QUANDELA

Introduction to quantum computing

PIERRE-EMMANUEL EMERIAU – QUANTUM ALGORITHM LEAD

POUR L'IMT ATLANTIQUE – NOVEMBRE 2024

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Overview

1. → **2.** → **3.** → **4.** → **5.**

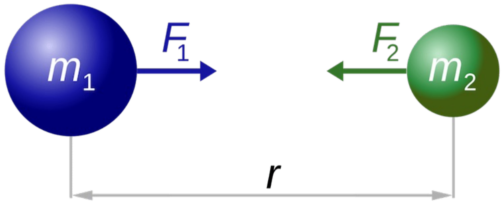
1. **A step back**
2. **The basis of quantum computing**
3. **A dive into quantum computing technologies**
4. **Quantum algorithms**
5. **Building an idealised quantum computer**

01.

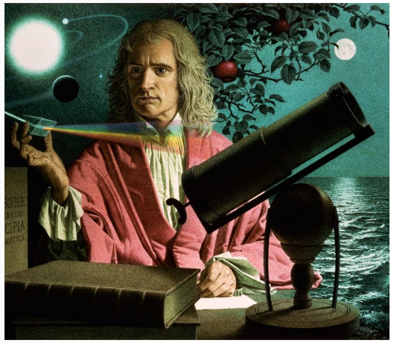
A step back

A brief historical perspective

A brief historical perspective



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$



- Behavior of light (transmission, reflection, refraction, diffraction)
- Motion of objects (stars, planets, …)
- Thermodynamics
- Electromagnetism

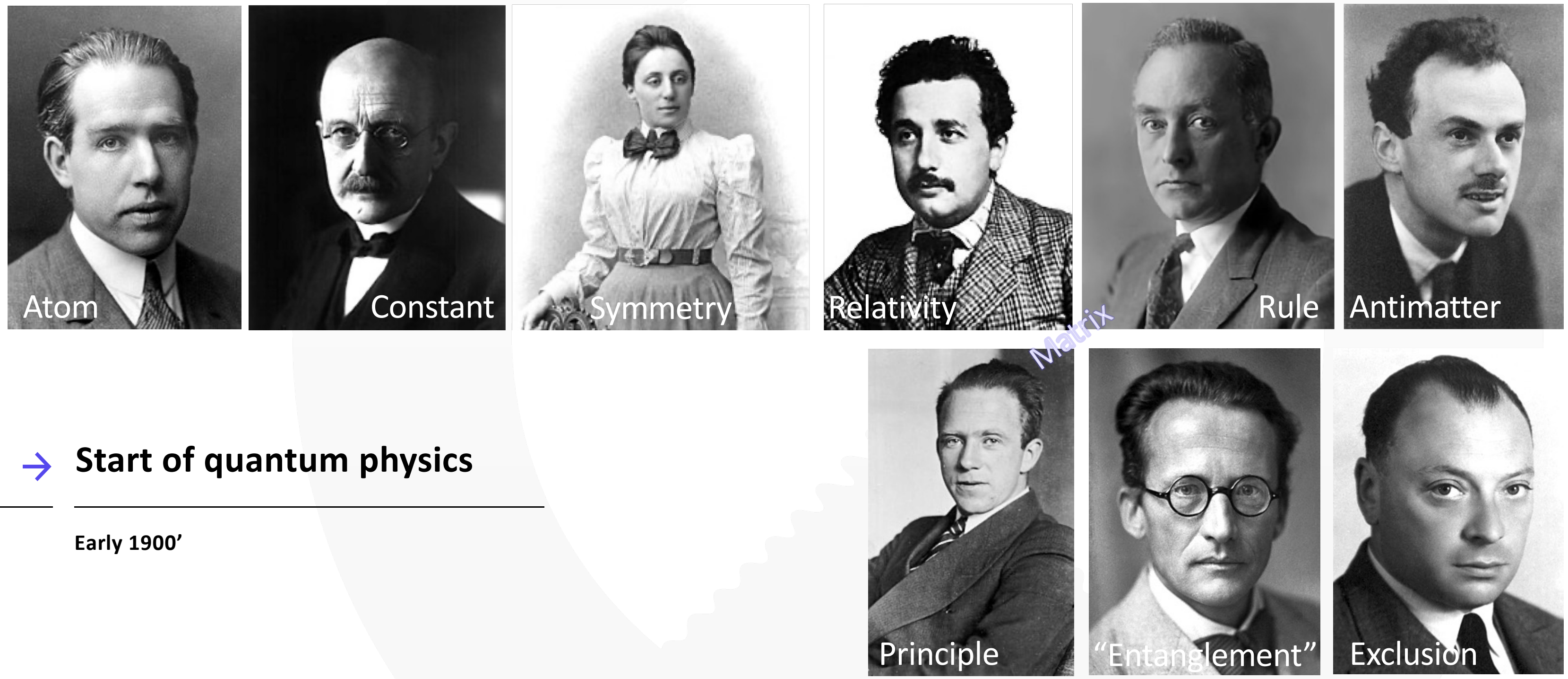
Newtonian physics

Up to 20th century

A brief historical perspective

Weird behaviors arose…
- Black-body radiation problem
- Photoelectric effects
- …

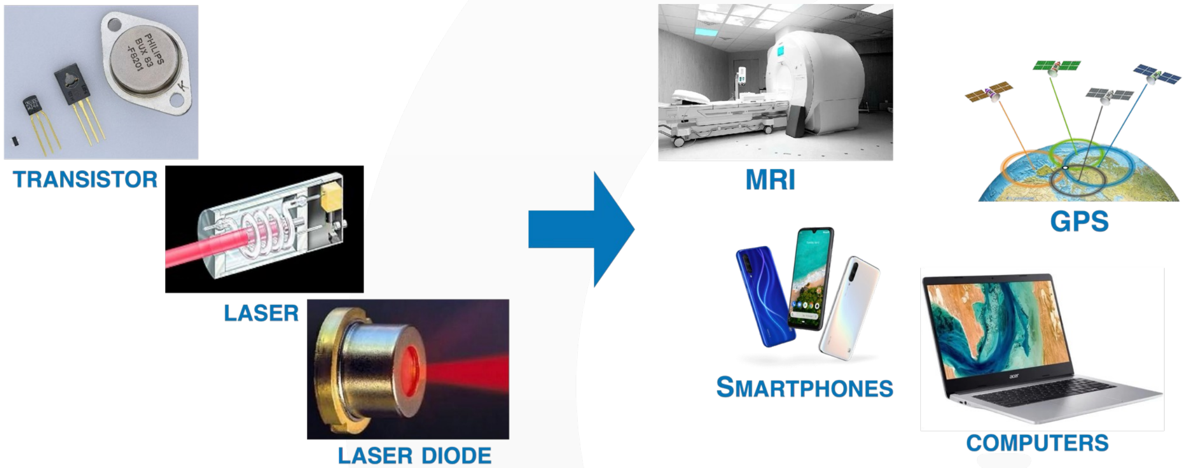
A need for a new ‘quantised’ physics



Newtonian physics → **Start of quantum physics**

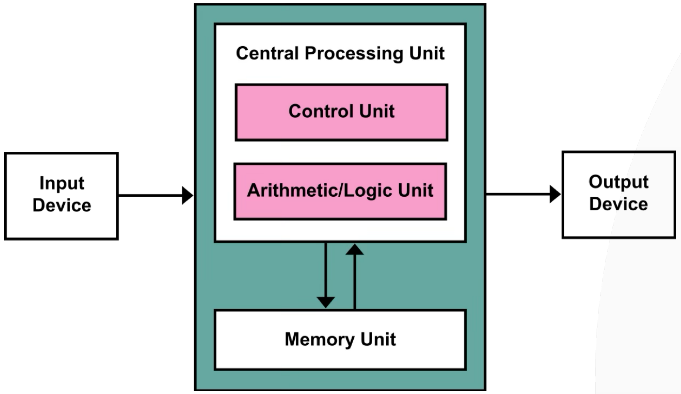
Newtonian physics	Start of quantum physics
Up to 20th century	Early 1900’

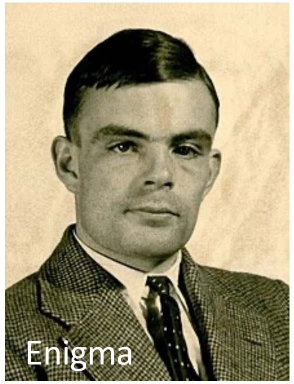
A brief historical perspective

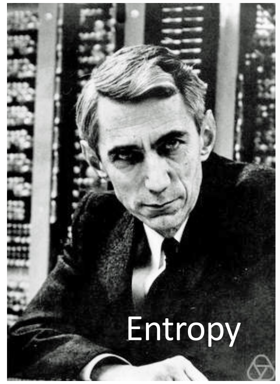


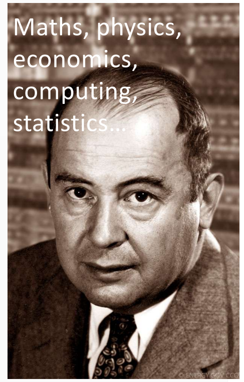
Newtonian physics →	Start of quantum physics →	1^{st} quantum revolution
Up to 20^{th} century	**Early 1900’**	**20^{th} century**

A brief historical perspective









Newtonian physics → **Start of quantum physics** → **1st quantum revolution**

Up to 20th century

Early 1900'

20th century

Information theory

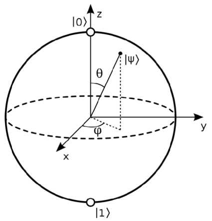
1940s onward

A brief historical perspective

SUPERPOSITION

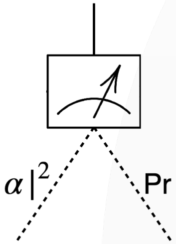
Classical bit: 0 or 1

Quantum bit: $\alpha|0\rangle + \beta|1\rangle$



MEASUREMENT

$\alpha|0\rangle + \beta|1\rangle$



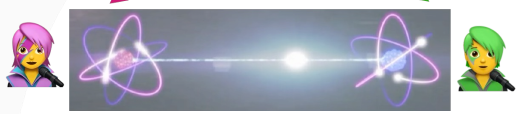
Pr = $|\alpha|^2$ Pr = $|\beta|^2$

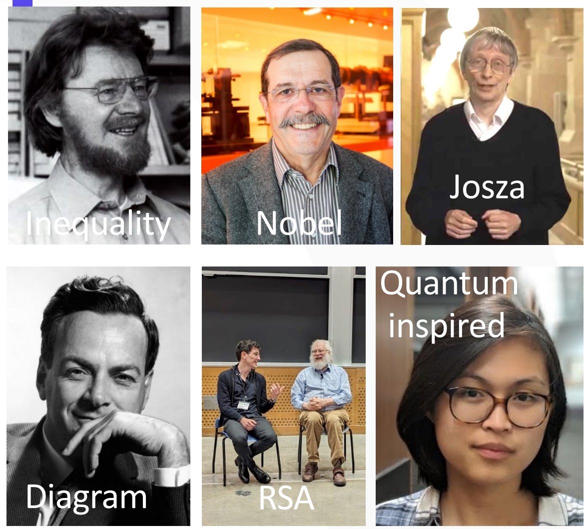
Result ‘0’
State $|0\rangle$

Result ‘1’
State $|1\rangle$

ENTANGLEMENT

$$|\Psi\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$





Newtonian physics → **Start of quantum physics** → **1st quantum revolution**

Up to 20th century | Early 1900’ | 20th century

Information theory

1940s onward

2nd quantum revolution

1980s onward

A brief historical perspective

Newtonian physics →

Up to 20^{th} century

Start of quantum physics →

Early 1900'

1^{st} quantum revolution

20^{th} century

Information theory

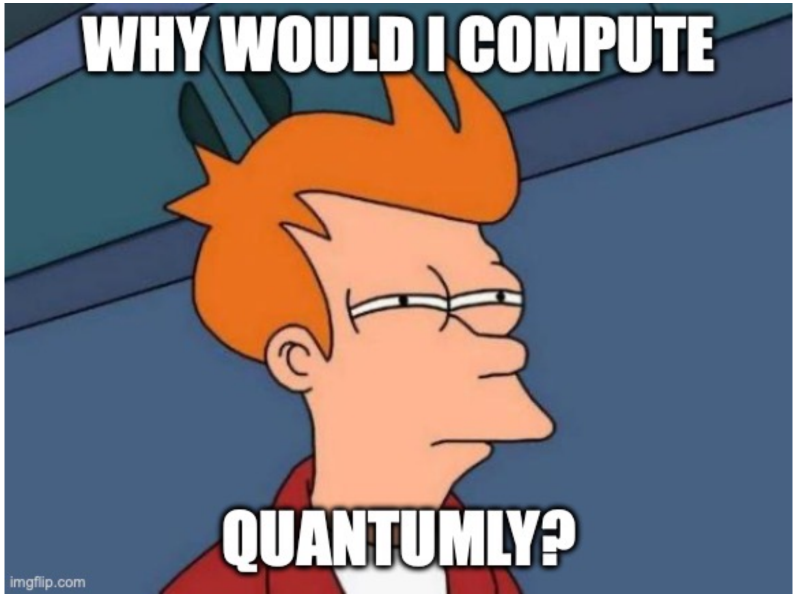
1940s onward

2nd quantum revolution

1980s onward

02.

The basis of quantum computing

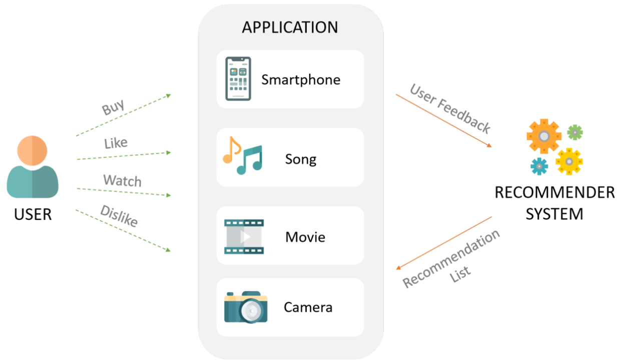


What makes a quantum algorithm quantum?

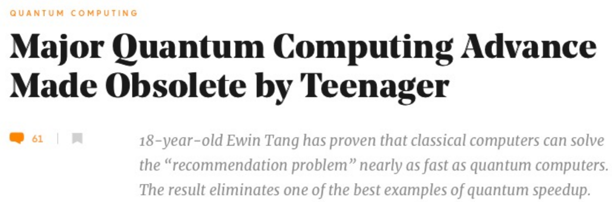
QUANTUM POWER?

- Find problems where quantum computers give advantage
- Make sure new algorithms are robust to improvements in classical computing
- ~~Parallelism powers QC~~
- Where does it come from physically?
- **Highly interdisciplinary** questions

QUANTUM RECOMMENDATION SYSTEM



~~QUANTUM~~ RECOMMENDATION SYSTEM


QUANTUM COMPUTING

Major Quantum Computing Advance Made Obsolete by Teenager

61

18-year-old Ewin Tang has proven that classical computers can solve the "recommendation problem" nearly as fast as quantum computers. The result eliminates one of the best examples of quantum speedup.

Cooking a quantum algorithm: the basic ingredients

SUPERPOSITION

If a system can be in state A or state B, it can also be in a "**mixture**" of the two states. If we measure it, we see either A or B, probabilistically.

ENTANGLEMENT

There exist systems of multiple parts which cannot be described only in terms of their constituent parts.

It is sustained by **coherence** and leads to **non-locality**.

COLLAPSE

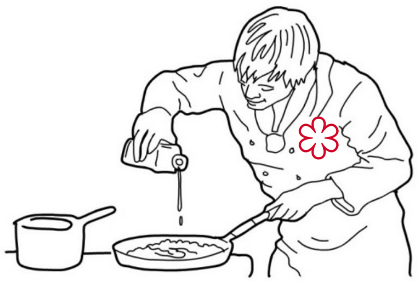
Any further measurements will give the same result.

UNCERTAINTY

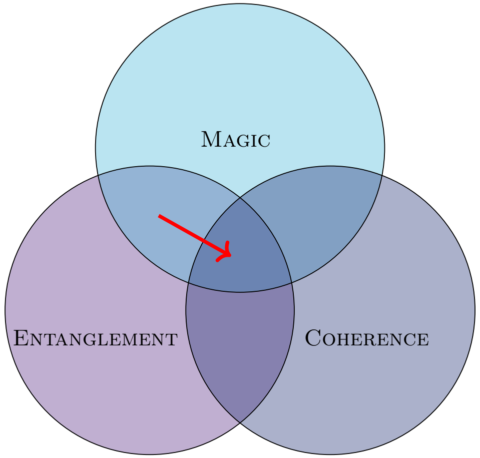
There are pairs of measurements where greater certainty of the outcome of one measurement implies greater uncertainty of the outcome of the other measurement.

The basic idea behind quantum computing is to **use these effects to our advantage** when **processing information** encoded onto **quantum systems**

Cooking a quantum algorithm: the chef ingredients



Resource theory!



ENTANGLEMENT

There exist systems of multiple parts which cannot be described only in terms of their constituent parts.

COHERENCE

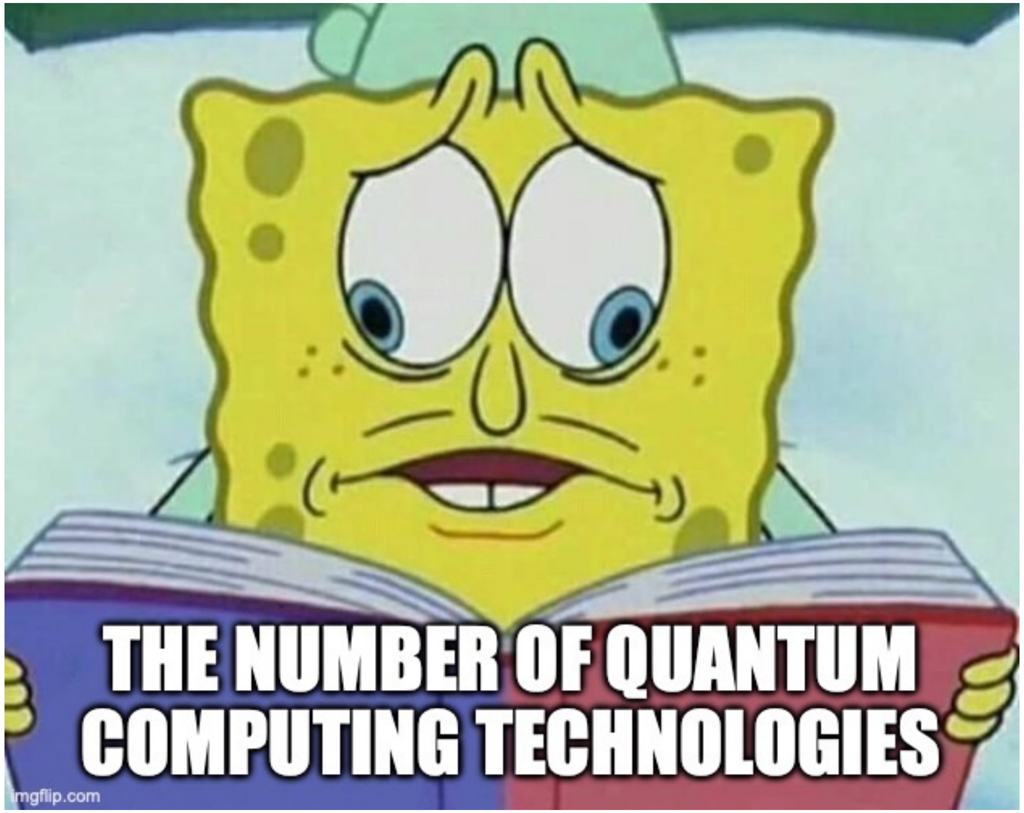
Ability to keep the quantum information.

MAGIC

Outside of stabiliser theory.

03.

A dive into quantum computing technologies



The Physical Implementation of Quantum Computation

David P. DiVincenzo

IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 USA

(February 1, 2008)

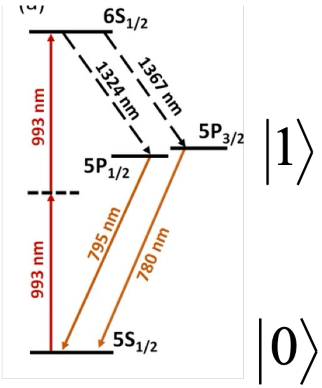
After a brief introduction to the principles and promise of quantum information processing, the requirements for the physical implementation of quantum computation are discussed. These five requirements, plus two relating to the communication of quantum information, are extensively explored and related to the many schemes in atomic physics, quantum optics, nuclear and electron magnetic resonance spectroscopy, superconducting electronics, and quantum-dot physics, for achieving quantum computing.

DiVincenzo, David P. (2000-04-13). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783.

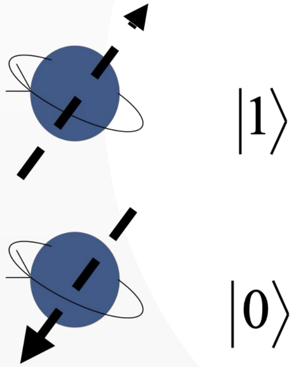
THE DIVICENZO CRITERIA

1. A **scalable** physical system with **well characterized qubits**
2. The ability to **initialize** the state of the qubits
3. Long **decoherence** times
4. A "**universal**" set of quantum gates
5. A qubit-specific **measurement capability**

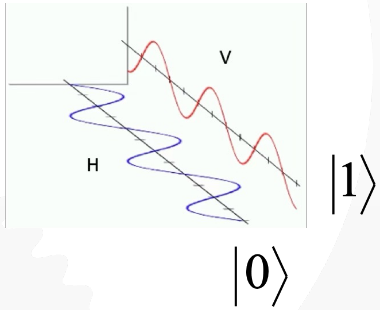
1. A scalable physical system with well characterized qubits



ATOM + ENERGY LEVELS

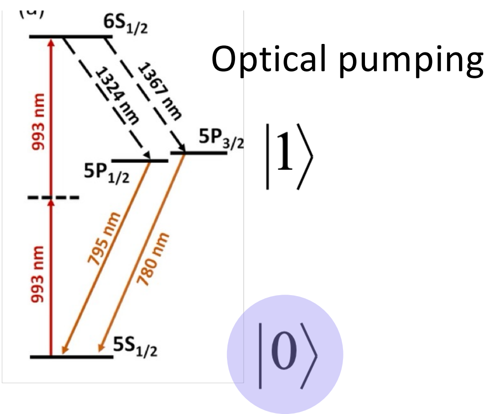


ELECTRON + SPIN

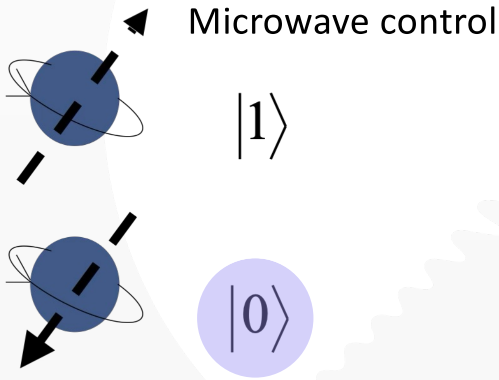


PHOTON + POLARISATION

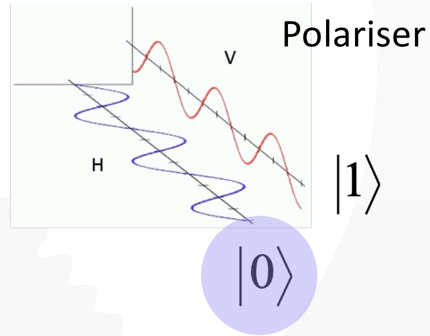
2. The ability to initialize the states of the qubits



ATOM + ENERGY LEVELS

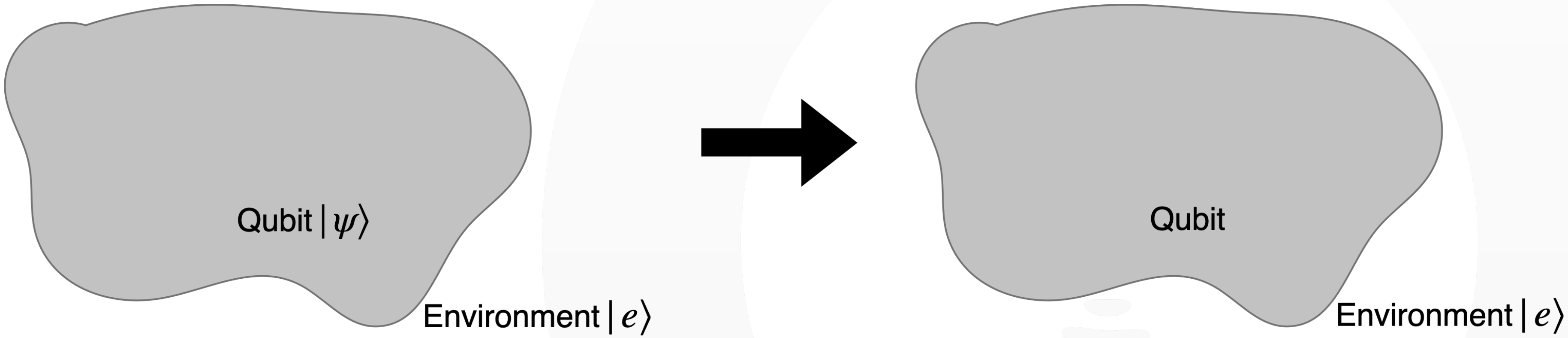


ELECTRON + SPIN



PHOTON + POLARISATION

3. Long decoherence times



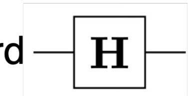
$$\rho = |\psi\rangle\langle\psi| \otimes |e\rangle\langle e|$$

$$\mathrm{Tr}_e(\rho) = \begin{pmatrix} p_1 & 0 \\ 0 & p_2 \end{pmatrix} \neq |\psi\rangle\langle\psi|$$

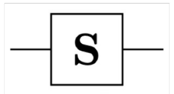
DIFFICULTY: We need isolated qubits to avoid decoherence **BUT** We need interactions to control the qubits and make them interfere

4. A universal set of quantum gates

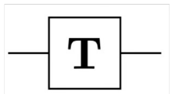
Universal = can implement any unitary transformation ⇒ *continuous!*

Hadamard 

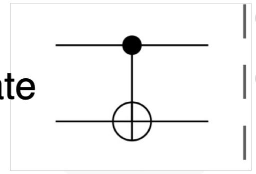
$|0\rangle \to (|0\rangle + |1\rangle)/\sqrt{2}$
$|1\rangle \to (|0\rangle - |1\rangle)/\sqrt{2}$

S gate 

$|0\rangle \to |0\rangle$
$|1\rangle \to i|1\rangle$

T gate 

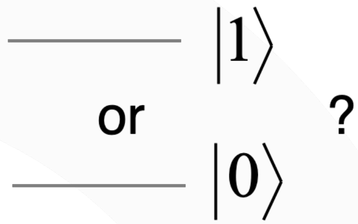
$|0\rangle \to |0\rangle$
$|1\rangle \to e^{i\pi/4}|1\rangle$

C-NOT gate 

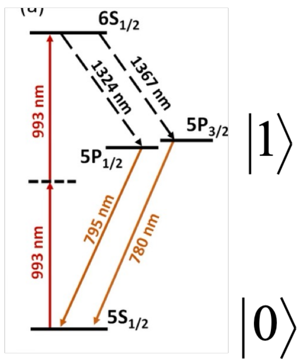
$|00\rangle \to |00\rangle$
$|01\rangle \to |01\rangle$
$|10\rangle \to |11\rangle$
$|11\rangle \to |10\rangle$

⇒ 3 SINGLE QUBIT GATES + 1 TWO-QUBIT GATE = APPROXIMATE ALL UNITAIRES

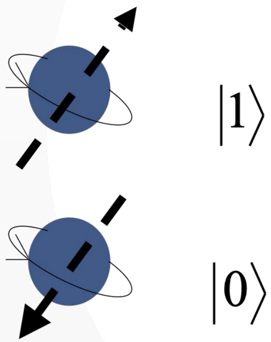
5. A qubit-specific readout capability

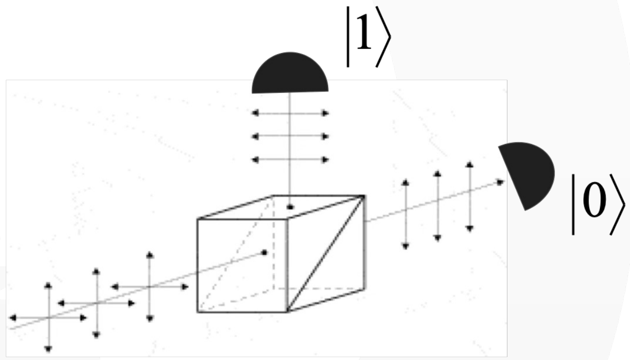


Fluorescence



Microwave readout





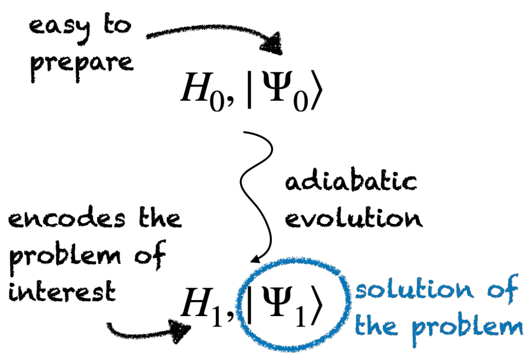
Polariser + single photon detectors

ATOM + ENERGY LEVELS **ELECTRON + SPIN** **PHOTON + POLARISATION**

Models of quantum computation

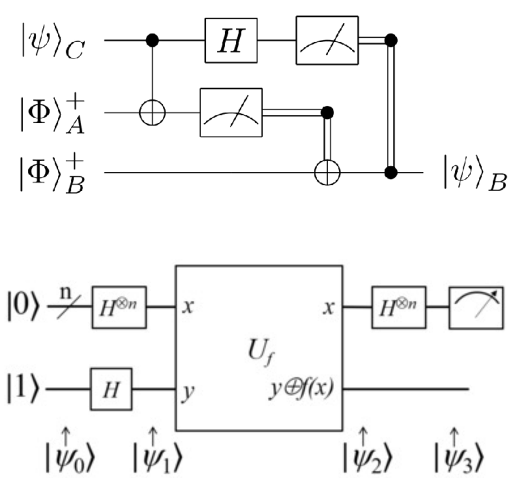
ANALOG

ADIABATIC



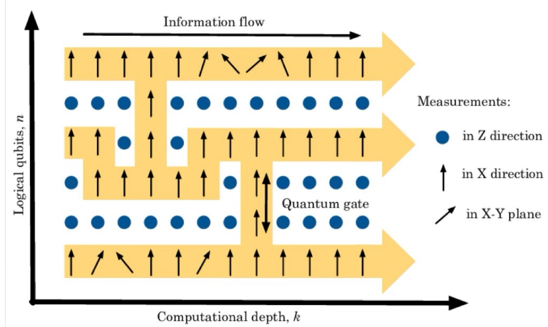
DIGITAL

GATE-BASED



DIGITAL

MEASUREMENT-BASED



PHYSICAL REVIEW A **68**, 022312 (2003)

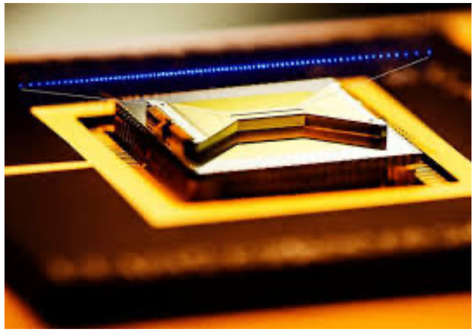
Measurement-based quantum computation on cluster states

Robert Raussendorf, Daniel E. Browne,* and Hans J. Briegel

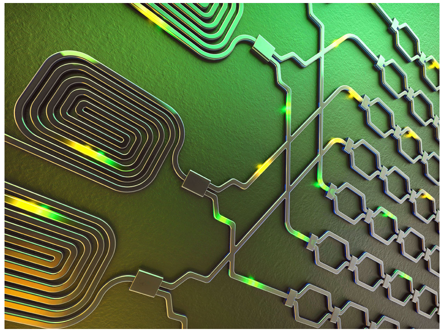
Theoretische Physik, Ludwig-Maximilians-Universität München, München, Germany

(Received 18 February 2003; published 25 August 2003)

Main physical implemenations of a quantum computer

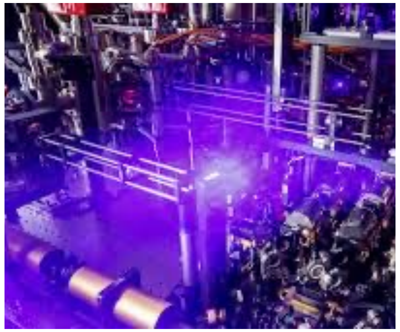


TRAPPED IONS

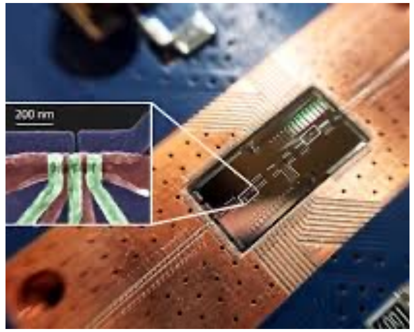


PHOTONS

SUPERCONDUCTING QUBITS

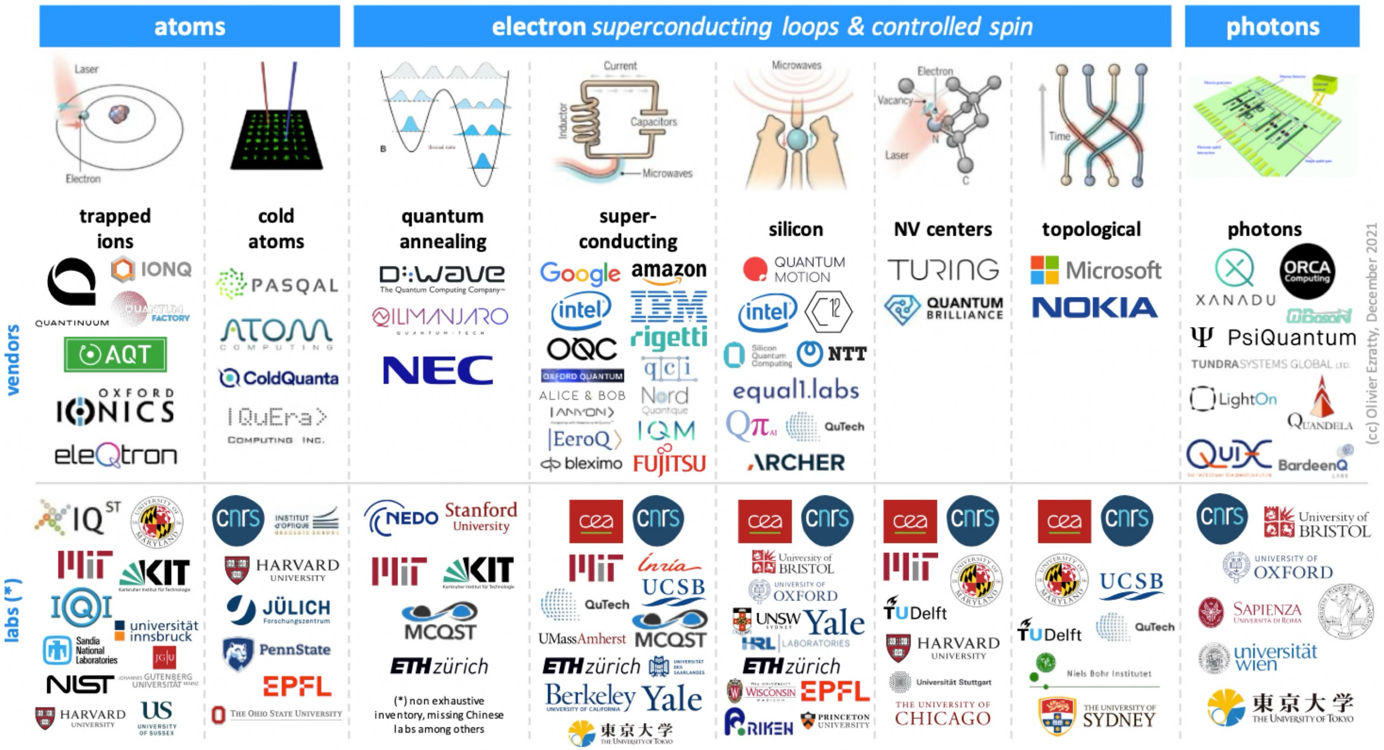


NEUTRAL ATOM



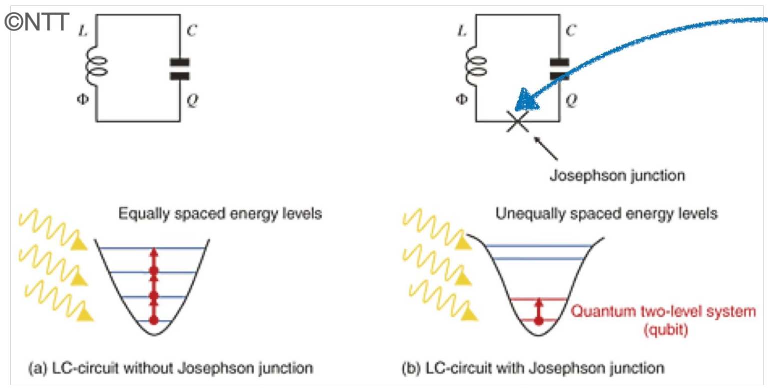
SILICON QUBITS

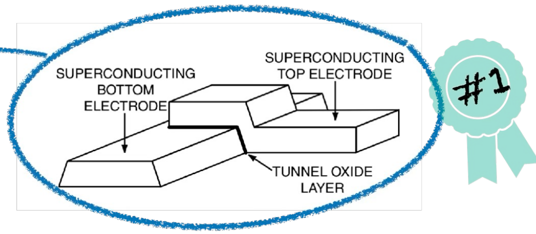
Main physical implemenations of a quantum computer

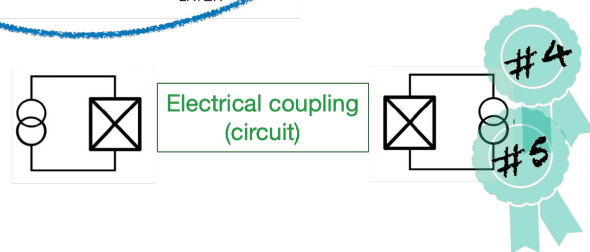


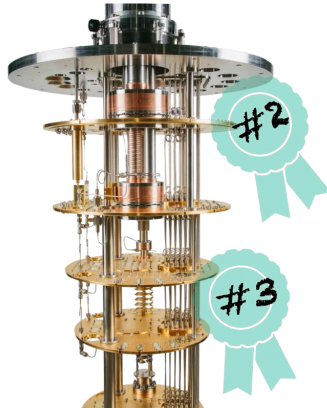
BACK TO DIVICENZO CRITERIA

SUPERCONDUCTING QUBITS









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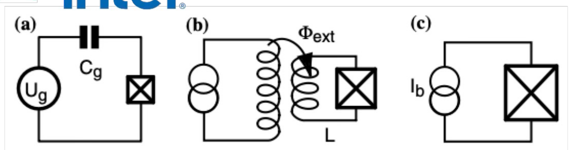
Quantum Information Processing, Vol. 3, Nos. 1–5, October 2004 (© 2004)

Implementing Qubits with Superconducting Integrated Circuits

Michel H. Devoret[1,4] and John M. Martinis[2,3]

IQM intel OQC IBM



Charge qubit (transmon)

Flux qubit

Phase qubit

rigetti amazon ALICE & BOB

SUPERCONDUCTING QUBITS

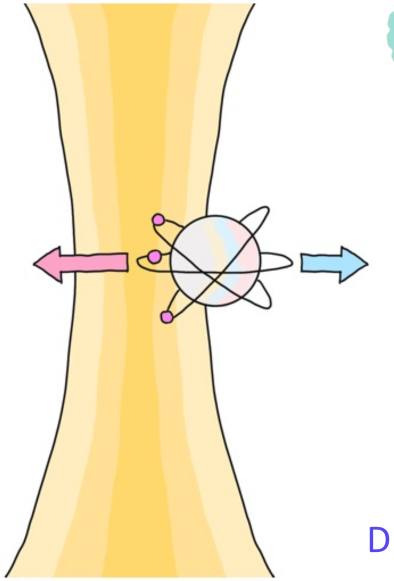
- Eletronics
- Easy and fast to control
- Several degrees of freedom

- Cryogeny (mK)
- Correlated noise
- Decoherence
- Wiring and connectivity

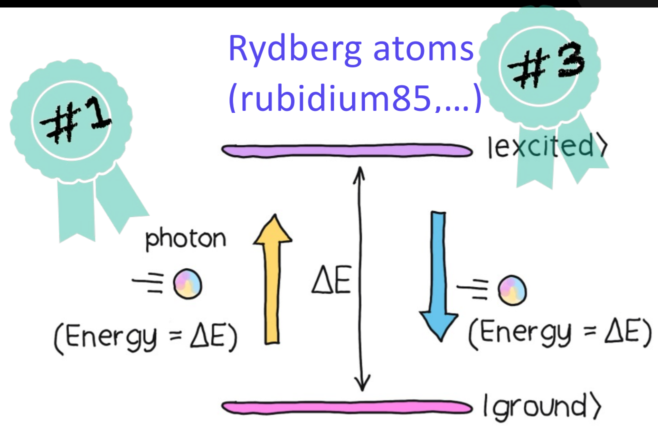
BACK TO DIVICENZO CRITERIA

NEUTRAL ATOMS

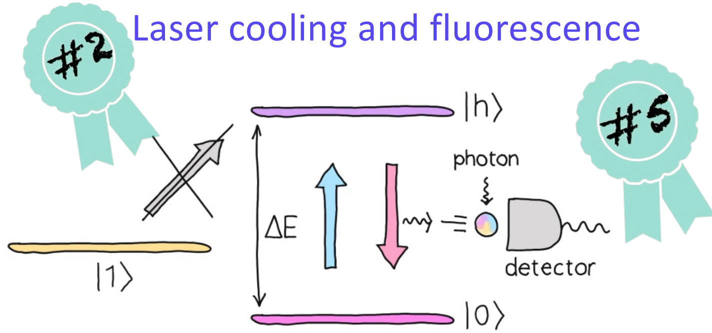
Optical tweezers



Rydberg atoms
(rubidium85,...)



Laser cooling and fluorescence



Drive hamiltonian with pulses
and Rydberg blockade (Van der Waals interaction)

Credit to Pennylane for drawings.

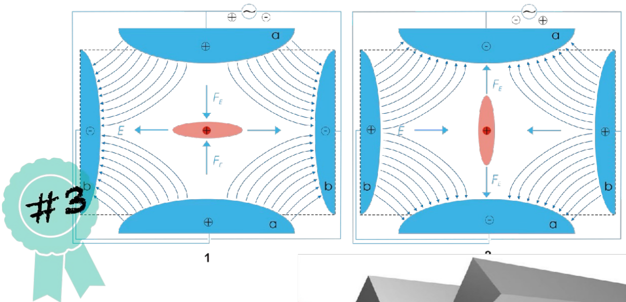
NEUTRAL ATOMS

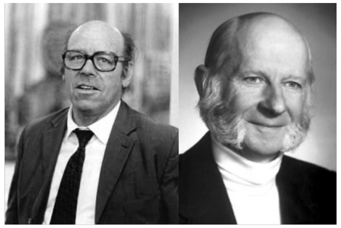
- Connectivity
- 4K to room temperature
- Great isolation

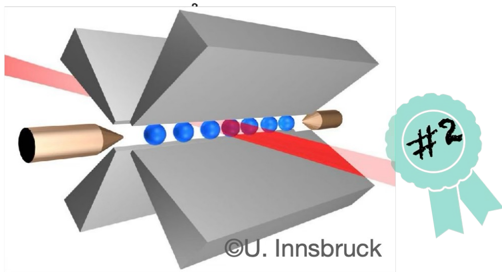
- Scalability
- Clock time

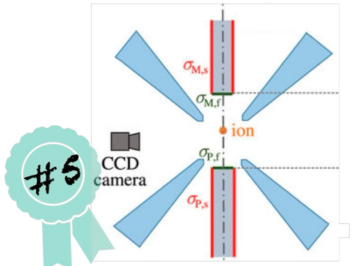
BACK TO DIVICENZO CRITERIA

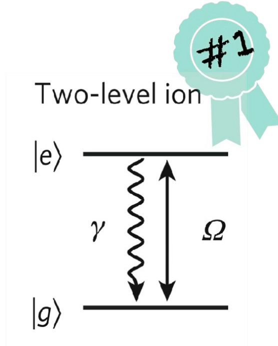
TRAPPED IONS

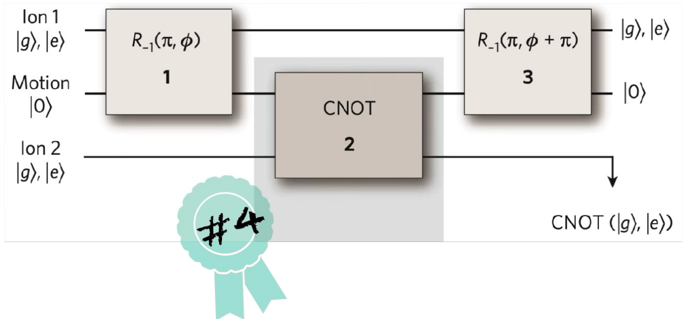












VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

(Received 30 November 1994)

AQT

IONQ

QUANTINUUM

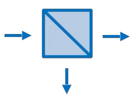
TRAPPED IONS

- Long coherence
- Connectivity
- 4K to room temperature
- Great isolation

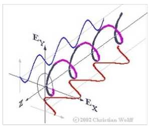
- Scalability (1D)
- Size
- Clock time

BACK TO DIVICENZO CRITERIA

PHOTONS



Path



Polarisation

OAM

$\sqrt{p_0}|0_a\rangle + \sqrt{p_1}e^{i\alpha_1}|1_a\rangle$

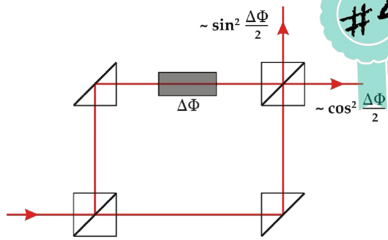
Photon number

…

#1

No decoherence

#3



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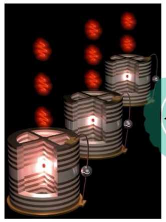
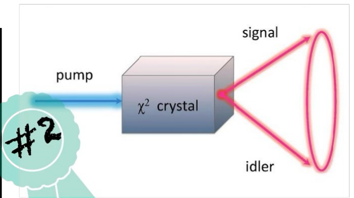


#2



#5

A scheme for efficient quantum computation with linear optics

E. Knill, R. Laflamme & G. J. Milburn

Nature **409**, 46–52 (2001) | Cite this article

38k Accesses | **4127** Citations | **57** Altmetric | Metrics

DISCRETE VARIABLE

Ψ PsiQuantum

QUIX QUANTUM

ORCA Computing

CONTINUOUS VARIABLE

XANADU

BACK TO DIVICENZO CRITERIA

PHOTONS

- Long coherence
- Connectivity
- 4K to room temperature
- Connection with network
- Single-qubit gates
- Modularity

- Photon loss
- Source efficiency
- Two-qubit gates

04.

Quantum algorithms

BACK TO HISTORY

The dawn of quantum algorithmic

1982 RICHARD FEYNMAN →

If you want to make a simulation of nature, you'b **better make it quantum mechanical**, and by golly it's a wonderful problem, because it doesn't look so easy. ”

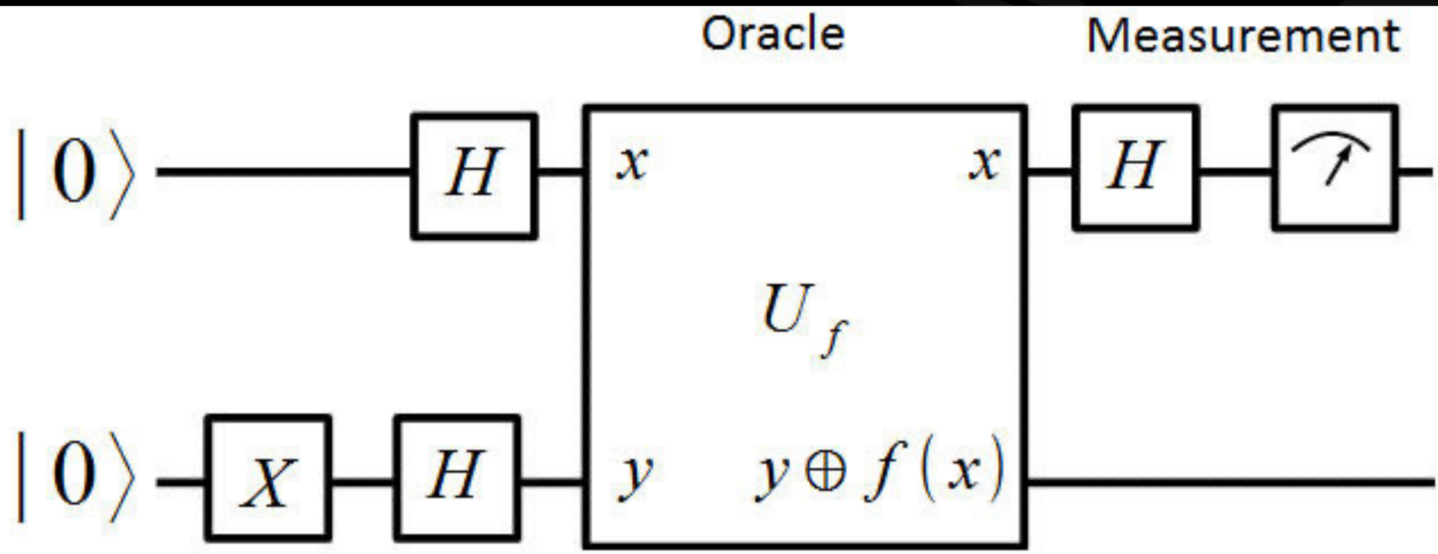
1985 DAVID DEUTSCH →

Computing devices resembling the **universal quantum computer** can, in principle, be built and would have many remarkable properties **not reproducible by any Turing machine**. ”

1992 DAVID DEUTSCH AND RICHARD JOZSA →

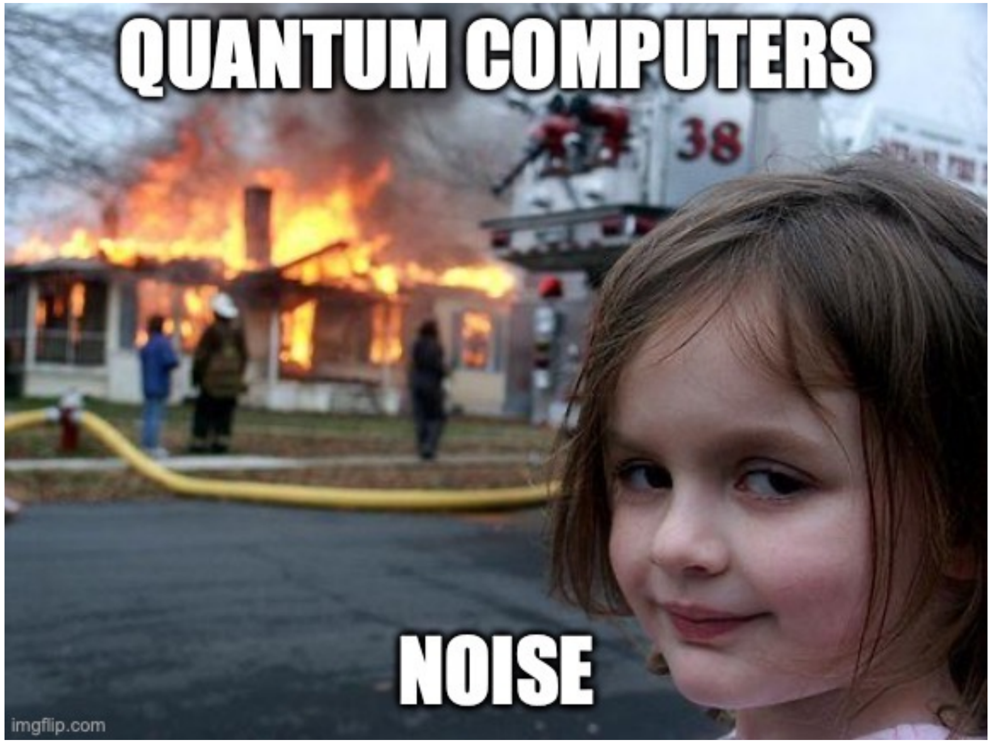
The quantum computation solves the problem with certainty **in exponentially less time** than any classical deterministic computation. ”

Exercise: the Deutsch algorithm



05.

Building an idealised quantum computer



Benchmarking quantum computers

Assessing the quality of near-term photonic quantum devices

Rawad Mezher and Shane Mansfield

Quandela SAS, 7 Rue Léonard de Vinci, 91300 Massy, France

PHYSICAL REVIEW A **100**, 032328 (2019)

Validating quantum computers using randomized model circuits

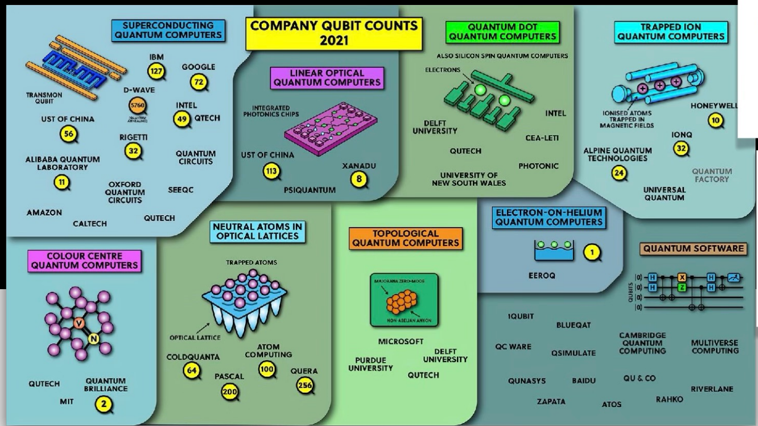
Andrew W. Cross,* Lev S. Bishop,† Sarah Sheldon, Paul D. Nation, and Jay M. Gambetta

IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA

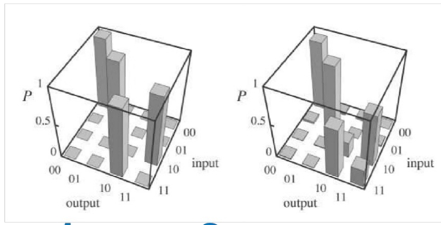
Characterizing quantum supremacy in near-term devices

Sergio Boixo, Sergei V. Isakov, Vadim N. Smelyanskiy, Ryan Babbush, Nan Ding, Zhang Jiang, Michael J. Bremner, John M. Martinis & Hartmut Neven

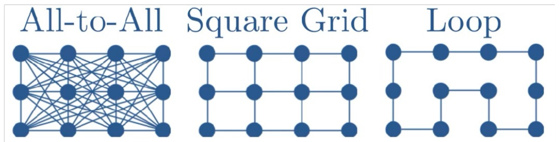
Nature Physics **14**, 595–600 (2018) | Cite this article



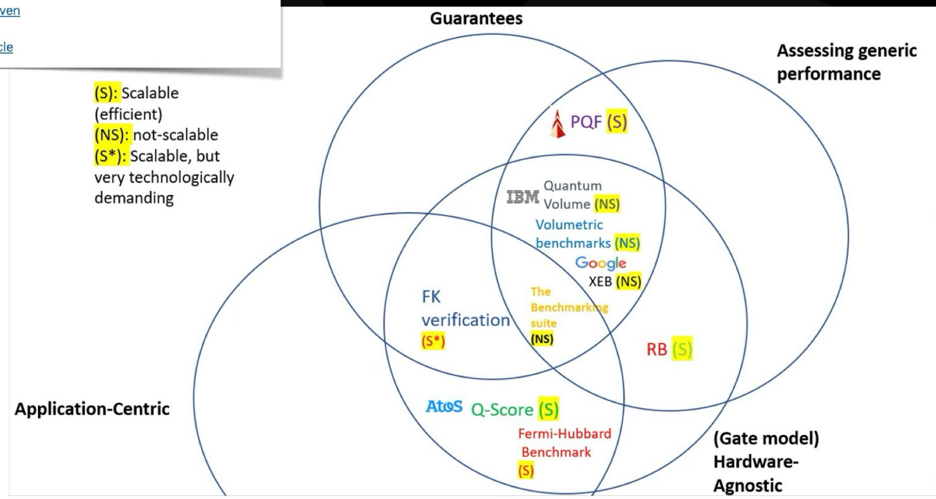
NUMBER OF QUBITS



1- AND 2-QUBIT GATE ERROR



CONNECTIVITY

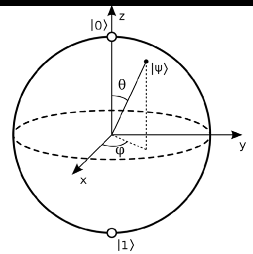


METRICS

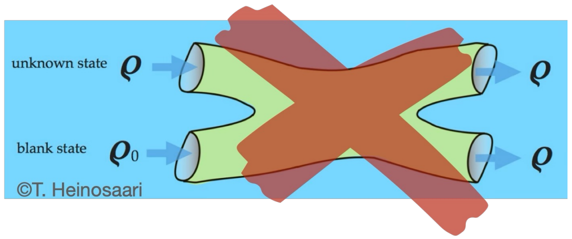
The noise: the main issue of quantum computing

CONTINUOUS ERRORS

Quantum bit: $\alpha|0\rangle + \beta|1\rangle$



NO CLONING



QUANTUM COMPUTING: DREAM OR NIGHTMARE?

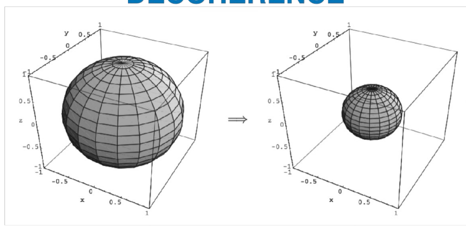
Recent experiments have deepened our insight into the wonderfully counterintuitive quantum theory. But are they really harbingers of quantum computing? We doubt it.

Serge Haroche and Jean-Michel Raimond

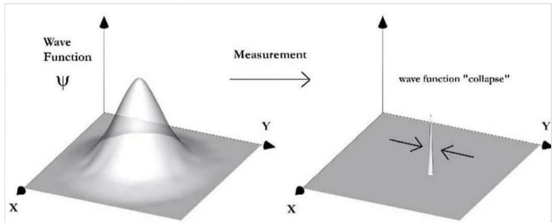
The principles of quantum computing were laid out about 15 years ago by computer scientists applying the superposition principle of quantum mechanics to computer operation. Quantum computing has recently become a hot topic in physics, with the recognition that a two-level system can be presented as a quantum bit, or "qubit," and that an interaction between such systems two interacting qubits: a "control" bit and a "target" bit. The control remains unchanged, but its state determines the evolution of the target: If the control is 0, nothing happens to the target; if it is 1, the target undergoes a well-defined transformation.

Quantum mechanics admits additional options. If the control is in some coherent superposition of 0 and 1, the output of the gate is

DECOHERENCE



MEASUREMENT COLLAPSE

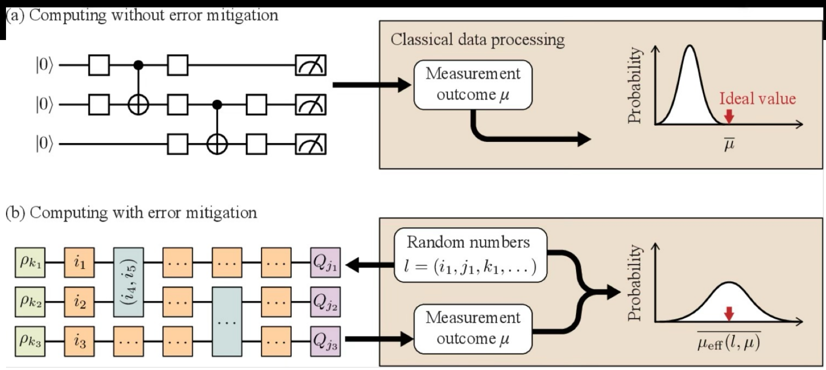


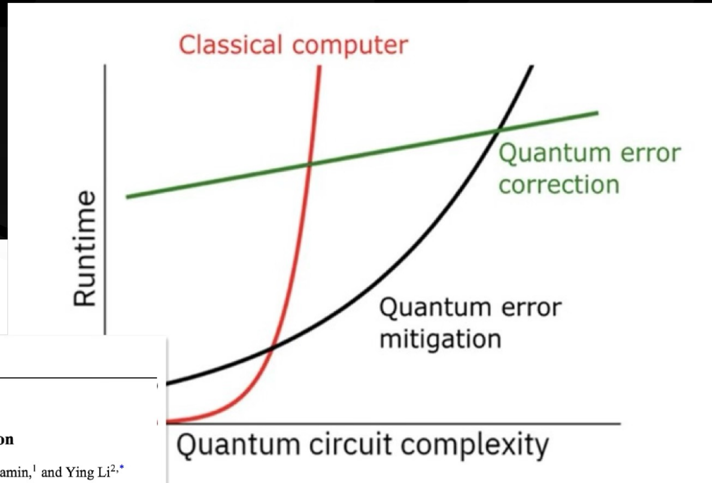
Short to mid term: error mitigation

PHYSICAL REVIEW X **8**, 031027 (2018)

Practical Quantum Error Mitigation for Near-Future Applications

Suguru Endo,[1] Simon C. Benjamin,[1] and Ying Li[2,1,*]
[1]*Department of Materials, University of Oxford, Oxford OX1 3PH, United Kingdom*
[2]*Graduate School of China Academy of Engineering Physics, Beijing 100193, China*

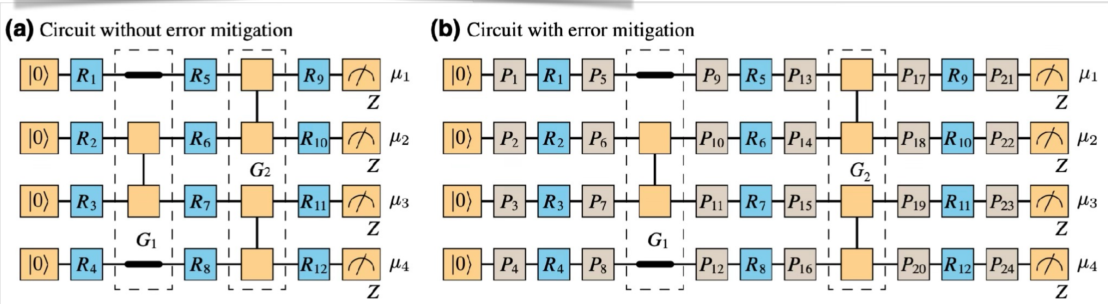




PRX QUANTUM **2**, 040330 (2021)

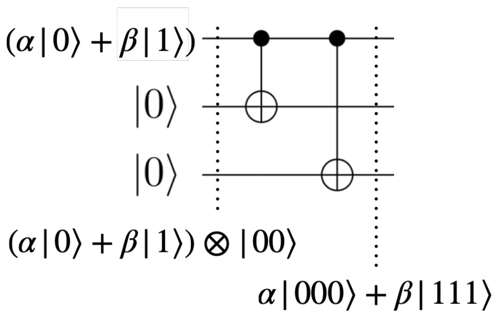
Learning-Based Quantum Error Mitigation

Armands Strikis,[1,†] Dayue Qin,[2,†] Yanzhu Chen,[3,4] Simon C. Benjamin,[1] and Ying Li[2,*]

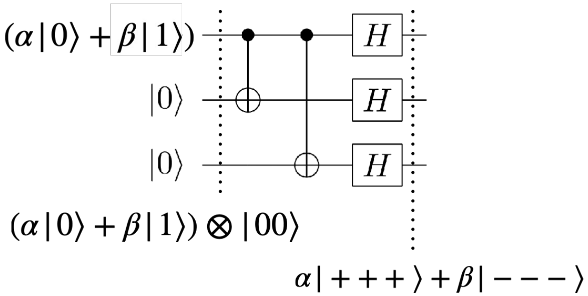


Long term: error correction

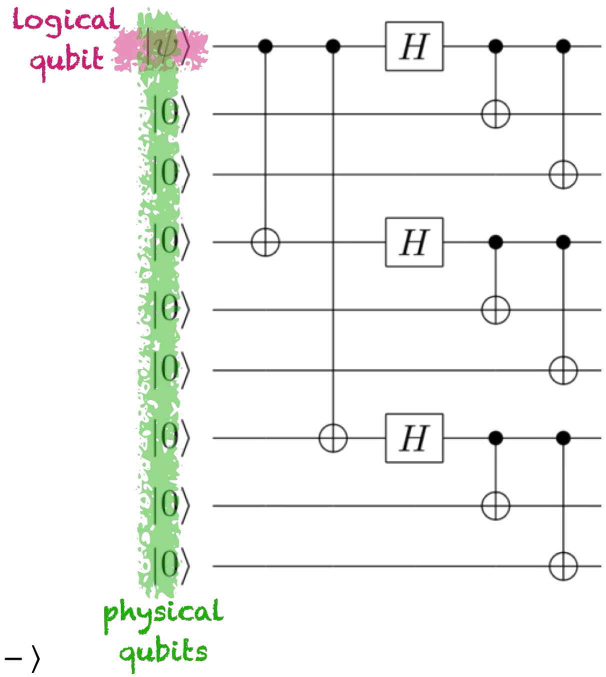
BIT FLIP



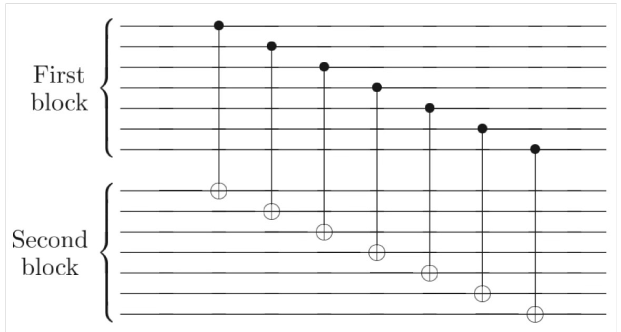
PHASE FLIP



BIT+PHASE: SHOR CODE



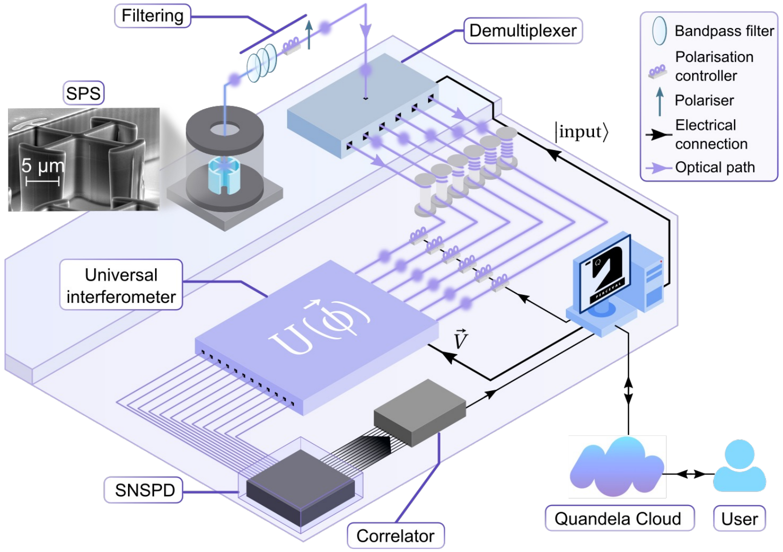
FAULT-TOLERANCE

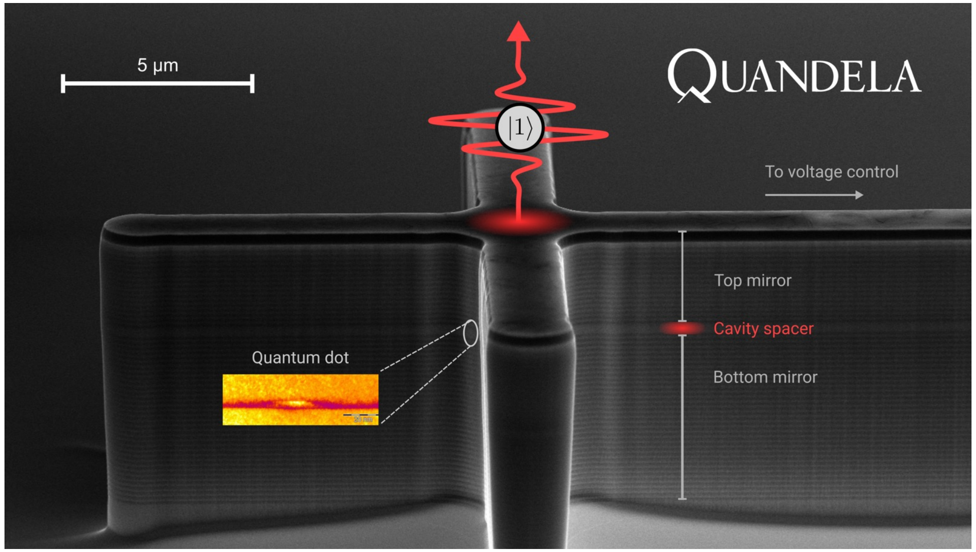


THRESHOLD THEOREM

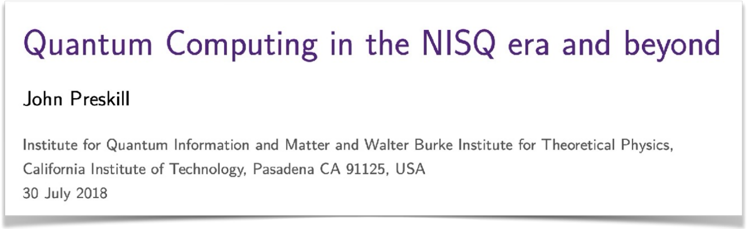
The threshold theorem: Provided the noise in individual quantum gates is below a certain constant threshold and obeys certain physically reasonable assumptions, it is possible to reliably perform an arbitrarily long quantum computation, with only a small overhead in the size of the circuit necessary to ensure reliability.

And what about Quandela?





If you want to go deeper in quantum information

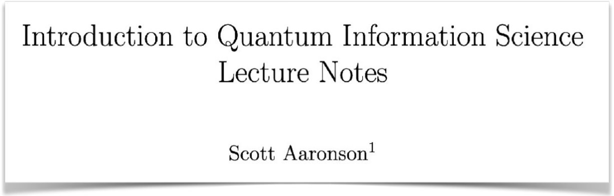


Quantum Computing in the NISQ era and beyond

John Preskill

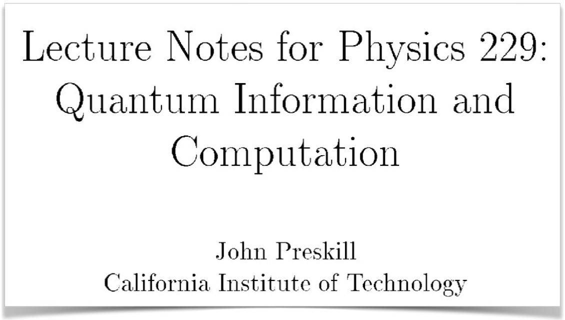
Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA

30 July 2018



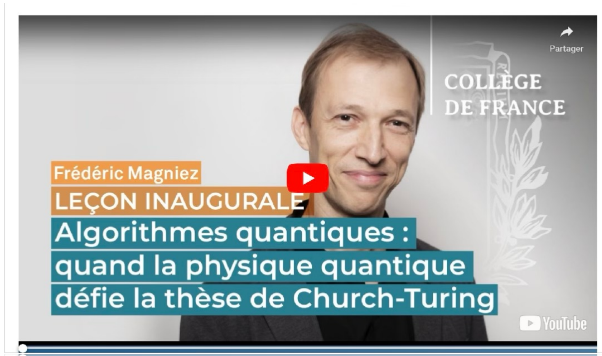
Introduction to Quantum Information Science
Lecture Notes

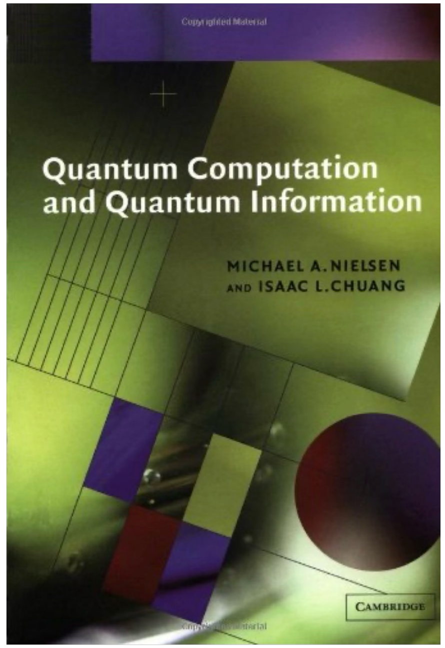
Scott Aaronson[1]



Lecture Notes for Physics 229: Quantum Information and Computation

John Preskill
California Institute of Technology






yarn.co
SEE? THAT WASN'T SO HARD!

QUANDELA

The end

→ www.quandela.com