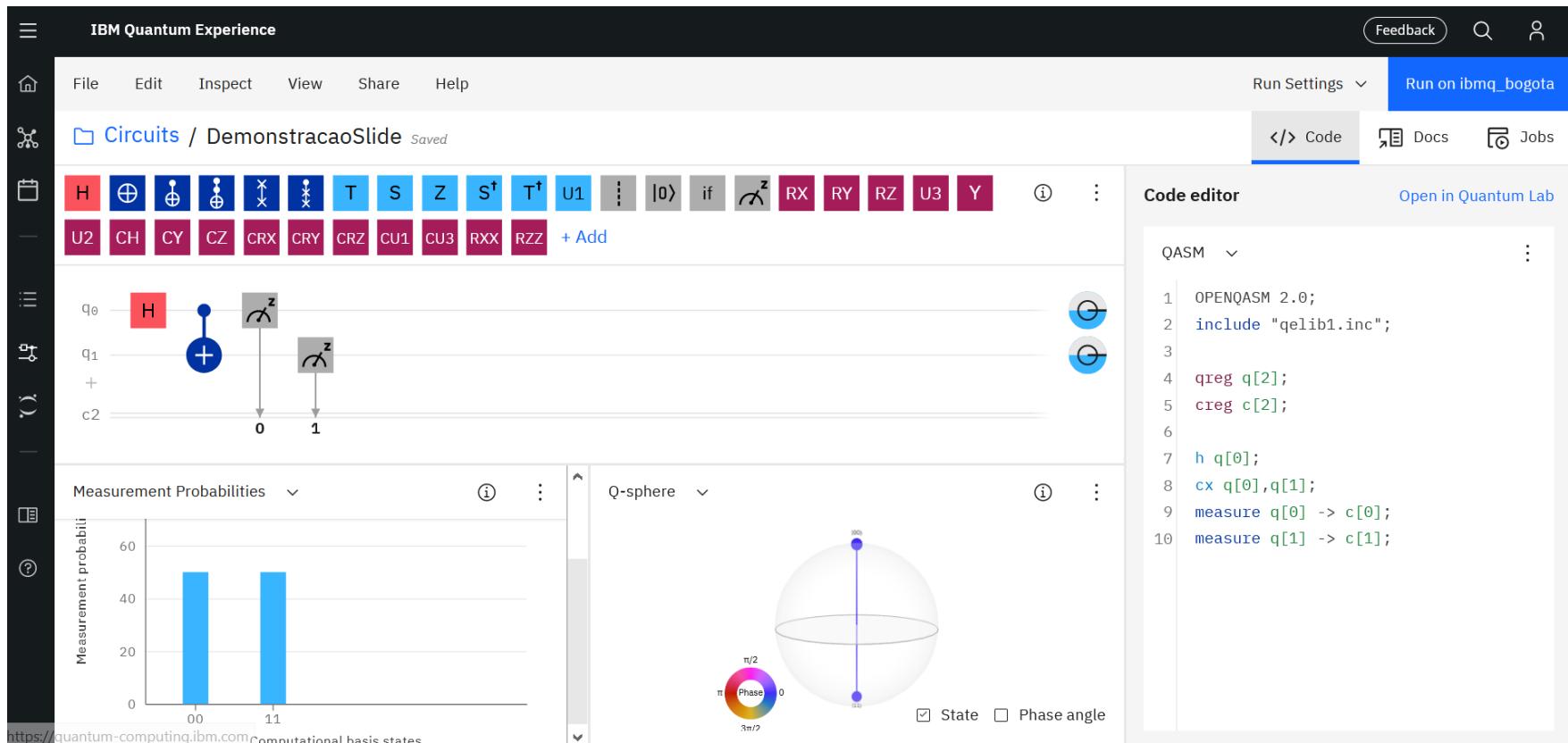
- **Boa oportunidade para experimentar computadores QREI**
- **Sistemas premium**
  - ▷ IBM Q Tokyo (20 qubits)
- **Sistemas públicos**
  - ▷ IBM Q Melbourne (14 qubits)
  - ▷ IBM Q Ourense, Vigo etc (5 qubits)
  - ▷ IBM QASM Simulator (até 32 qubits simulados)



(\*) IBM Research

# Como programar o IBM Q

- Comece online!
- Vá até <https://quantum-computing.ibm.com>
- Comece pelo Circuit Composer



IBM Quantum Experience

Feedback Run Settings Run on ibmq\_bogota

File Edit Inspect View Share Help

Circuits / DemonstracaoSlide Saved

Code editor Open in Quantum Lab

QASM

```
1 OPENQASM 2.0;
2 include "qelib1.inc";
3
4 qreg q[2];
5 creg c[2];
6
7 h q[0];
8 cx q[0],q[1];
9 measure q[0] -> c[0];
10 measure q[1] -> c[1];
```

Measurement Probabilities

State	Probability
00	50
11	50

Q-sphere

Phase angle

State

https://quantum-computing.ibm.com Computational basis states

(C) IBM Quantum Experience.  
Disclaimer: I am not an IBM Employee and I do not represent IBM.

# Como programar o IBM Q

- O código é gerado automaticamente em QASM e em Python (Qiskit)

The screenshot shows the IBM Quantum Experience web interface. The top navigation bar includes 'File', 'Edit', 'Inspect', 'View', 'Share', 'Help', 'Run Settings', and a 'Run on ibmq\_bogota' button. The left sidebar has sections for 'Circuits' and 'DemonstracaoSlide'. The main area displays a quantum circuit with three qubits (q0, q1, q2) and two classical bits (c0, c1). The circuit consists of an H gate on q0, a CNOT gate with control on q1 and target on q0, and another CNOT gate with control on q2 and target on q0. The bottom left shows a 'Measurement Probabilities' bar chart with two bars for computational basis states '00' and '11', both around 50%. The bottom right shows a 'Q-sphere' visualization with a point on the surface representing the state of the qubits.

Code editor

```
1 from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
2 from numpy import pi
3
4 qreg_q = QuantumRegister(2, 'q')
5 creg_c = ClassicalRegister(2, 'c')
6 circuit = QuantumCircuit(qreg_q, creg_c)
7
8 circuit.h(qreg_q[0])
9 circuit.cx(qreg_q[0], qreg_q[1])
10 circuit.measure(qreg_q[0], creg_c[0])
11 circuit.measure(qreg_q[1], creg_c[1])
```

(C) IBM Quantum Experience.  
Disclaimer: I am not an IBM Employee and I do not represent IBM.

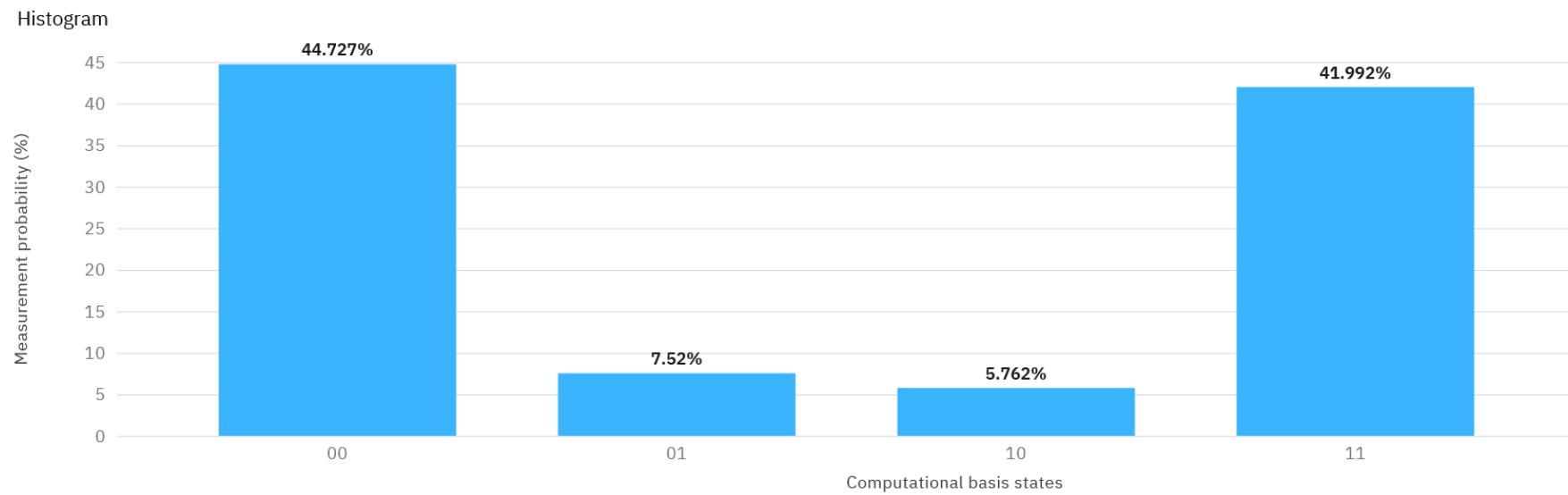
# Como programar o IBM Q

- Jobs submetidos para o computador quântico real podem demorar! Também é possível simular

The screenshot shows the IBM Quantum Experience web interface. At the top, the menu bar includes File, Edit, Inspect, View, Share, Help, Run Settings (set to 'Run on ibmq\_bogota'), and a search bar. The main workspace shows a quantum circuit with three qubits (q0, q1, q2). The circuit consists of an H gate on q0, a CNOT gate between q0 and q1, and a Z gate on q1. The measurement probabilities for the 00 and 11 states are both approximately 50%. Below the circuit, a Q-sphere visualization shows the state vector in the complex plane, with the 00 state at the top and the 11 state at the bottom. The footer contains a copyright notice: "(C) IBM Quantum Experience. Disclaimer: I am not an IBM Employee and I do not represent IBM."

# Como ler os resultados

Result



# Mapa de acoplamentos

online

ibmq\_santiago (5 qubits, QV32)



Queue: 34 jobs

online

ibmq\_bogota (5 qubits, QV32)



Queue: 14 jobs

Reservable

online

ibmq\_rome (5 qubits, QV32)

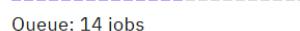


Queue: 32 jobs

1 upcoming reservations

ibmq\_bogota v1.0.4

online

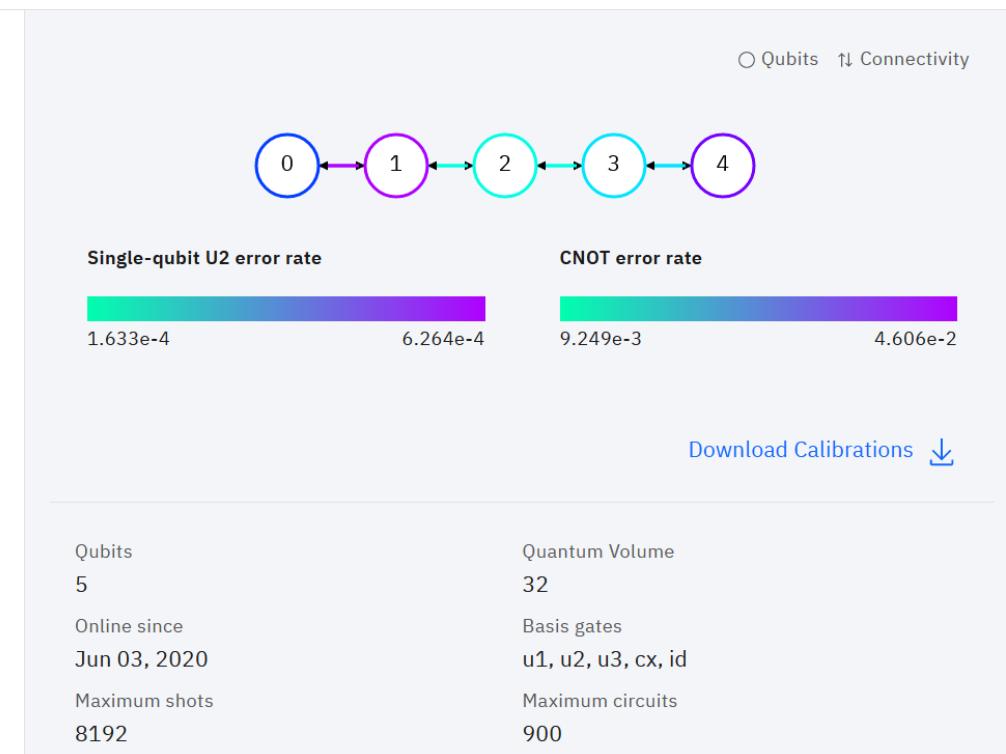


Queue: 14 jobs

Reservable

Providers with access:

ibm-q-research/Franklin-Marquez  
/main



# Programando em alto nível

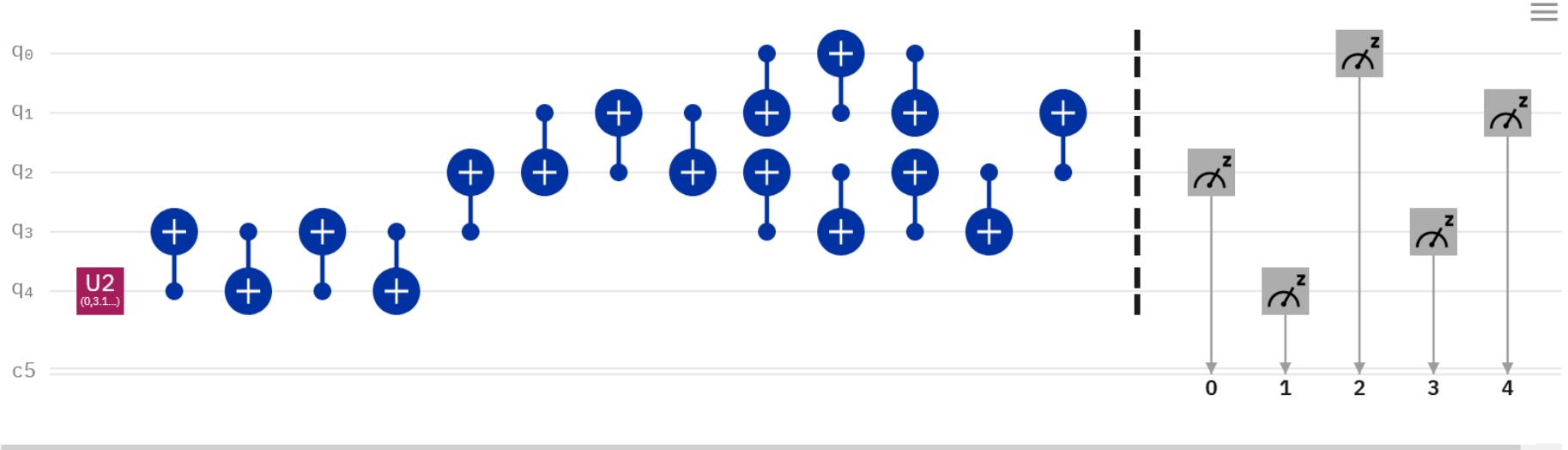
The screenshot shows the IBM Quantum Experience interface. At the top, there is a navigation bar with File, Edit, Inspect, View, Share, Help, Run Settings, and Run on `ibmq_bogota`. Below the navigation bar is a toolbar with various quantum gate icons: H,  $\oplus$ ,  $\ominus$ ,  $\otimes$ ,  $\times$ , T, S, Z,  $S^\dagger$ ,  $T^\dagger$ , U1,  $|0\rangle$ , if,  $\otimes^z$ , RX, RY, and an info icon. There is also a plus icon for adding gates. The main area shows a quantum circuit with six qubits (q0 to q5) and one classical register (c5). The circuit consists of a sequence of operations: q0 starts with an H gate, followed by a sequence of CNOT gates (q0 to q1, q0 to q2, q0 to q3, q0 to q4), then a sequence of  $\otimes^z$  gates (q0 to q1, q0 to q2, q0 to q3, q0 to q4, q0 to q5). The circuit is currently in measurement mode, with measurement probabilities shown for each qubit. On the right, the **Code editor** displays the generated QASM code:

```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[5];
creg c[5];
h q[0];
cx q[0],q[1];
cx q[0],q[2];
cx q[0],q[3];
cx q[0],q[4];
measure q[0] -> c[0];
measure q[1] -> c[1];
measure q[2] -> c[2];
```

(C) IBM Quantum Experience.  
Disclaimer: I am not an IBM Employee and I do not represent IBM.

# Transpilação

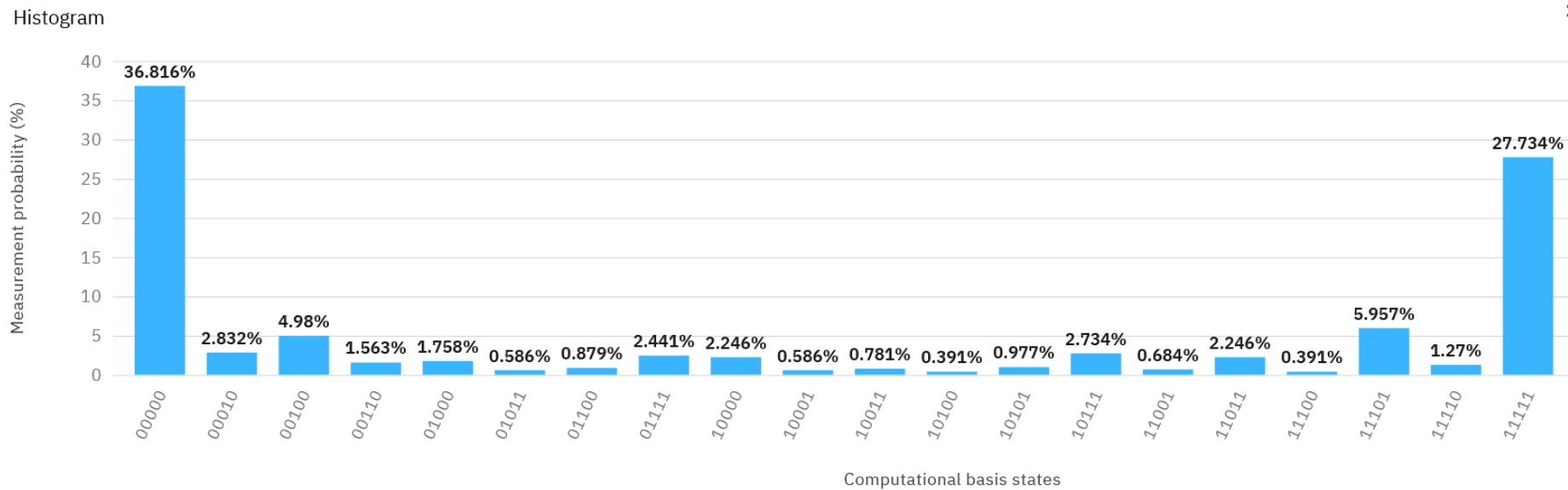
Transpiled circuit



(C) IBM Quantum Experience.  
Disclaimer: I am not an IBM Employee and I do not represent IBM.

# Resultado obtido pelo circuito transpilado

Result



(C) IBM Quantum Experience.  
Disclaimer: I am not an IBM Employee and I do not represent IBM.

# Executando no Quantum Lab (Notebook)

IBM Quantum Experience

Feedback  Q 

File Edit View Insert Cell Kernel Widgets Help

Trusted Python 3  POWERED BY 

In [7]:

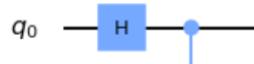
```
qreg_q = QuantumRegister(2, 'q')
creg_c = ClassicalRegister(2, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.h(qreg_q[0])
circuit.cx(qreg_q[0], qreg_q[1])
```

<qiskit.circuit.instructionset.InstructionSet at 0x7f24414ec550>

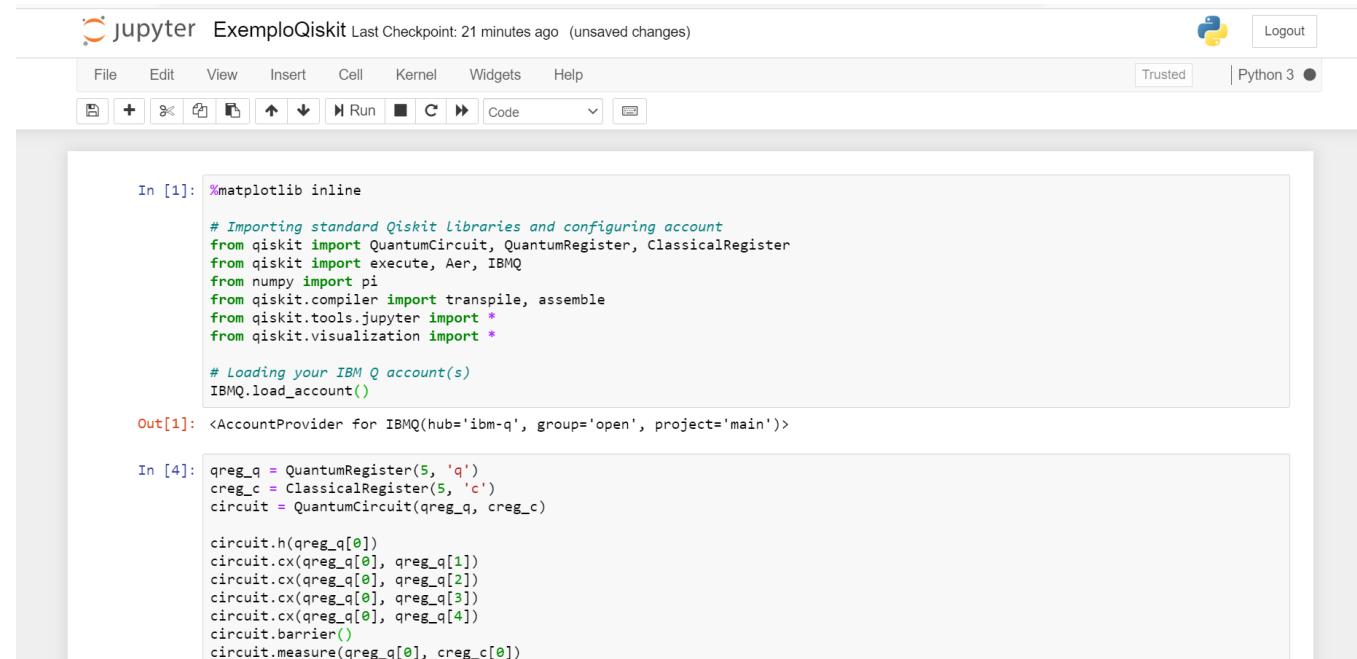
In [8]:

```
circuit.draw('mpl')
```



# Executando localmente

- Necessário Python 3
- Recomendável Jupyter Notebook
- Baixe o qiskit em <https://qiskit.org> ou via pip install qiskit
- Recomendável pip install qiskit[visualization]



The screenshot shows a Jupyter Notebook interface with the following details:

- Header:** jupyter ExemploQiskit Last Checkpoint: 21 minutes ago (unsaved changes) | Logout | Trusted | Python 3
- Toolbar:** File, Edit, View, Insert, Cell, Kernel, Widgets, Help, various icons for file operations and cell execution.
- Code Cell (In [1]):**

```
%matplotlib inline

# Importing standard Qiskit Libraries and configuring account
from qiskit import QuantumCircuit, QuantumRegister, ClassicalRegister
from qiskit import execute, Aer, IBMQ
from numpy import pi
from qiskit.compiler import transpile, assemble
from qiskit.tools.jupyter import *
from qiskit.visualization import *

# Loading your IBM Q account(s)
IBMQ.load_account()
```
- Output Cell (Out[1]):**

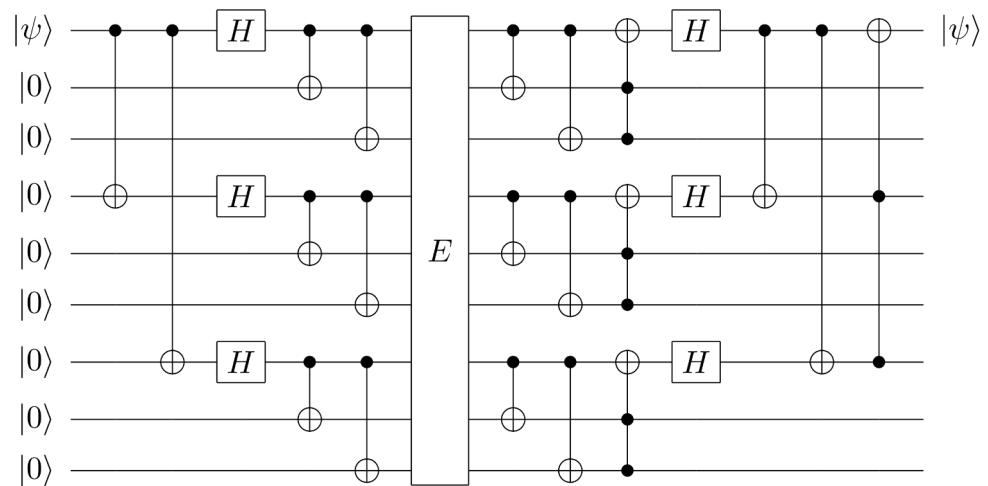
```
<AccountProvider for IBMQ(hub='ibm-q', group='open', project='main')>
```
- Code Cell (In [4]):**

```
qreg_q = QuantumRegister(5, 'q')
creg_c = ClassicalRegister(5, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.h(qreg_q[0])
circuit.cx(qreg_q[0], qreg_q[1])
circuit.cx(qreg_q[0], qreg_q[2])
circuit.cx(qreg_q[0], qreg_q[3])
circuit.cx(qreg_q[0], qreg_q[4])
circuit.barrier()
circuit.measure(qreg_q[0], creg_c[0])
```

# Correção de erros quânticos

- É possível corrigir erros
- Nós *devemos* corrigir erros de computadores quânticos
- Entretanto, é caro (requer muitos qubits)
- Taxa de erros precisa estar abaixo de um limiar



(\*) Shor code: 1 logical qubit is mapped to 9 physical qubits.  
Source: Wikipedia.

# Algoritmos importantes

- **Algoritmos**

- ▷ Shor (1994)
- ▷ Grover (1996)
- ▷ Element distinctness (2004)
- ▷ HHL (2009)

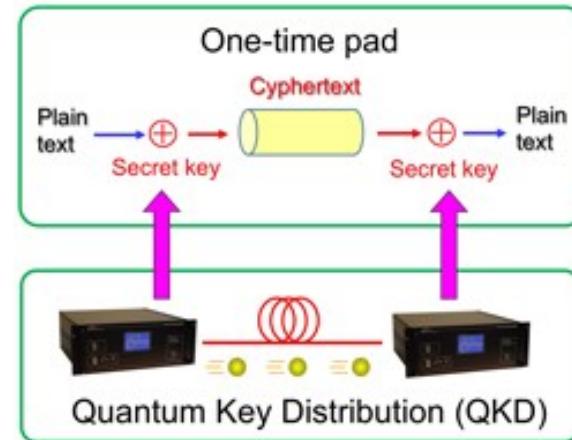
- **Técnicas**

- ▷ HSP
- ▷ Amplitude amplification
- ▷ Quantum walks
- ▷ QAOA
- ▷ Quantum annealing

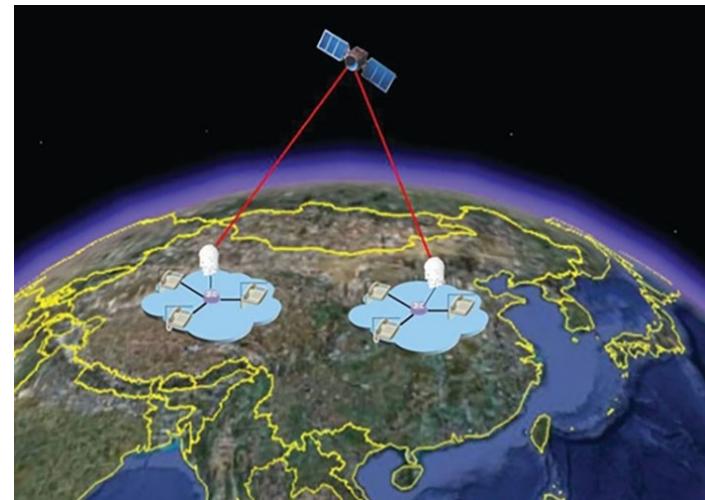
- **Para uma lista completa veja <http://quantumalgorithmzoo.org/>**

# Consequências para criptografia

- CQ quebra RSA  
(mas requer muitos qubits)
- Motiva a criptografia  
pós-quântica
- Novas oportunidades para troca de  
chaves e comunicação segura



(\*) Source: www.nict.go.jp



(\*) Source: physicsworld.com

# Como se preparar nessa área

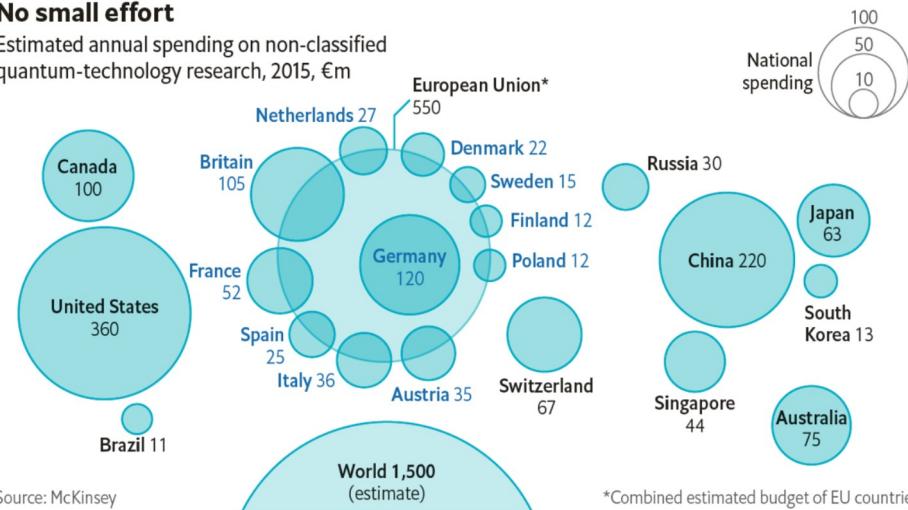
- Graduação: matemática, computação, engenharia, física etc (várias possibilidades)
- Muita atenção aos cursos de Álgebra Linear
- Aprenda a programar os computadores quânticos da IBM (github `programaquantica`)
- Iniciação científica, se possível, é interessante!
- Mestrado/Doutorado

# Conclusão

- Supremacia quântica: demonstrada (mesmo?)
- QREI / Impacto limitado em negócios: próximos 5-10 anos
- Correção de erros / Impacto mais amplo: 10-20 anos
- Tolerância a falhas / Escala completa: 20+ anos
- Fiquem atentos! Muitas oportunidades na academia e na indústria

## No small effort

Estimated annual spending on non-classified quantum-technology research, 2015, €m



The New York Times

## *The Next Tech Talent Shortage: Quantum Computing Researchers*

By Cade Metz

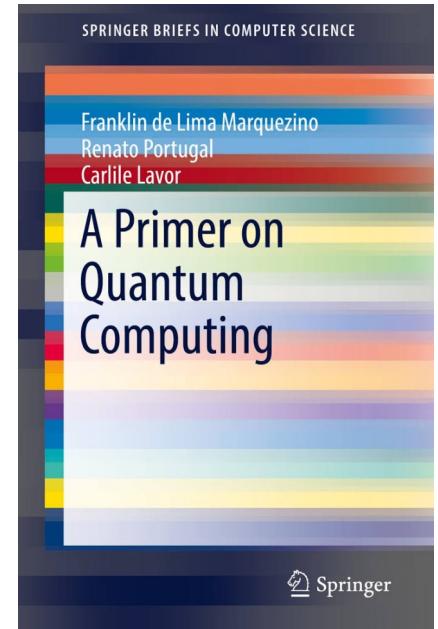
Oct. 21, 2018

Christopher Savoie, founder and chief executive of a start-up called Zapata, offered jobs this year to three scientists who specialize in an increasingly important technology called quantum computing. They accepted.

Several months later, the Cambridge, Mass., company was still waiting for the State

# Para saber mais

- **Apostila**  
[github.com/programaquantica](https://github.com/programaquantica)
- **Livro**  
[www.springer.com/gp/book/9783030190651](https://www.springer.com/gp/book/9783030190651)
- **Seminário PESC**  
[www.youtube.com/watch?v=MXovwCMx3uA%22](https://www.youtube.com/watch?v=MXovwCMx3uA%22)



# Obrigado!

## Computação Quântica

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