

(*) 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

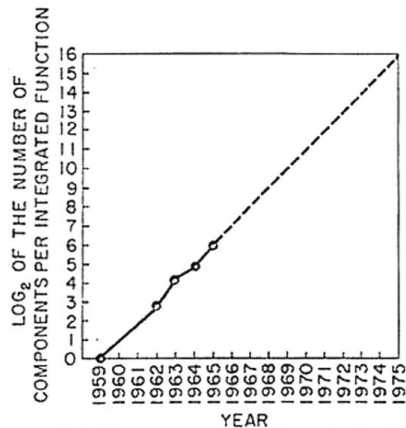


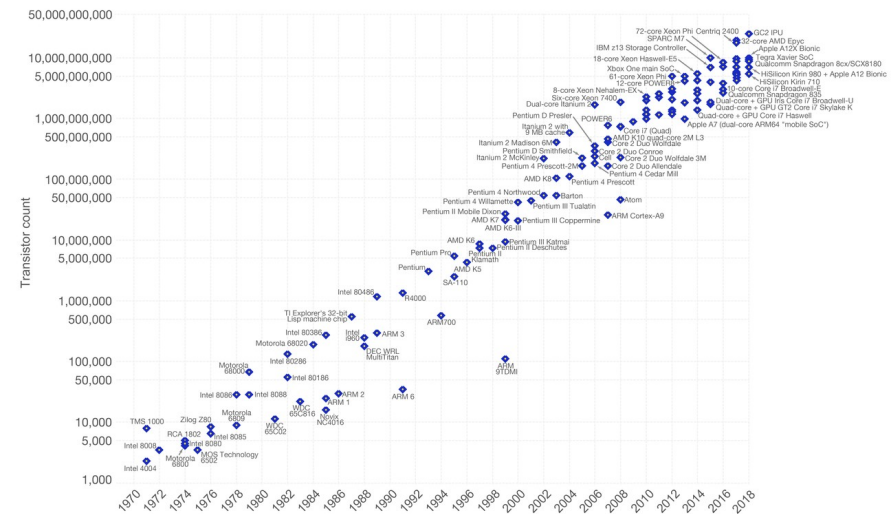
Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

(*) 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.

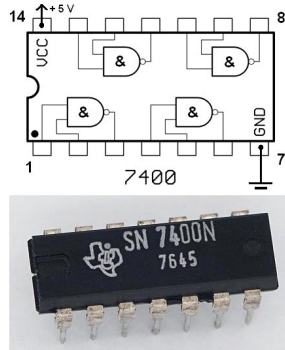
OurWorld
in Data



Data source: Wikipedia (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.

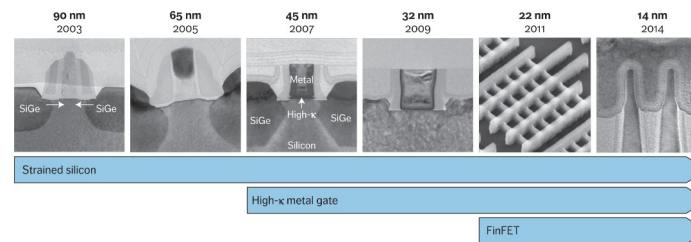
Licensed under CC-BY-SA by the author Max Roser.

Miniaturização



1960s

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



(*) Source: IEEE Micro, www.computer

2015



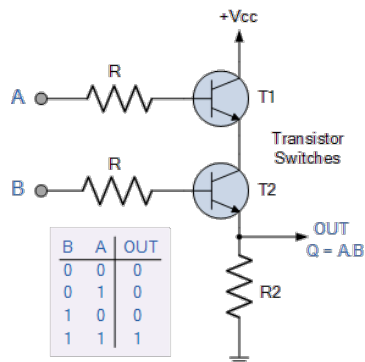
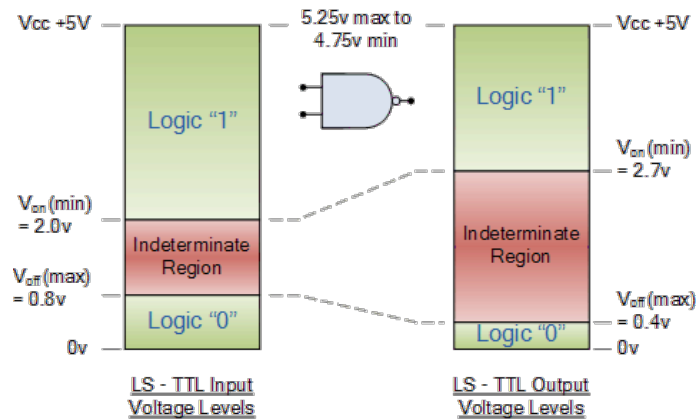
Mecânica quântica



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

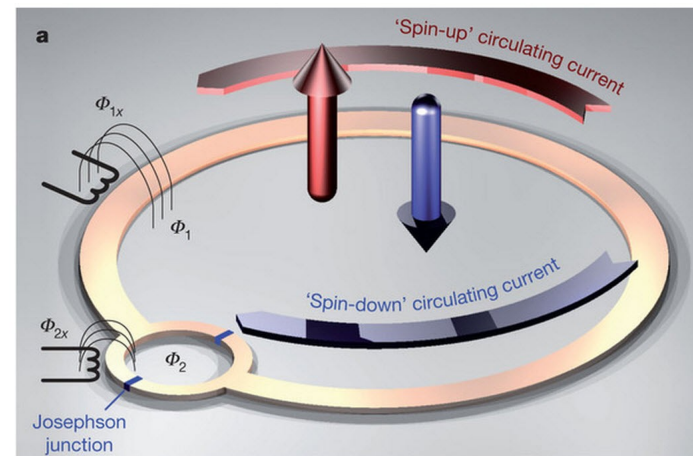
Apresentando os bits quânticos

- Bits (clássicos) podem ser 0 ou 1



(*) Source: www.electronics-tutorials.ws

- 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

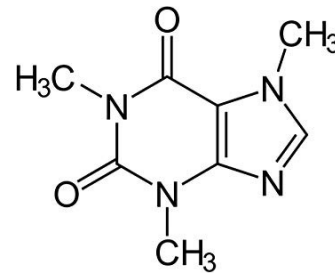
- Finanças
- Óleo & gás

▪ Machine learning

▪ Buscas

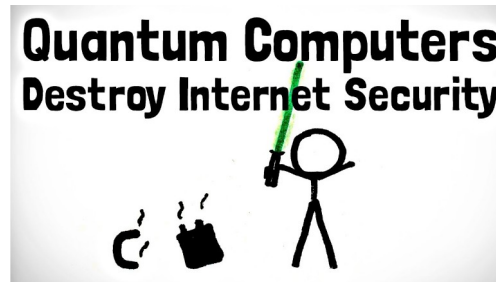
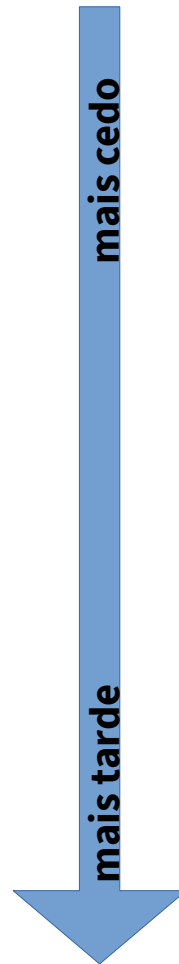
▪ Fatoração

▪ etc.



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

Simulação quântica, 160 qubits



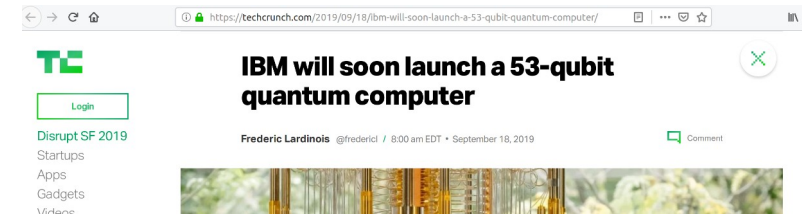
Requer muitos qubits e tolerância a falhas

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
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- 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
computado

▪ Não precisa

▪ Candidato

▷ Fatoração

▷ Amostragem

▷ Amostragem

▪ Supremacia

▷ Simulações

qubits até h

▷ 9 PB para s

requisito

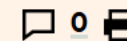
Quantum technologies

+ 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



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

quantum-computer/

53-qubit

Comment



caling-with-128-qubit-architecture/

ADVANCED SCALE FORUM HPC ON WALL S



h 128-Qubit Architecture


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](#)

Supremacia

Simulações
qubits até h

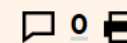
9 PB para s
requisito

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

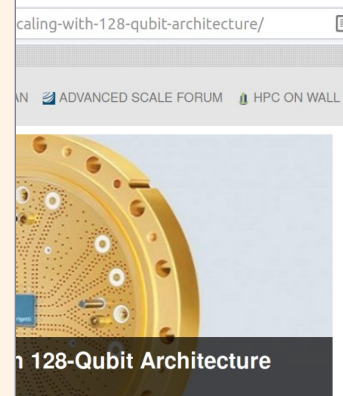
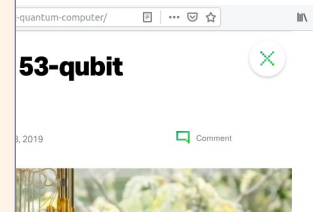
A paper by Google's researchers seen by the FT, that was briefly posted earlier this week on a Nasa website before being removed, claimed that their processor

ed quantum

and an impossible problem for ordinary



computer that can carry out



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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9 PB para s
requisito

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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

 Resource Library

 Subject

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

h 128-Qubit Architecture

Supremacia quântica

nature

Article | Published: 23 October 2019

Quant
progra
proces

THE DAILY NEWSLETTER

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News Podcasts Video Technology

It's official: Google
quantum supremacy



PHYSICS 23 October 2019

By Daniel Cossins

A paper by Google's researchers
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

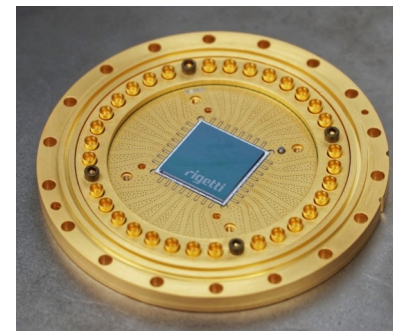
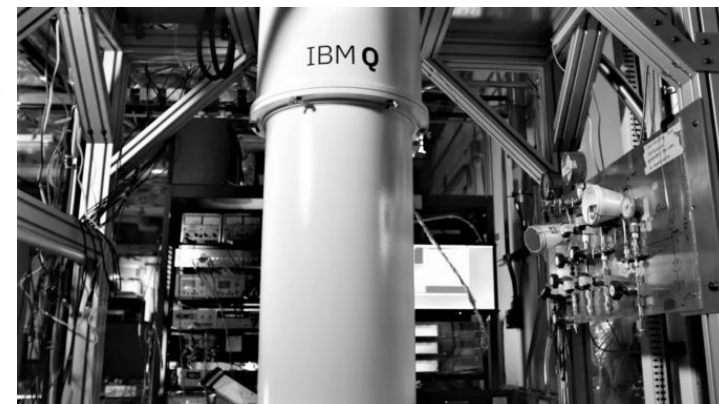
Dr. Aaronson is the founding director of the Quantum Information Center at the University of Texas at Austin.

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



QILIMANJARO

|EeroQ>

Hardware quântico



... e muitas outras

Empresas

THE EUROPEAN QUANTUM COMPUTING STARTUP LANDSCAPE

Hardware

Computing



Components & Materials



Software

Operating Systems



Applications

Security & Encryption



Chemistry & Pharma



Others

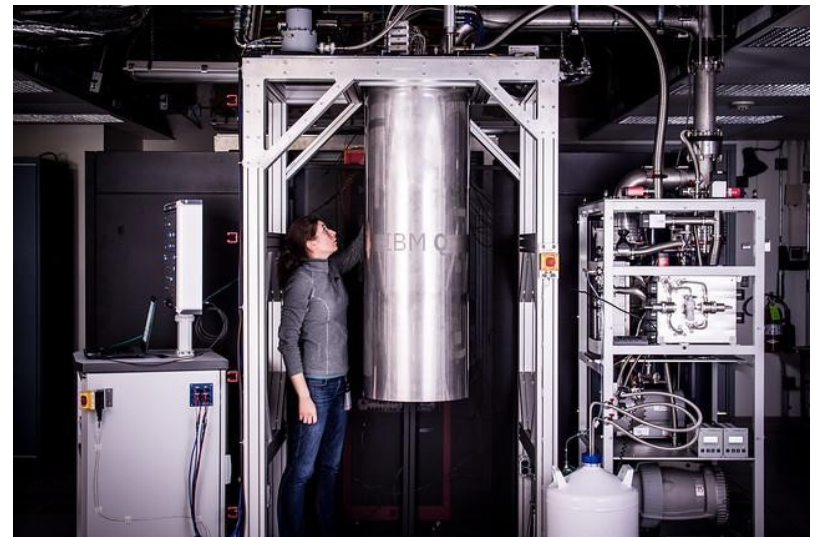


Programando um computador quântico

- 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

The screenshot displays the IBM Quantum Experience web application. The top navigation bar includes 'File', 'Edit', 'Inspect', 'View', 'Share', and 'Help'. The main workspace shows a quantum circuit with three qubits (q0, q1, c2). The circuit includes an H gate on q0, a CNOT gate with q0 as control and q1 as target, and Z gates on both q0 and q1. The circuit is followed by measurements on q0 and q1, with classical bits 0 and 1 respectively. The 'Measurement Probabilities' section shows a bar chart with two bars for outcomes 00 and 11, both at approximately 50% probability. The 'Q-sphere' section shows a Bloch sphere visualization with a state vector pointing towards the top pole. The 'Code editor' on the right shows QASM code for the circuit.

IBM Quantum Experience

File Edit Inspect View Share Help

Circuits / DemonstracaoSlide Saved

Run Settings Run on ibmq_bogota

Code Docs Jobs

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

Measurement probability

00 11

Q-sphere

State Phase angle

(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 displays the IBM Quantum Experience web interface. At the top, the title bar reads "IBM Quantum Experience" with a "Feedback" button and search icons. Below this is a navigation bar with "File", "Edit", "Inspect", "View", "Share", and "Help". The main area is titled "Circuits / DemonstracaoSlide Saved". A toolbar contains various quantum gates and operations like H, CNOT, T, S, Z, S†, T†, U1, |0⟩, if, RX, RY, RZ, U3, Y, U2, CH, CY, CZ, CRX, CRY, CRZ, CU1, CU3, RXX, and RZZ. The circuit diagram shows three qubits: q0, q1, and c2. q0 has an H gate, followed by a CNOT with q1 as the control and q0 as the target. q1 has a CNOT with q0 as the control and q1 as the target. Both q0 and q1 are then measured into classical registers c2 and c1 respectively. Below the circuit, the "Measurement Probabilities" section shows a bar chart for computational basis states 00 and 11, both with a probability of approximately 50%. The "Q-sphere" section shows a Bloch sphere visualization of the state, with a phase angle indicator.

Code editor

```
Qiskit
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

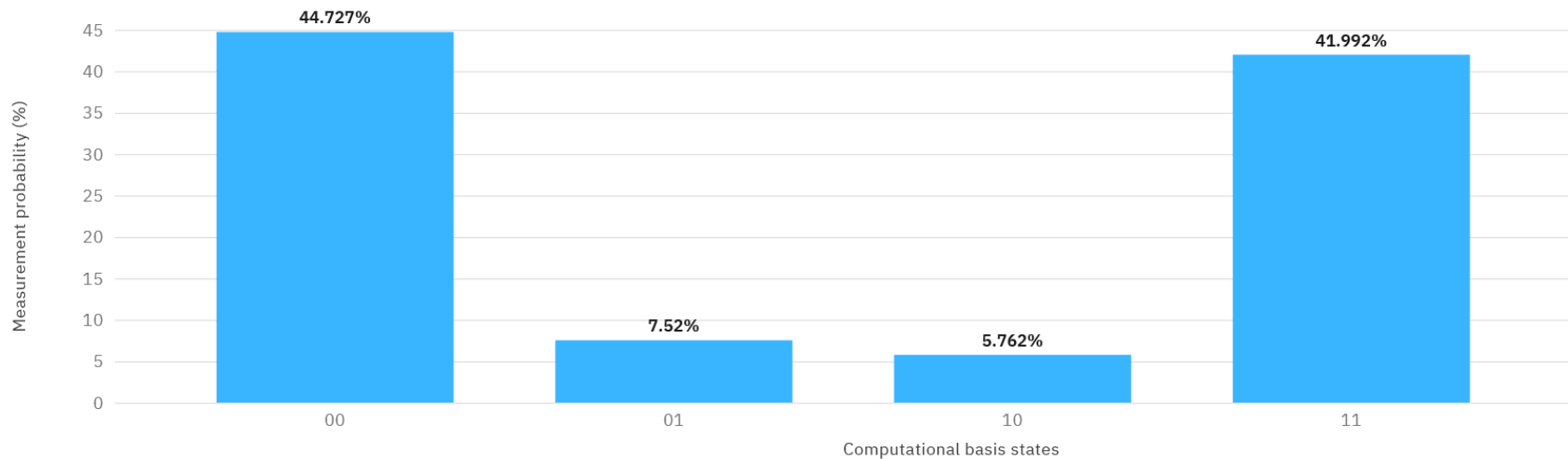
- Jobs submetidos para o computador quântico real podem demorar! Também é possível simular

The screenshot displays the IBM Quantum Experience web application. The top navigation bar includes 'File', 'Edit', 'Inspect', 'View', 'Share', and 'Help'. The main workspace shows a quantum circuit with qubits q_0 , q_1 , and c_2 . The circuit includes a Hadamard gate on q_0 , a CNOT gate with q_0 as control and q_1 as target, and Z-basis measurements on both q_0 and q_1 . Below the circuit, the 'Measurement Probabilities' section shows a bar chart with two bars for computational basis states '00' and '11', both at a probability of approximately 50%. To the right, the 'Q-sphere' visualization shows a Bloch sphere with a state vector pointing towards the top pole. The right sidebar contains a 'Jobs' tab with a list of 'Jobs from this circuit'. One job is shown as 'QUEUED' with ID '5f7cc9b8146c6100138599...'. The job details indicate the backend is 'ibmq_bogota', the provider is 'ibm-q-research/Franklin-Marquez/main', and it is expected to run in 2 hours. The bottom right corner of the interface includes a disclaimer: '(C) IBM Quantum Experience. Disclaimer: I am not an IBM Employee and I do not represent IBM.'

Como ler os resultados

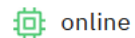
Result

Histogram



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

Mapa de acoplamentos

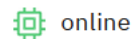


online

ibmq_santiago (5 qubits, QV32)



Queue: 34 jobs



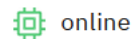
online

ibmq_bogota (5 qubits, QV32)



Queue: 14 jobs

Reservable



online

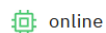
ibmq_rome (5 qubits, QV32)



Queue: 32 jobs

1 upcoming reservations

ibmq_bogota v1.0.4



online



Queue: 14 jobs

Reservable

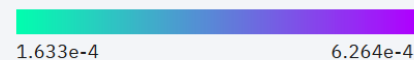
Providers with access:

ibm-q-research/Franklin-Marquez
/main

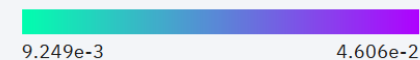
○ Qubits ↕ Connectivity



Single-qubit U2 error rate



CNOT error rate



[Download Calibrations](#)

Qubits

5

Online since

Jun 03, 2020

Maximum shots

8192

Quantum Volume

32

Basis gates

u1, u2, u3, cx, id

Maximum circuits

900

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Programando em alto nível

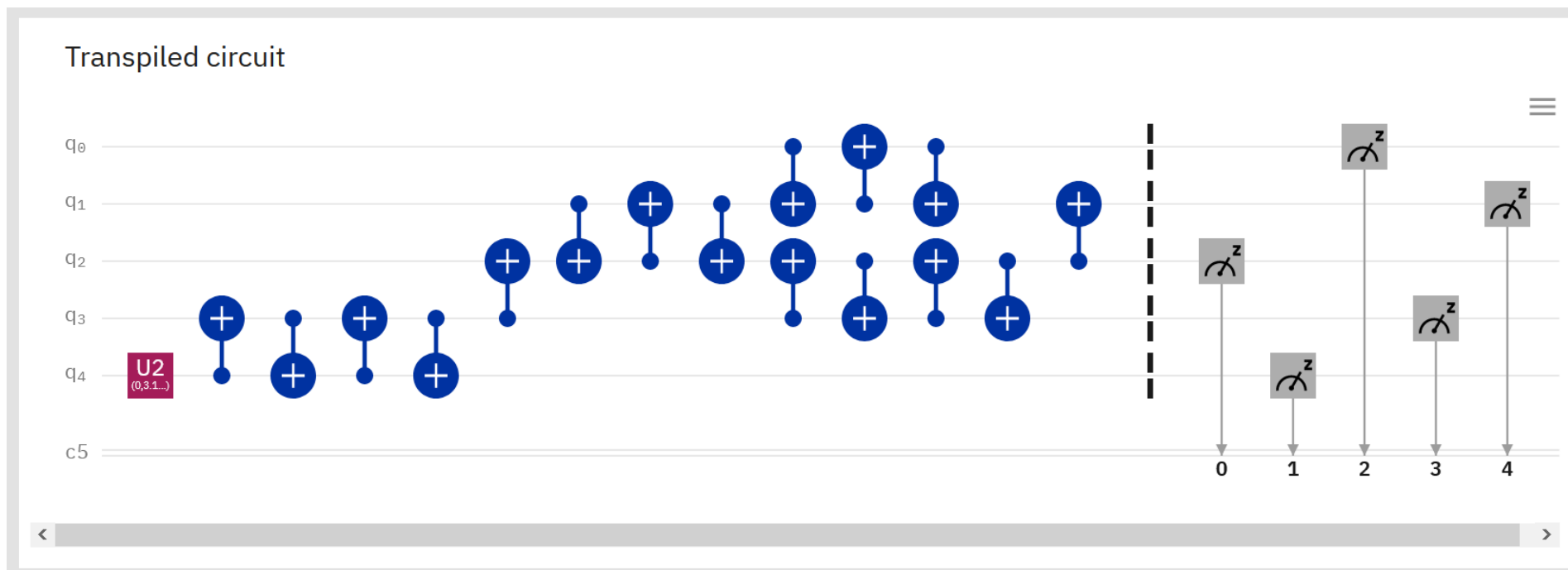
The screenshot displays the IBM Quantum Lab interface. At the top, there is a menu bar with 'File', 'Edit', 'Inspect', 'View', 'Share', and 'Help'. On the right, there are 'Run Settings' and a 'Run on ibmq_bogota' button. Below the menu, the file path 'Circuits / DemonstrationSlideTranspiler Saved' is shown. A toolbar contains various quantum gates: H, \oplus , \otimes , \otimes , \otimes , \otimes , T, S, Z, S^\dagger , T^\dagger , U1, $|0\rangle$, if, \otimes^z , RX, and RY. Below the toolbar, a second row of gates includes RZ, U3, Y, U2, CH, CY, CZ, CRX, CRY, CRZ, CU1, CU3, RXX, and RZZ, followed by a '+ Add' button. The main workspace shows a quantum circuit with five qubits (q0 to q4) and one classical bit (c5). The circuit starts with an H gate on q0, followed by a series of CNOT gates and Z gates. The bottom of the interface features 'Measurement Probabilities' and 'Q-sphere' tabs. The 'Q-sphere' tab is active, showing a Bloch sphere visualization with 'State' and 'Phase angle' checkboxes. On the right, a 'Code editor' window displays the QASM code for the circuit.

Code editor

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

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

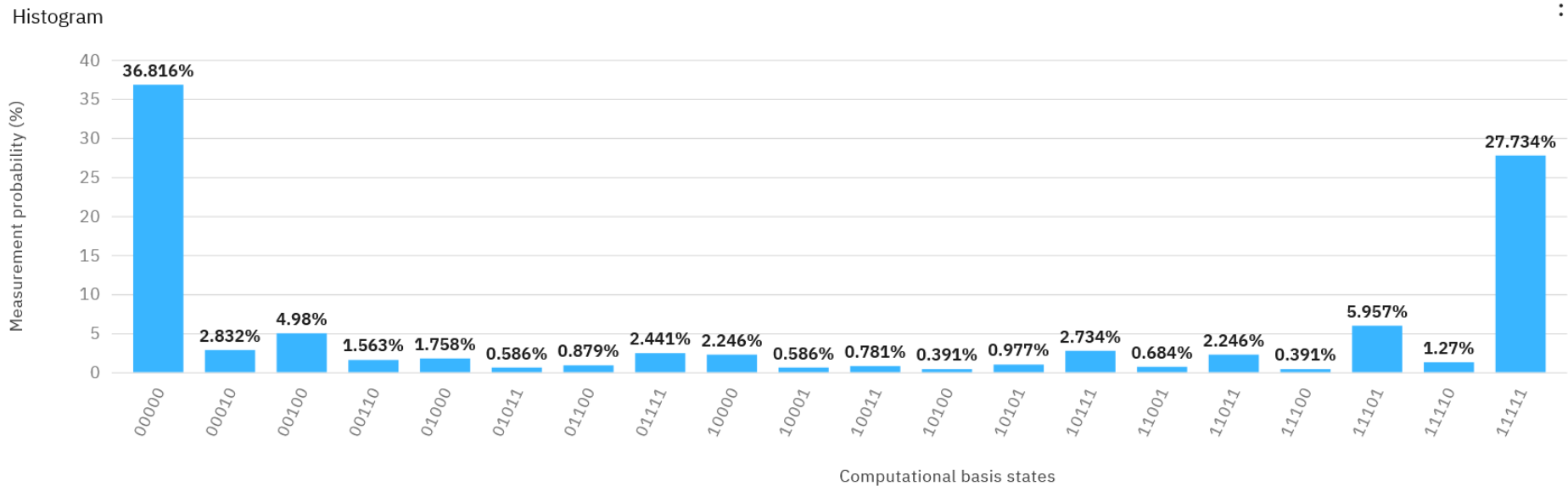
Transpilação



(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)

The screenshot displays the IBM Quantum Experience Jupyter Notebook interface. The top navigation bar includes the IBM Quantum Experience logo, a Feedback button, and search and user icons. Below this is a menu bar with File, Edit, View, Insert, Cell, Kernel, Widgets, and Help. A toolbar contains icons for saving, adding, deleting, copying, pasting, undo, redo, running, and code execution. The main area shows two code cells. The first cell, labeled 'In [7]:', contains the following Python code:

```
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])
```

The output of this cell is a string representation of the instruction set: `<qiskit.circuit.instructionset.InstructionSet at 0x7f24414ec550>`. The second cell, labeled 'In [8]:', contains the code:

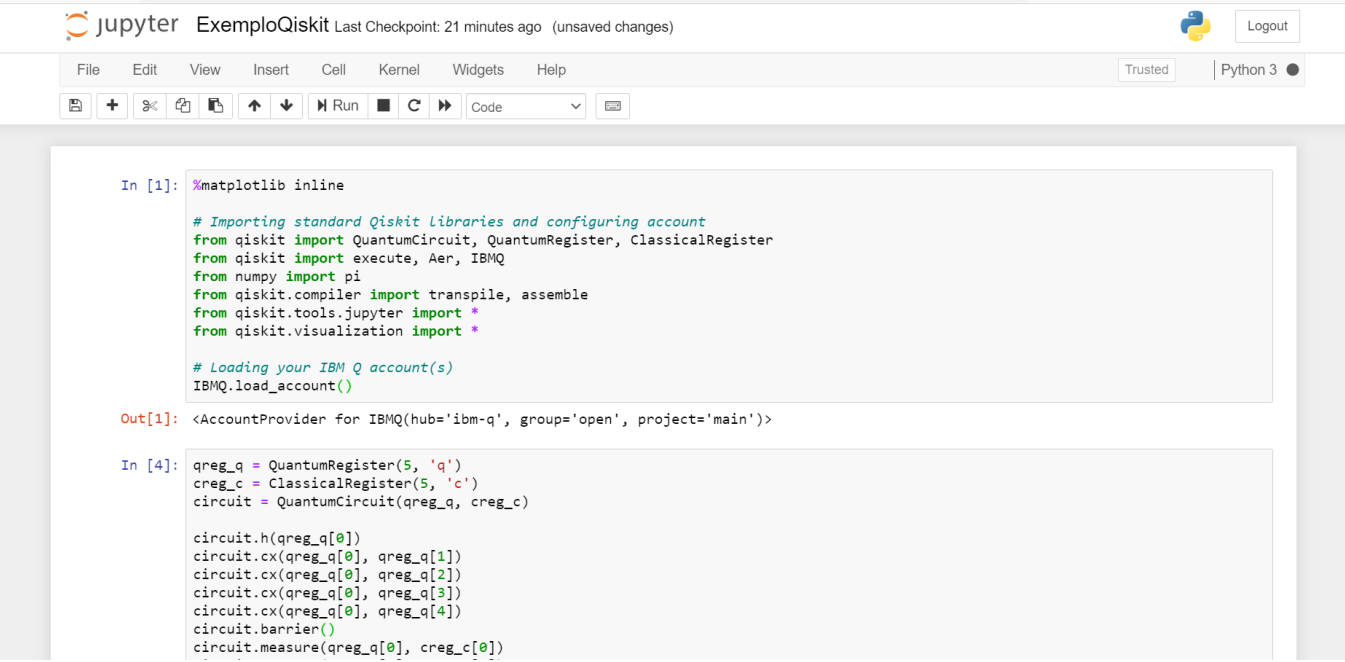
```
circuit.draw('mpl')
```

The output of the second cell is a quantum circuit diagram. It shows a single qubit line labeled q_0 with a blue square gate labeled 'H' (Hadamard gate) applied to it. A blue dot on the line indicates the measurement point.

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

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 titled "ExemploQiskit" with a last checkpoint 21 minutes ago. The interface includes a top bar with the Jupyter logo, a menu bar (File, Edit, View, Insert, Cell, Kernel, Widgets, Help), and a toolbar with icons for saving, running, and other actions. The notebook content is divided into two cells. The first cell, labeled "In [1]:", contains code for importing Qiskit libraries and loading an IBM Q account. The output, labeled "Out[1]:", shows the account provider information. The second cell, labeled "In [4]:", contains code for creating a quantum circuit with 5 qubits and 1 classical bit, performing a Hadamard gate on the first qubit, followed by CNOT gates from the first qubit to the other four qubits, and finally measuring the first qubit and storing the result in the classical bit.

```
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()

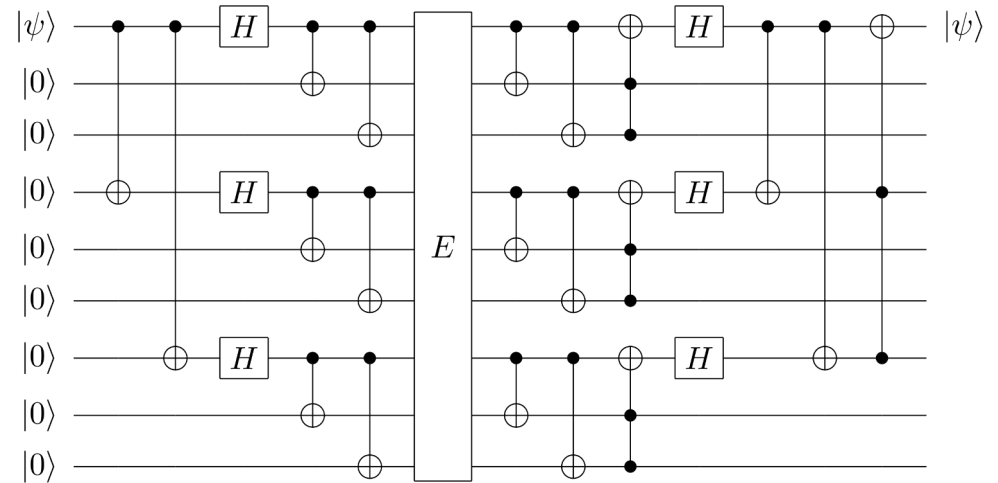
Out[1]: <AccountProvider for IBMQ(hub='ibm-q', group='open', project='main')>

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)

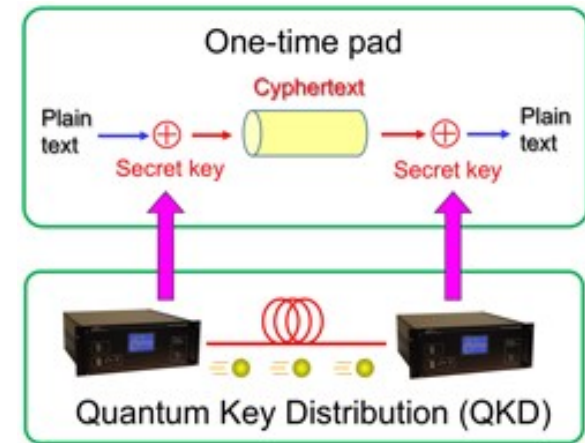
- **Técnicas**

- ▷ 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

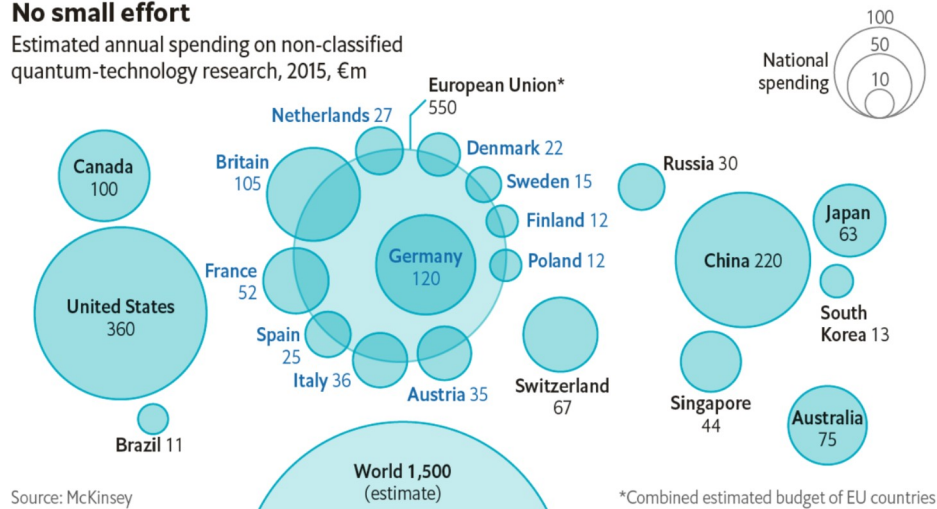
- Graduação: matemática, computação, engenharia, física etc (várias possibilidades)
- Muita atenção aos cursos de Álgebra Linear
- Aprenda a programar os computadores quânticos da IBM (github programaquantica)
- Iniciação científica, se possível, é interessante!
- Mestrado/Doutorado

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

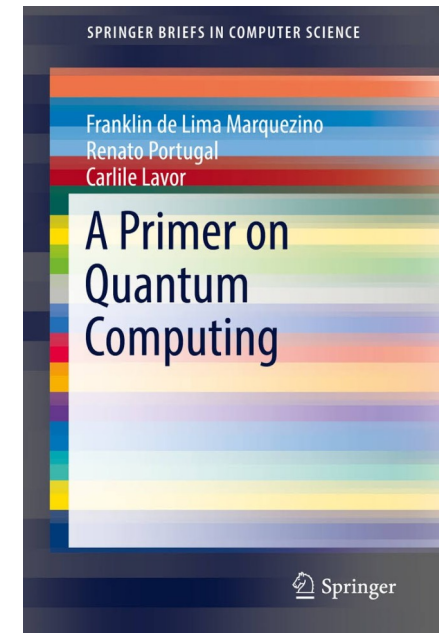
Oct. 21, 2018

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
- Livro
www.springer.com/gp/book/9783030190651
- Seminário PESC
www.youtube.com/watch?v=MXovwCMx3uA%22



Obrigado!

Computação Quântica

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