Introduction to Quantum Computing

Jara Juana Bermejo-Vega
University de Granada

Spring School on Near-Term Quantum Computing

April 2024

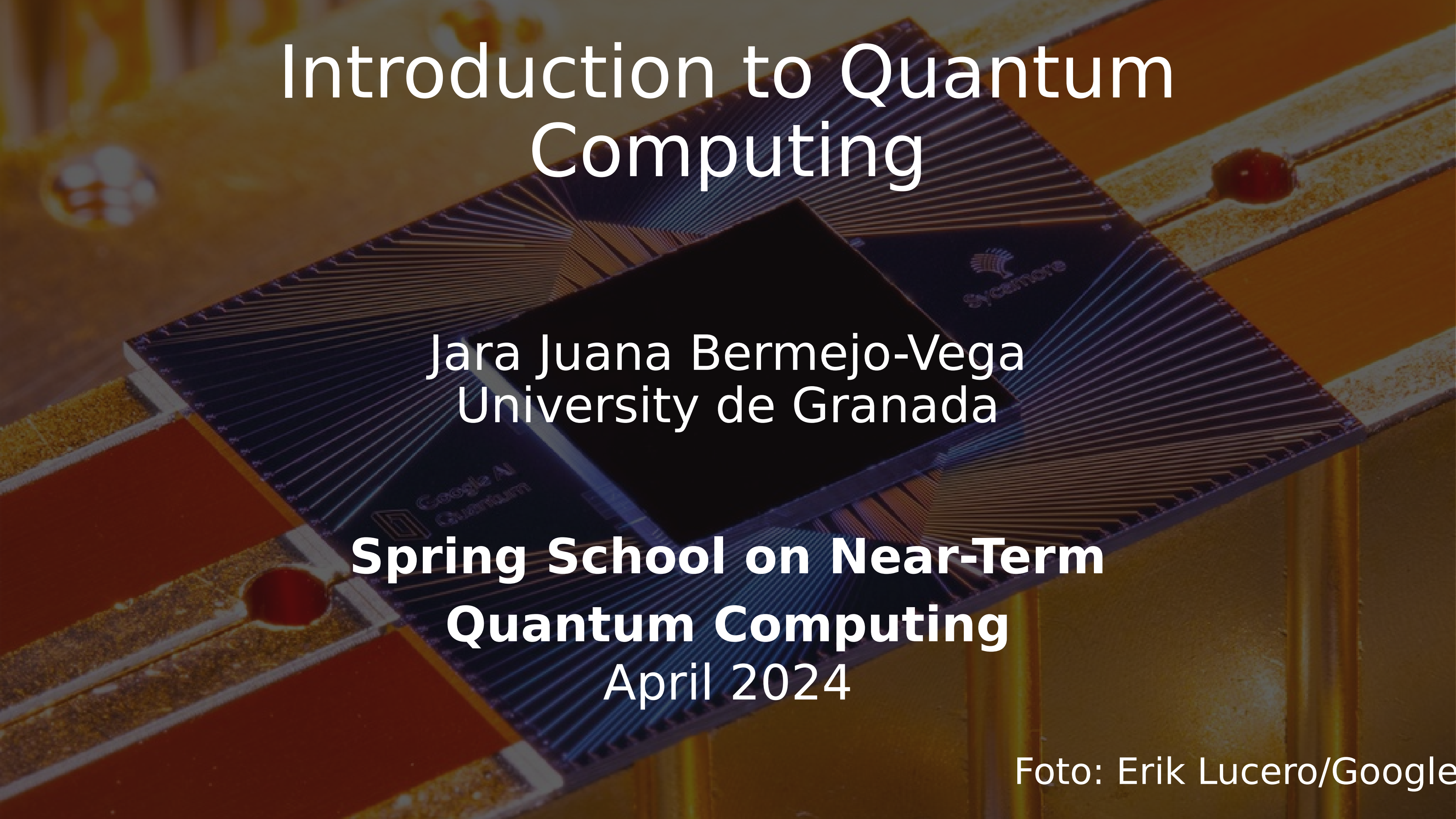
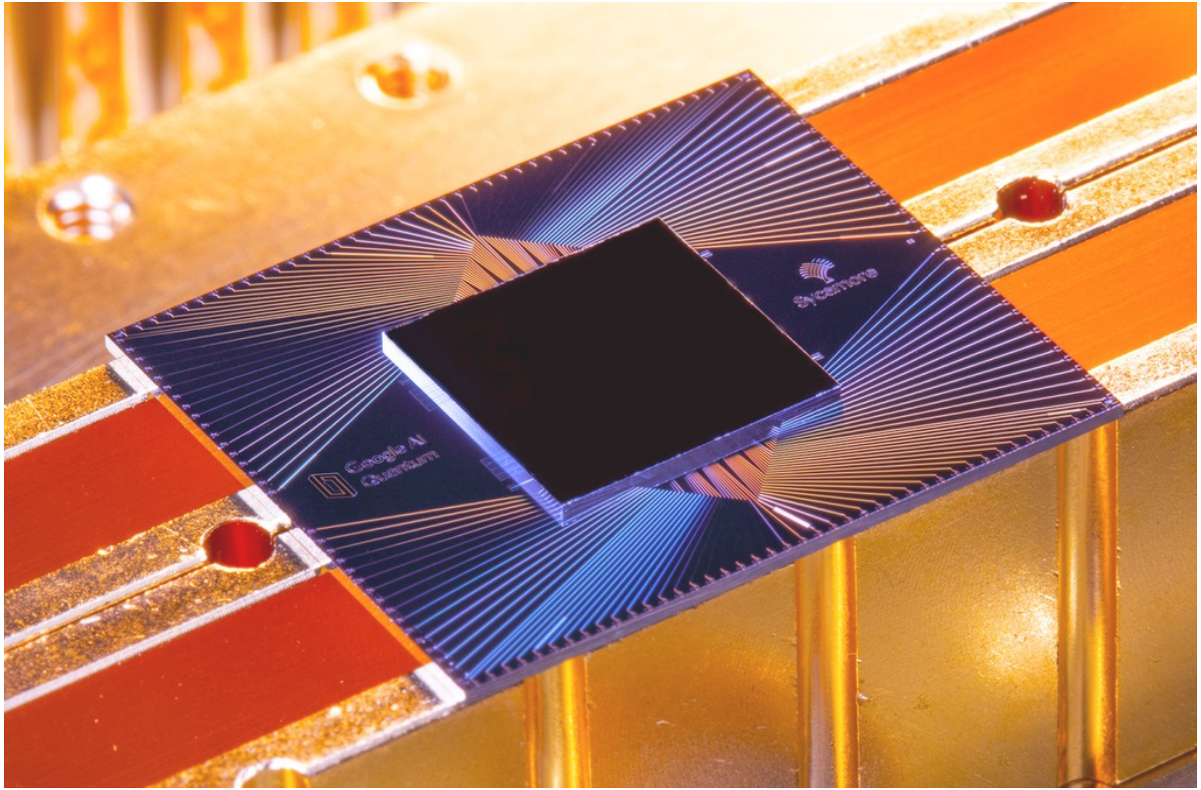


Foto: Erik Lucero/Google

Course Outline

- Today
  - Roadmap to Near-Term Quantum Computing: potentials and limitations
  - Quantum Algorithms
  - Complexity Theory
- Today & Tomorrow
  - Quantum Error Correction & Fault Tolerance
  - Reliable quantum advantages from quantum simulation
  - Verifiable advantages based on sampling problems
  - Robust advantages based on many-body problems



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

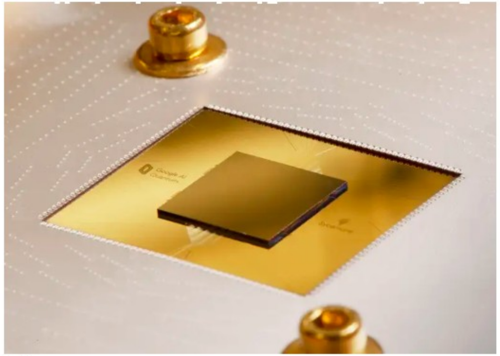
Abstract

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2,3,4,5,6,7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8,9,10,11,12,13,14] for this specific computational task, heralding a much-anticipated computing paradigm.

Quantum supremacy has arrived – what happens to computing now?

The claim that a quantum computer has done something a classical machine can't has generated plenty of excitement, but true quantum computing will take time to appear

TECHNOLOGY | LEADER 30 October 2019



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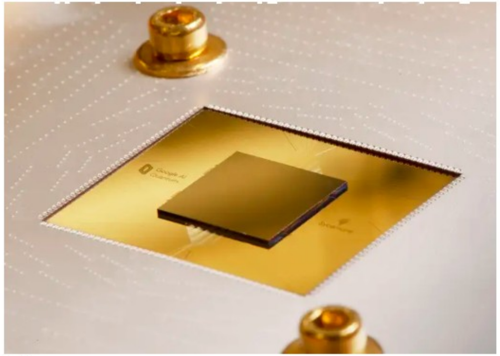

The New York Times

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.

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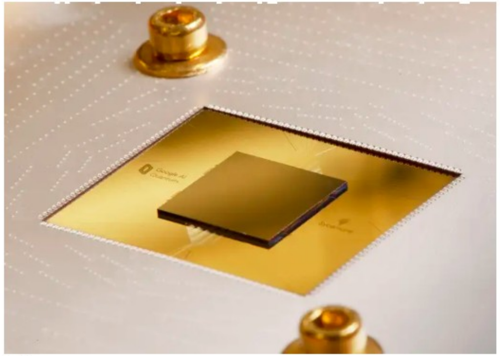

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IBM

IBM Research Blog Topics Labs About

Quantum Computing

On "Quantum Supremacy"

October 21, 2019 | Written by: Edwin Pednault, John Gunnels & Dmitri Maslov, and Jay Gambetta

Science Contents News Careers Journals

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Google researchers in Santa Barbara, California, say their advance may lead to near-term applications of quantum computers. ISTOCK.COM/JHVEPHOTO

IBM casts doubt on Google's claims of quantum supremacy

By Adrian Cho | Oct. 23, 2019 , 5:40 AM

OMG what is this quantum computing thing?

What is a quantum computer?

Does Google have one?

Have they shown “supremacy”?

Do we have this in Spain?

I am La Juani

@queenofquant

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement Nº 754446 and UGR Research and Knowledge Transfer Found – Athenea3i

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Quantum Computing, Information & Thermodynamics

Jara Juana Bermejo Vega

Daniel Manzano

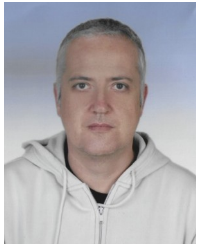
Rhea Alexander

Álvaro Tejero

Dolores Esteve-Díaz

Antonio Jesús Rivera Pérez

Carlos Cano



Michalis Skotiniotis

Giulio Camillo

Ana Martínez-Sabiote

Noelia Sánchez Gómez

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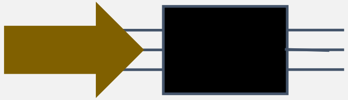
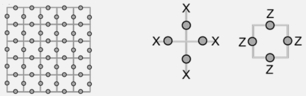
Quantum and Classical Computing in Granada

Quantum foundations



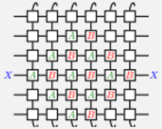
JBV, Delfosse, Browne, Okay, Raussendorf, *PRL* 119 (2017)
Raussendorf, Browne, Delfosse, Okay, **JBV** , *PRA* 95 (2017)
Delfosse, Okay, **JBV**, Browne, Raussendorf, *NJP* 19 (2017)

Classical simulation



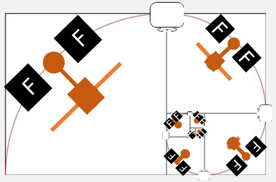
JBV, Van den Nest, QIC 14, No 3&4 (2014)
JBV, Lin, Van den Nest, QIC 5&6 (2016),

Many-body theory



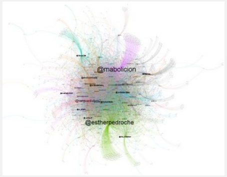
Stephen, Nautrup, **JBV**, Eisert, Raussendorf, Quantum 3 (2019)

Quantum algorithms

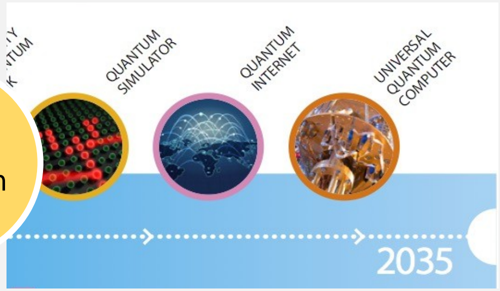


JBV, Zatloukal, arXiv:1509.05806 .
JBV, Lin, Van den Nest, arXiv:1409.4800 .

Machine learning



Near term quantum devices



UGR Quantum Machine Learning Group

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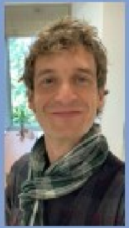
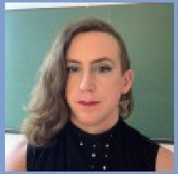


Prof. Carlos Cano

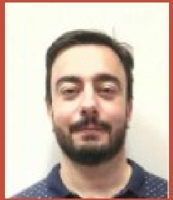
Prof. Antonio Lasanta

Prof. Joaquín J. Torres

Prof. Carlos Pérez-Espigares



Dr. Jara J. Bermejo-Vega



Prof. Ricardo Gutiérrez

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Quantum Machine learning

Entanglement detection with classical deep neural networks

Julio Ureña, Antonio M. Sojo, Jara J. Bermejo-Vega, and Daniel Manzano

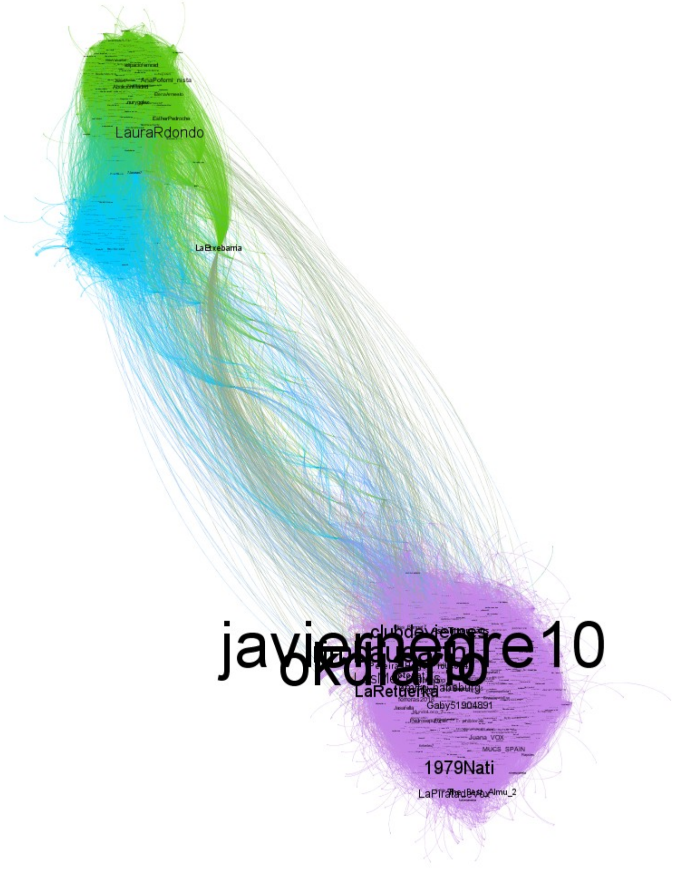
Electromagnetism and Matter Physics Department and Institute Carlos I of Theoretical and Computational Physics, University of Granada, E-18071, España.

Entanglement is one of the most important features of quantum mechanics, and its detection and classification is a hard problem. In this paper we present a novel approach to this problem by training a multi layer perceptron to detect entanglement in two and three qubits systems. Our network achieves high efficiencies around 100% in the two qubits case and above 90% for the three qubits one. We also show that is possible to train the network to classify the states between the different entanglement families with a success ratio up to 77%.

Machin learning of hate networks

Joint work with
- Atenea Medrán
- @pynomaly (GitHub), Python Developer
- Daniel Manzano, University of Granada
- Ana Valdivia, King’s College London

https://vimeo.com/754259618



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WE ARE
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WE ORGANIZE
inclusive quantum information conferences

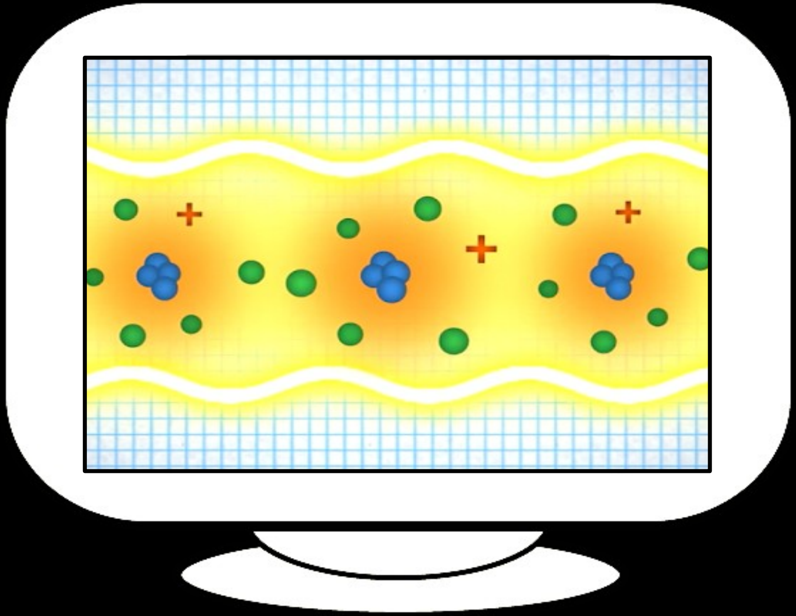
WE CARE ABOUT
working conditions, equity, diversity, privilege, bias, health, safety, responsible research, harassment- and discrimination-free environments

WE ARE A SAFE SPACE FOR
underrepresented groups in quantum STEM: womxn, POC, LGBTQ, chronically ill academics ++

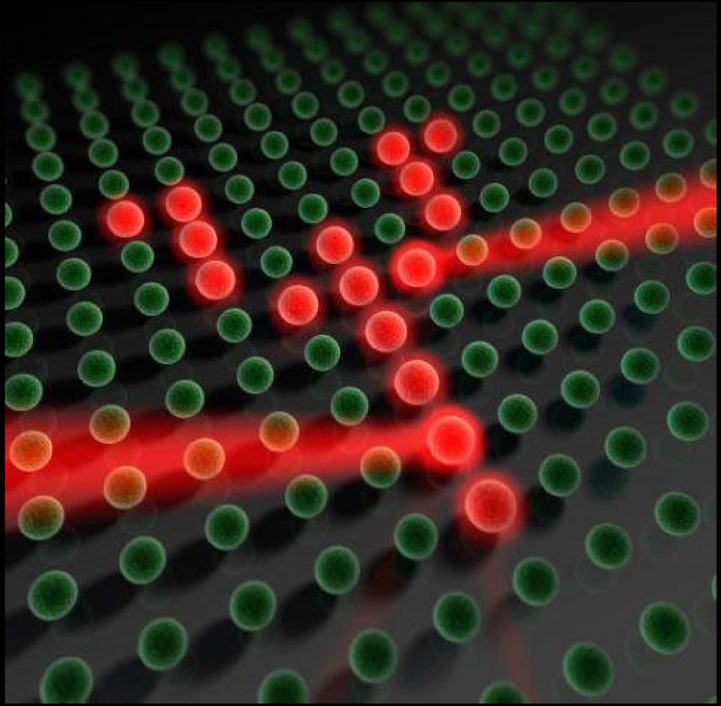
CONTACT
Email: qturnworkshop@gmail.com

What is a quantum computer?

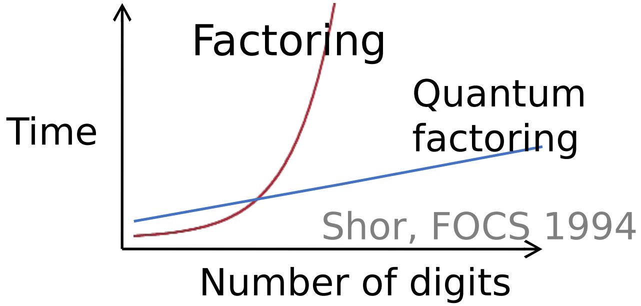
A machine that uses coherent quantum systems to speed-up calculations



Incoherence VS Coherence



Quantum Computing is Different



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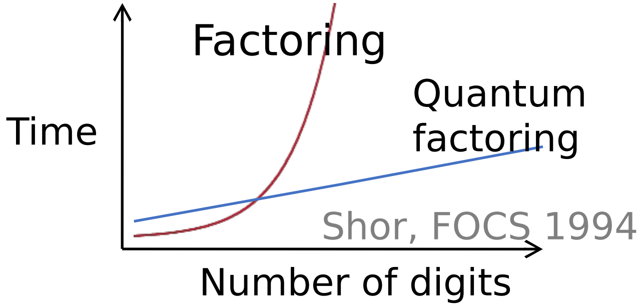

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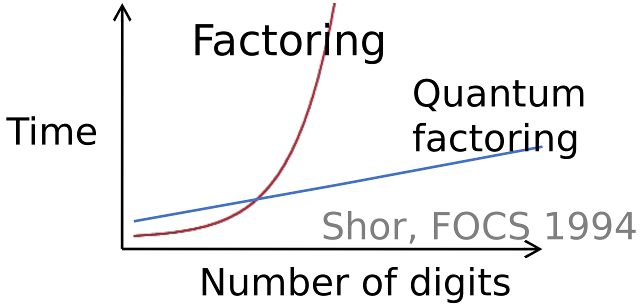
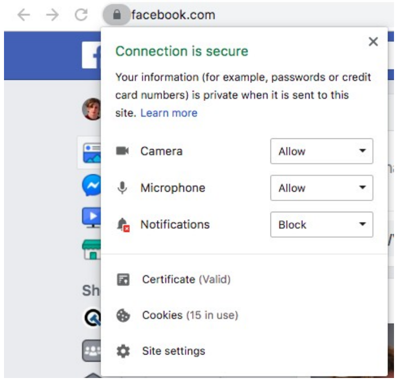
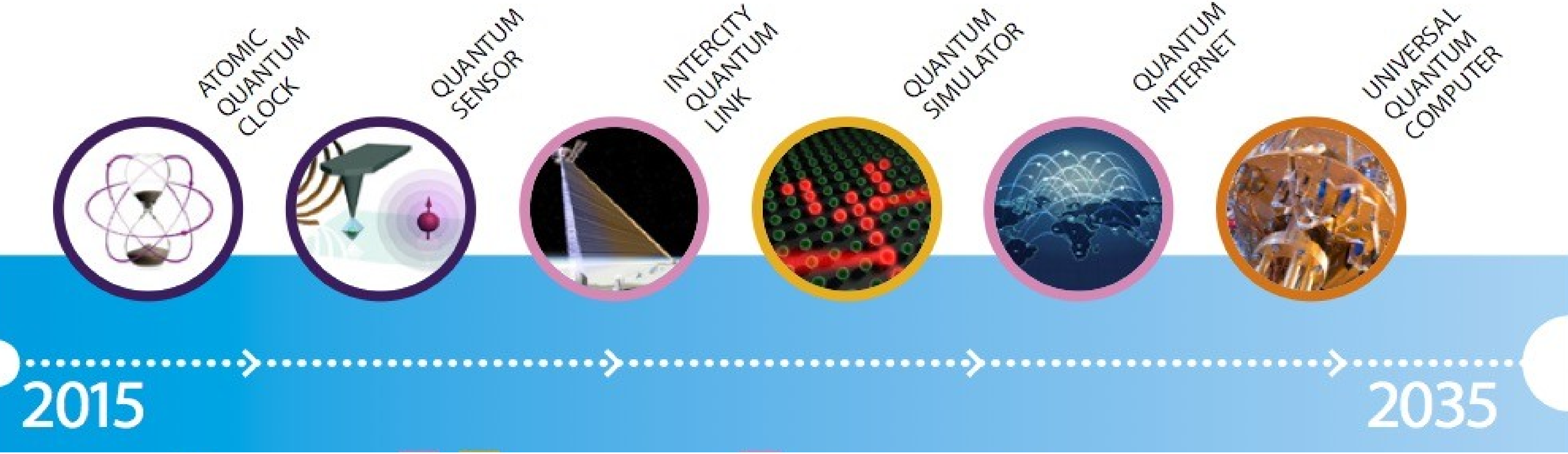




Roadmap to Quantum Technologies



Quantum computers could revolutionize computation, and cryptography but are extremely hard to build

Quantum computers could revolutionize computation, and cryptography but are extremely hard to build

How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits

Craig Gidney, Martin Ekerå

We significantly reduce the cost of factoring integers and computing discrete logarithms in finite fields on a quantum computer by combining techniques from Shor 1994, Griffiths-Niu 1996, Zalka 2006, Fowler 2012, Ekerå-Håstad 2017, Ekerå 2017, Ekerå 2018, Gidney-Fowler 2019, Gidney 2019. We estimate the approximate cost of our construction using plausible physical assumptions for large-scale superconducting qubit platforms: a planar grid of qubits with nearest-neighbor connectivity, a characteristic physical gate error rate of 10^{-3}, a surface code cycle time of 1 microsecond, and a reaction time of 10 microseconds. We account for factors that are normally ignored such as noise, the need to make repeated attempts, and the spacetime layout of the computation. When factoring 2048 bit RSA integers, our construction's spacetime volume is a hundredfold less than comparable estimates from earlier works (Fowler et al. 2012, Gheorghiu et al. 2019). In the abstract circuit model (which ignores overheads from distillation, routing, and error correction) our construction uses $3n + 0.002n \lg n$ logical qubits, $0.3n^3 + 0.0005n^3 \lg n$ Toffolis, and $500n^2 + n^2 \lg n$ measurement depth to factor n-bit RSA integers. We quantify the cryptographic implications of our work, both for RSA and for schemes based on the DLP in finite fields.

Comments: 26 pages, 10 figures, 5 tables
Subjects: **Quantum Physics (quant-ph)**
Cite as: arXiv:1905.09749 **[quant-ph]**
(or arXiv:1905.09749v2 **[quant-ph]** for this version)

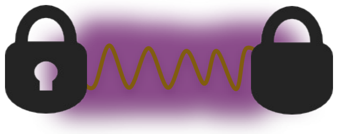
Long term applications
(Use many resources)

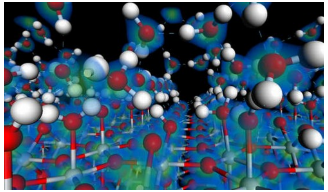
Long term applications
(Use many resources)

Well understood

Cryptography

Simulation





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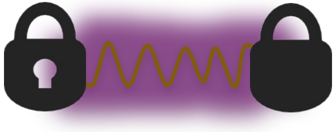
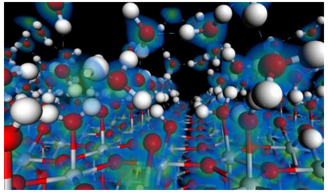


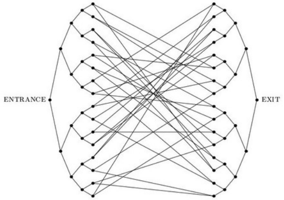


Under Investigation

Graph

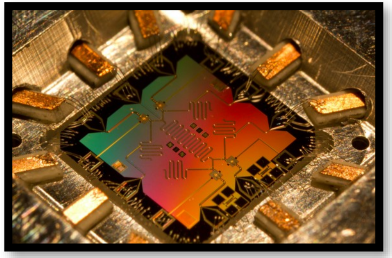
Problems

Machine learning



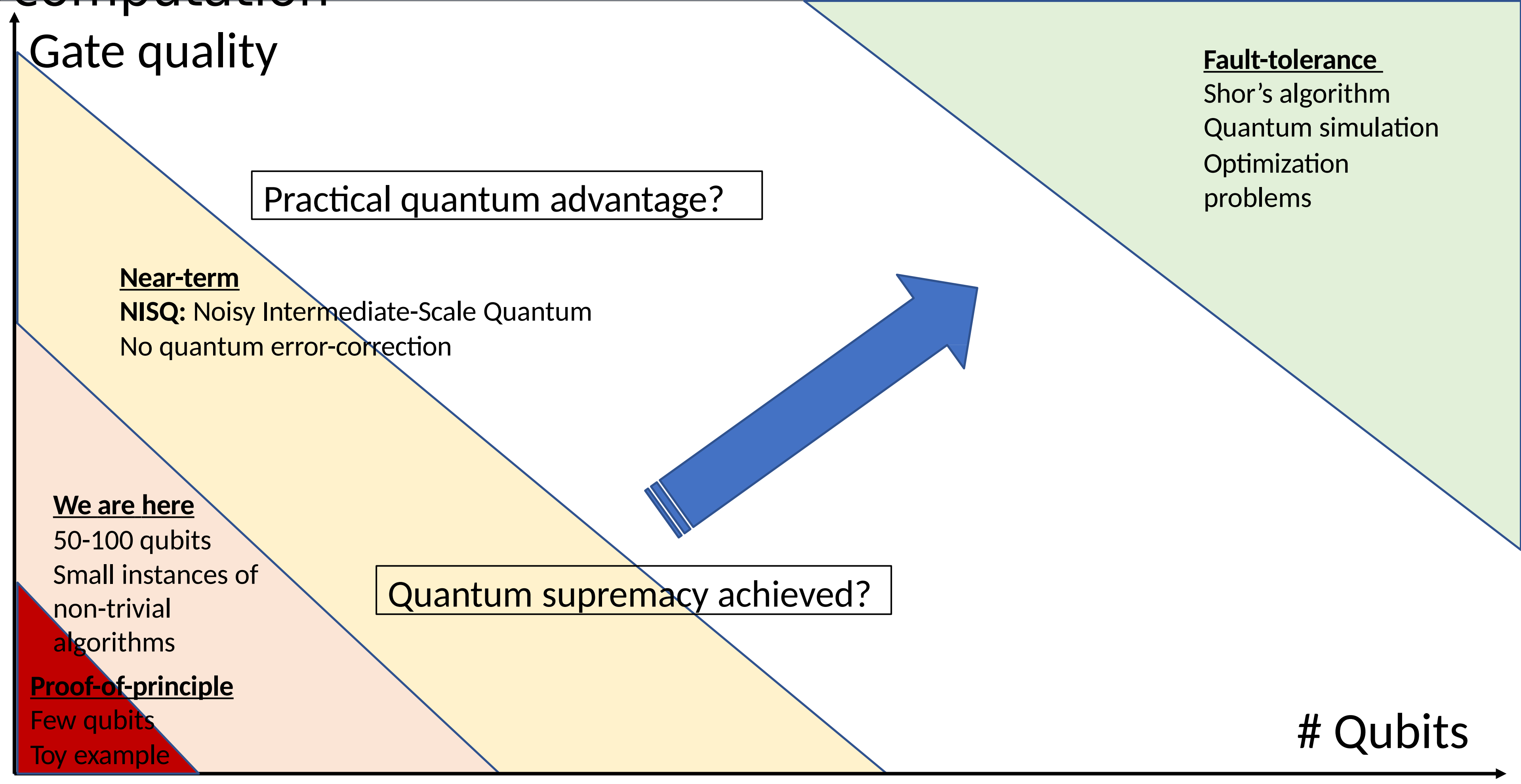
Noisy Intermediate Scale Quantum computers (NISQ)

- Quantum computers offer advantages in computation
- 100 (1000) qubits devices are “available” (being “developed”)



- Quantum applications are hard to find and implement

The prospects of quantum computation

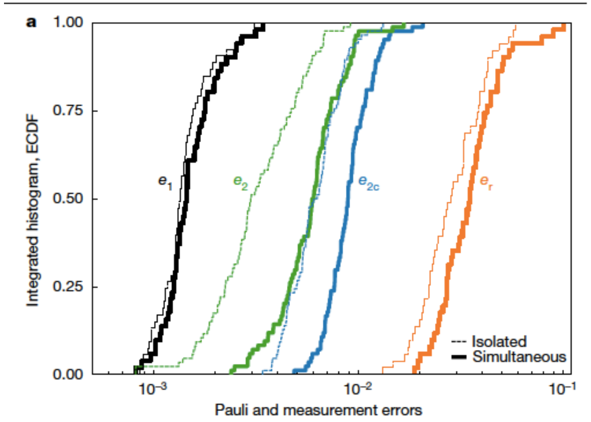


Where are we

50 qubits
Circuit depth ⇡ 100 : 20 cycles of 5 gates

- Quality of gates

1 qubit gate error:	$1.6 \cdot 10^{-3}$
2 qubit gate error:	$6.2 \cdot 10^{-3}$
3 Measurement error:	$3.8\ 10^{-2}$



Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%

b

Quantum supremacy using a programmable superconducting processor,
Frank Arute, Kunal Arya, […], John M. Martinis, Nature volume **574**, 505 (2019)

Where are we

50 qubits

Circuit depth ⇡ 100 : 20 cycles of 5 gates

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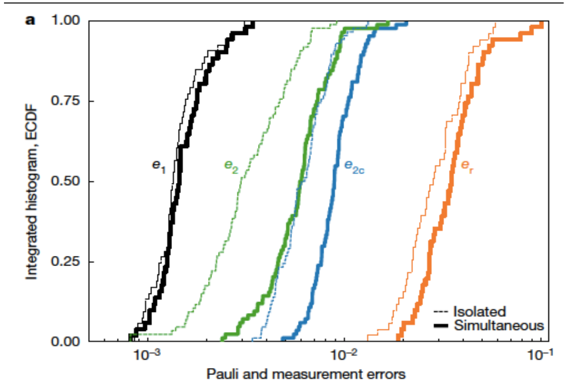

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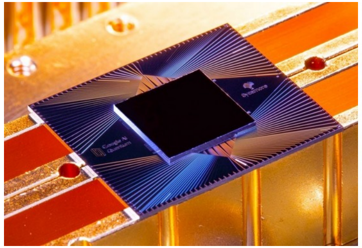
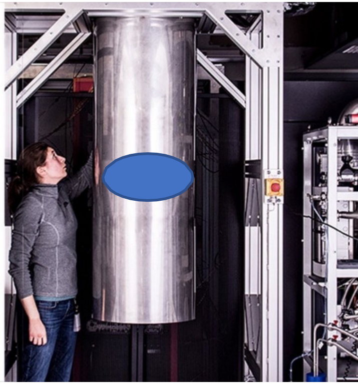
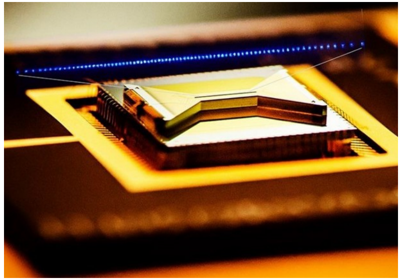
Hardware architectures

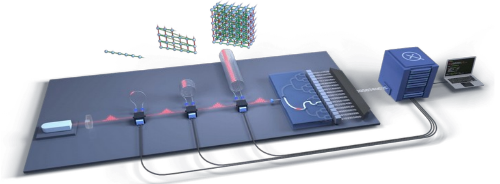
- Superconducting circuits





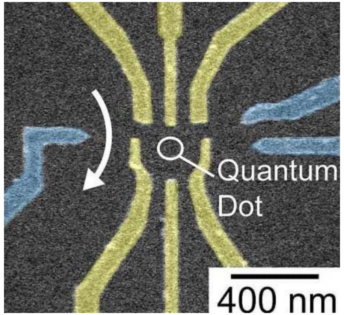
- Ion Traps





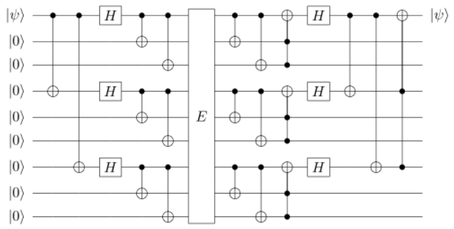
- Photonics

- Quantum dots

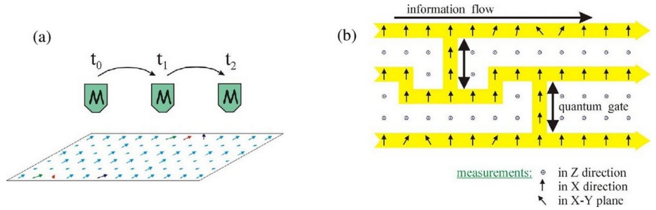


Models of Quantum Computation

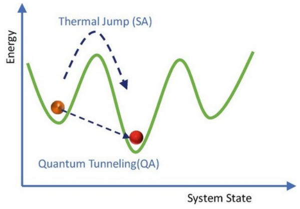
- Quantum Circuits



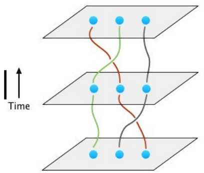
- Measurement-based Quantum Computation



- Adiabatic Quantum Computation
  Quantum annealers



- Topological Quantum Computation



Ethical challenges of Q-tech

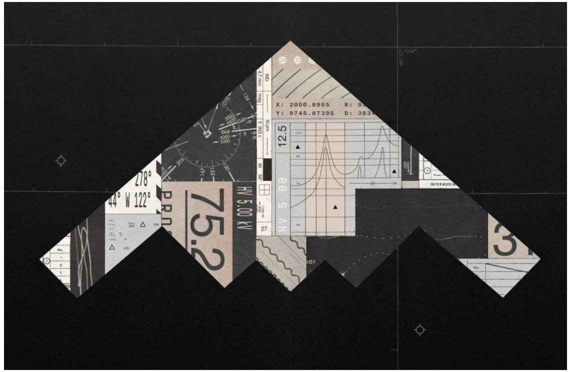
MIT Technology Review　　Topics

Computing / Quantum computing

The US and China are in a quantum arms race that will transform warfare

Radar that can spot stealth aircraft and other quantum innovations could give their militaries a strategic edge.

by **Martin Giles**　　January 3, 2019



Ethical challenges of Q-tech

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The US and China are in a quantum arms race that will transform warfare

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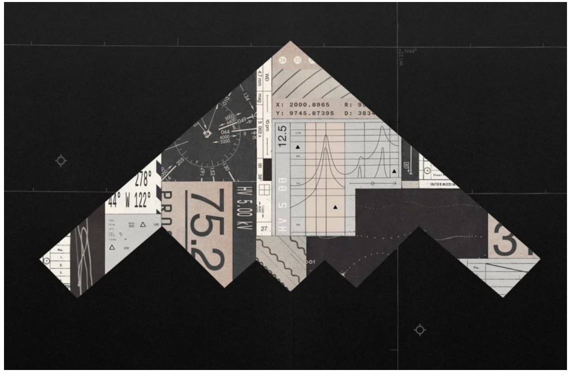

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  - Quantum sensing could be used for radar
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  - Quantum simulation could speedup material research

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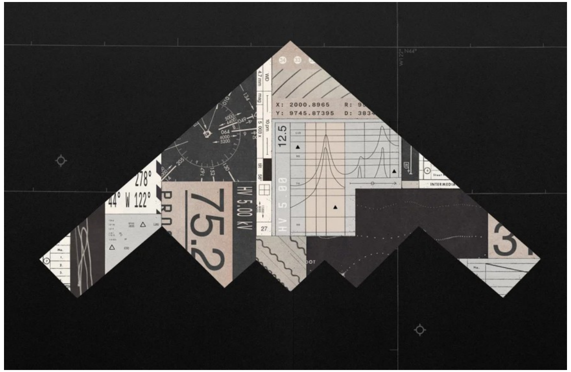

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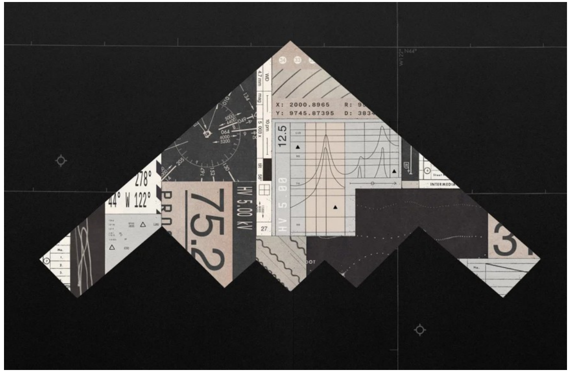

- Will it be militarized?
  - Quantum sensing could be used for radar
  - Quantum cryptoattacks
  - Quantum simulation could speedup material research
- Faster computers/AI can increase inequality & bias
- Expensive resources: how and where will they be extracted?

Questions

What makes quantum computing powerful?
What can we do with small quantum devices?

   

How can you build a quantum computer that outperforms a classical one for some (potentially irrelevant) problem?

How can you build a quantum computer that outperforms a classical one for some (potentially irrelevant) problem?

WIRED — The Revolutionary Quantum Computer That May Not Be Q

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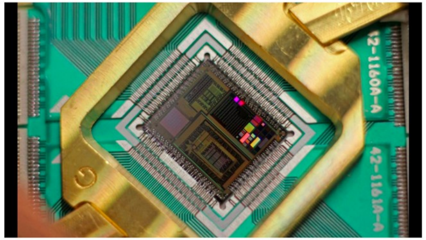

Quantum annealer. To solve a problem, D-Wave's chip seeks the lowest energy state of 512 interacting quantum bits, or qubits, fashioned from tiny rings of superconductor. COURTESY OF D-WAVE SYSTEMS INC.

Quantum or not, controversial computer runs no faster than a normal one

By Adrian Cho | Jun. 19, 2014, 2:15 PM

arXiv.org > cs > arXiv:1505.03424

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Beating the random assignment on constraint satisfaction problems of bounded degree

Boaz Barak, Ankur Moitra, Ryan O'Donnell, Prasad Raghavendra, Oded Regev, David Steurer, Luca Trevisan, Aravindan Vijayaraghavan, David Witmer, John Wright

(Submitted on 13 May 2015 (v1), last revised 11 Aug 2015 (this version, v2))

We show that for any odd k and any instance of the Max-kXOR constraint satisfaction problem, there is an efficient algorithm that finds an assignment satisfying at least a $\frac{1}{2}+\Omega(1/\sqrt{D})$ fraction of constraints, where D is a bound on the number of constraints that each variable occurs in. This improves both qualitatively and quantitatively on the recent work of Farhi, Goldstone, and Gutmann (2014), which gave a \emph{quantum} algorithm to find an assignment satisfying a $\frac{1}{2}+\Omega(D^{-3/4})$ fraction of the equations.
For arbitrary constraint satisfaction problems, we give a similar result for "triangle-free" instances; i.e., an efficient algorithm that finds an assignment satisfying at least a $\mu+\Omega(1/\sqrt{D})$ fraction of constraints, where μ is the fraction that would be satisfied by a uniformly random assignment.

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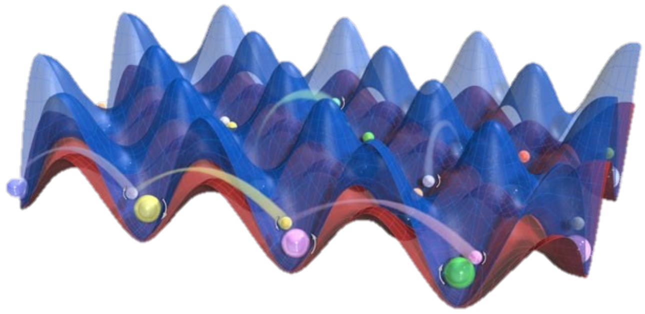
QUANTUM COMPUTING

Major Quantum Computing Advance Made Obsolete by Teenager

Quantum Simulation

Dynamical quantum simulators (e.g., using 10^4-10^5 cold atoms in optical lattices) cannot be efficiently classically simulated with state-of-the-art tensor-network algorithms (a la DMRG). *But are these good enough?*

Trotzky et. al., Nature Phys. 8 (2012), Choi et al., Science 352 (2016)



$$\hat{H} = \sum_j \left[-J\left(\hat{a}_j^\dagger \hat{a}_{j+1} + \mathrm{h.c.}\right) + \frac{U}{2}\hat{n}_j(\hat{n}_j - 1) + \frac{K}{2}\hat{n}_j j^2 \right]$$

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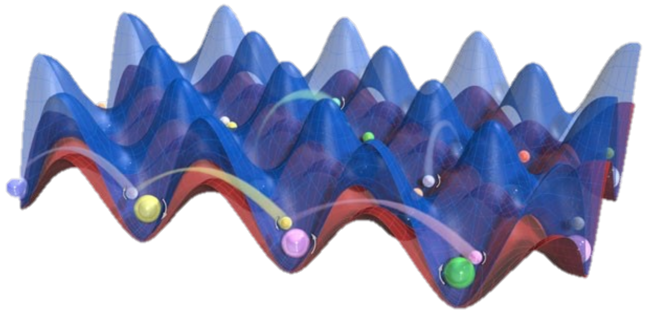
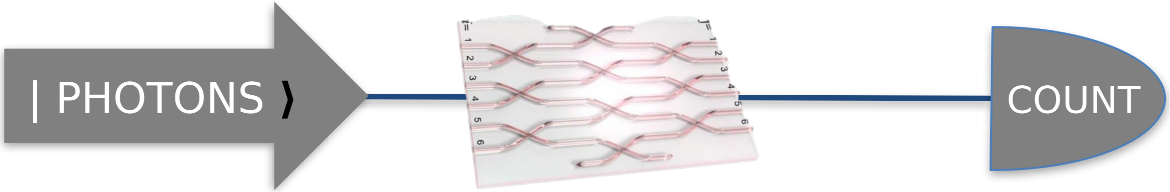


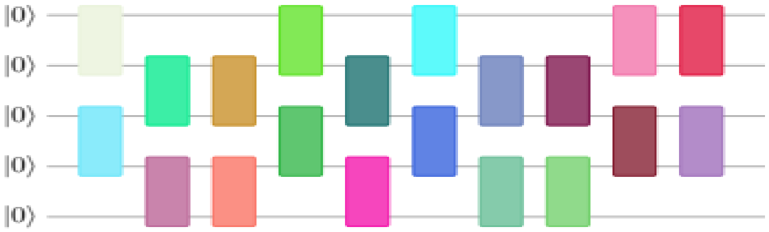
Quantum Sampling Problems

Boson sampling
Generates random numbers using a random photonic circuit, hard to simulate based on complexity theoretic evidence.



Aaronson, Arkhipov, Th. Comp. 9 (2013)

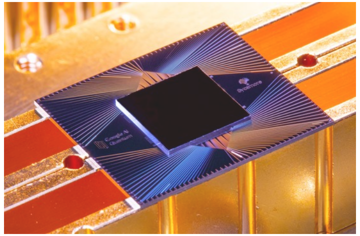
Random circuit sampling (“Google”)
They apply a long circuit of random physical interactions on superconducting qubits.



Boixo et al., Nature Phys. 14 (2016)
Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Arute, Nature, Vol 574, 505 (2019)

Google’s experiment

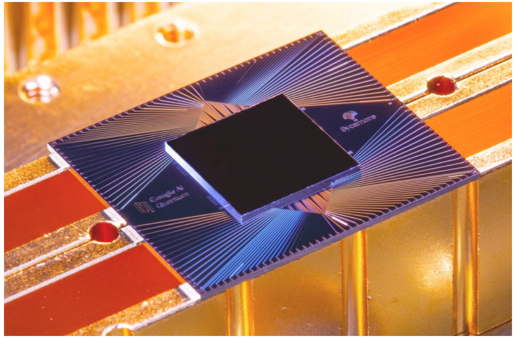
Arute, Nature, Vol 574, 505 (2019)

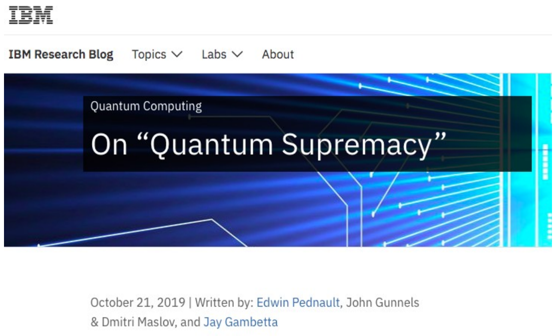


Google’s experiment

Arute, Nature, Vol 574, 505 (2019)

- Implementan un circuito cuántico aleatorio con 53 qubits, depth 40 (1500+ operaciones)
- Runs for 200 seconds
- They estimate a classical computer would require “10,000 years on a 100,000 core supercluster” to simulate the same process
- **The computer can still be simulated by classical computersand cannot be efficiently verified**





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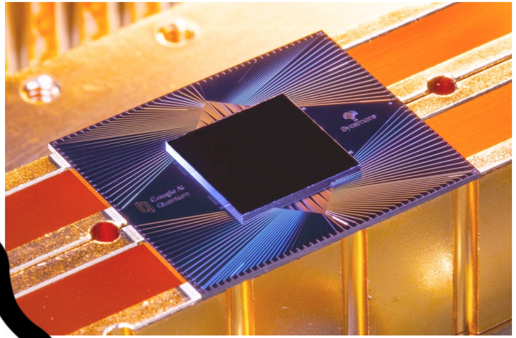

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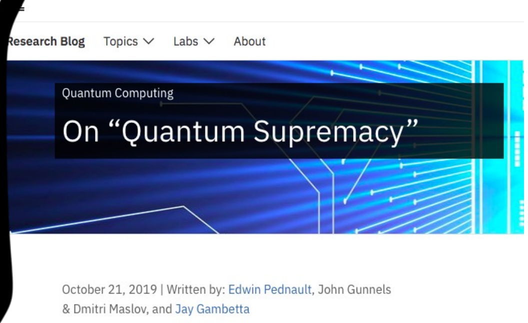


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Resources

- News: https://thequantumdaily.com/
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  - https://quantumcomputingreport.com/
  - https://qt.eu/
- Research: https://scirate.com/
- Network: QIPC Spain, QUROPE

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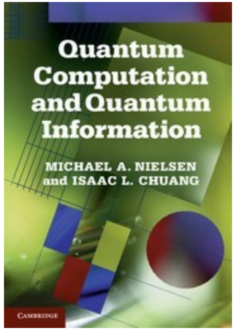

- Quantum Computing Lecture Notes
  by Ronald de Wolf
  https://arxiv.org/abs/1907.09415

- Introduction to Quantum Computation
  Sevag Gharibian
  Lectures notes link

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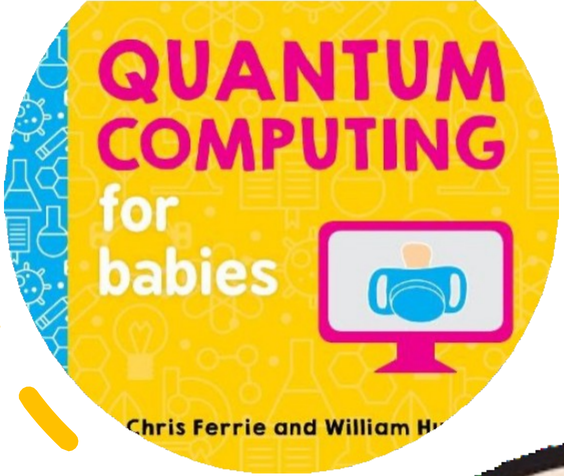

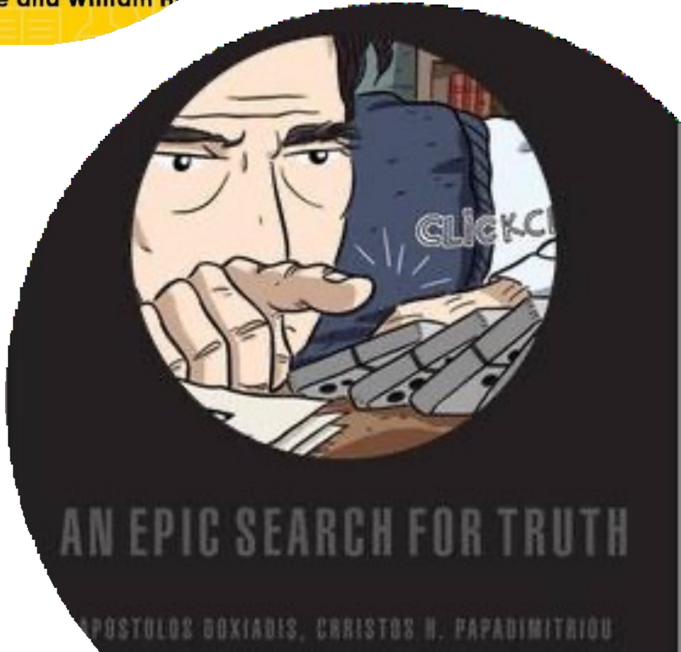

Quantum Computer algorithms

what can we do with them and how can we realize them?

Jara Juana Bermejo-Vega
University de Granada

Spring School on Near-Term Quantum Computing
April 2024

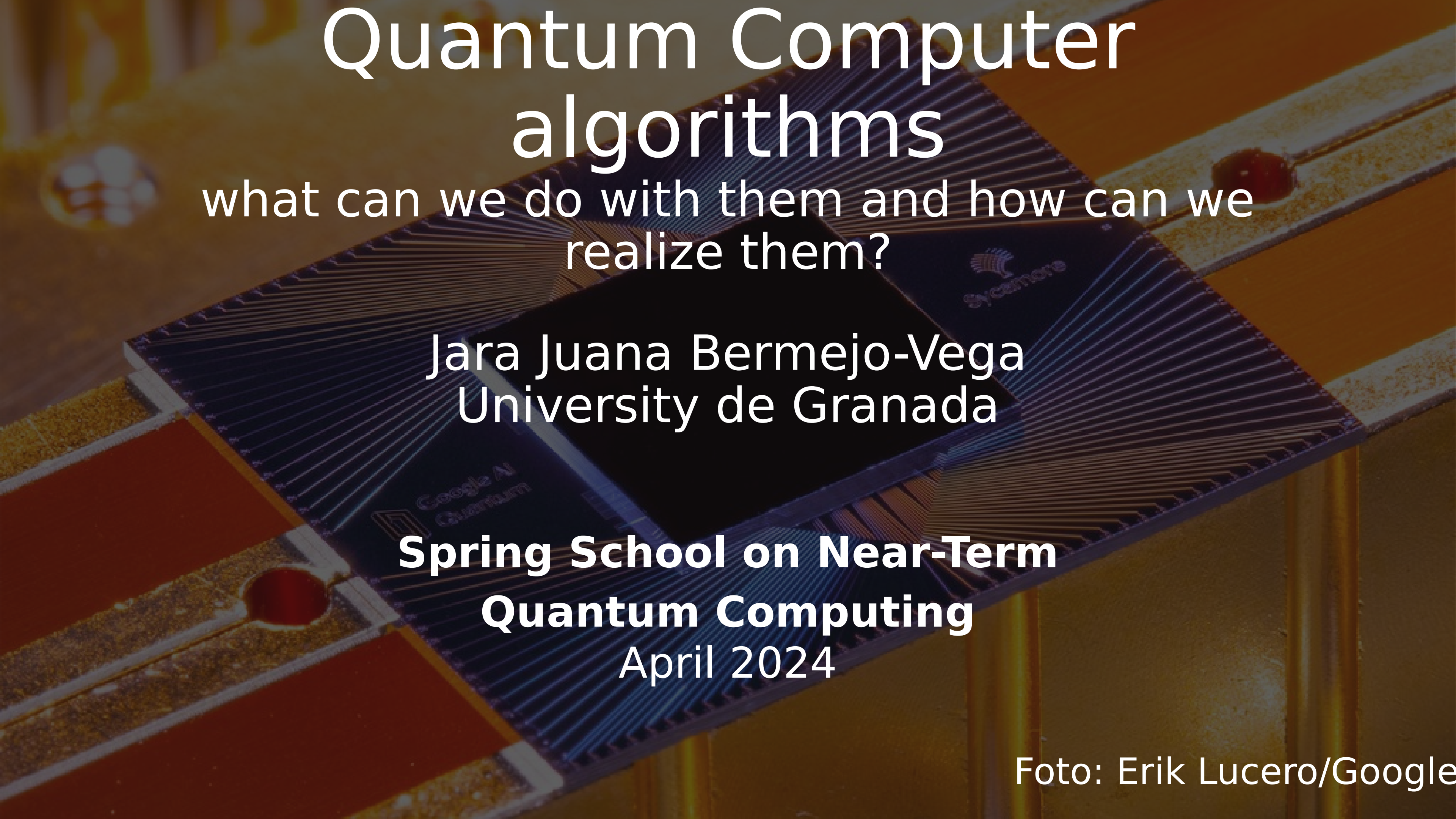

Foto: Erik Lucero/Google

Quantum computer algorithms: what can we do with them and how can we realize them?

1. Quantum algorithms
    1. Hamiltonian simulation
    2. Deutsch-Jozsa's
    3. QFT
    4. Phase Estimation
    5. Shor's algorithm
    6. Grover's search

2. Quantum realizations
    1. Quantum error correction
    2. Magic states
    3. Gate Teleportation

Reference
IQC Introduction to Quantum Computing - Petros Wallden
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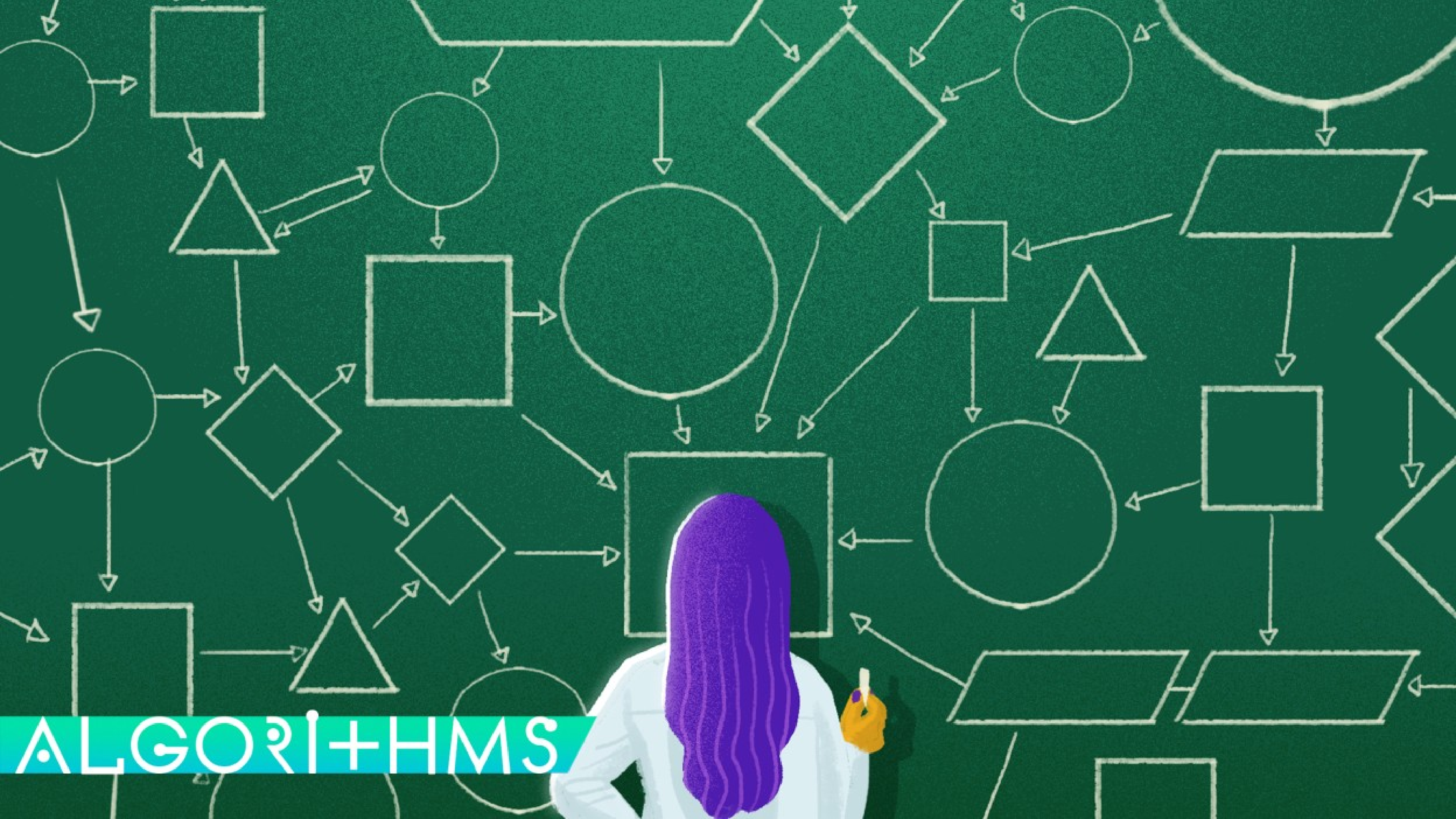
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