



Quantum Information

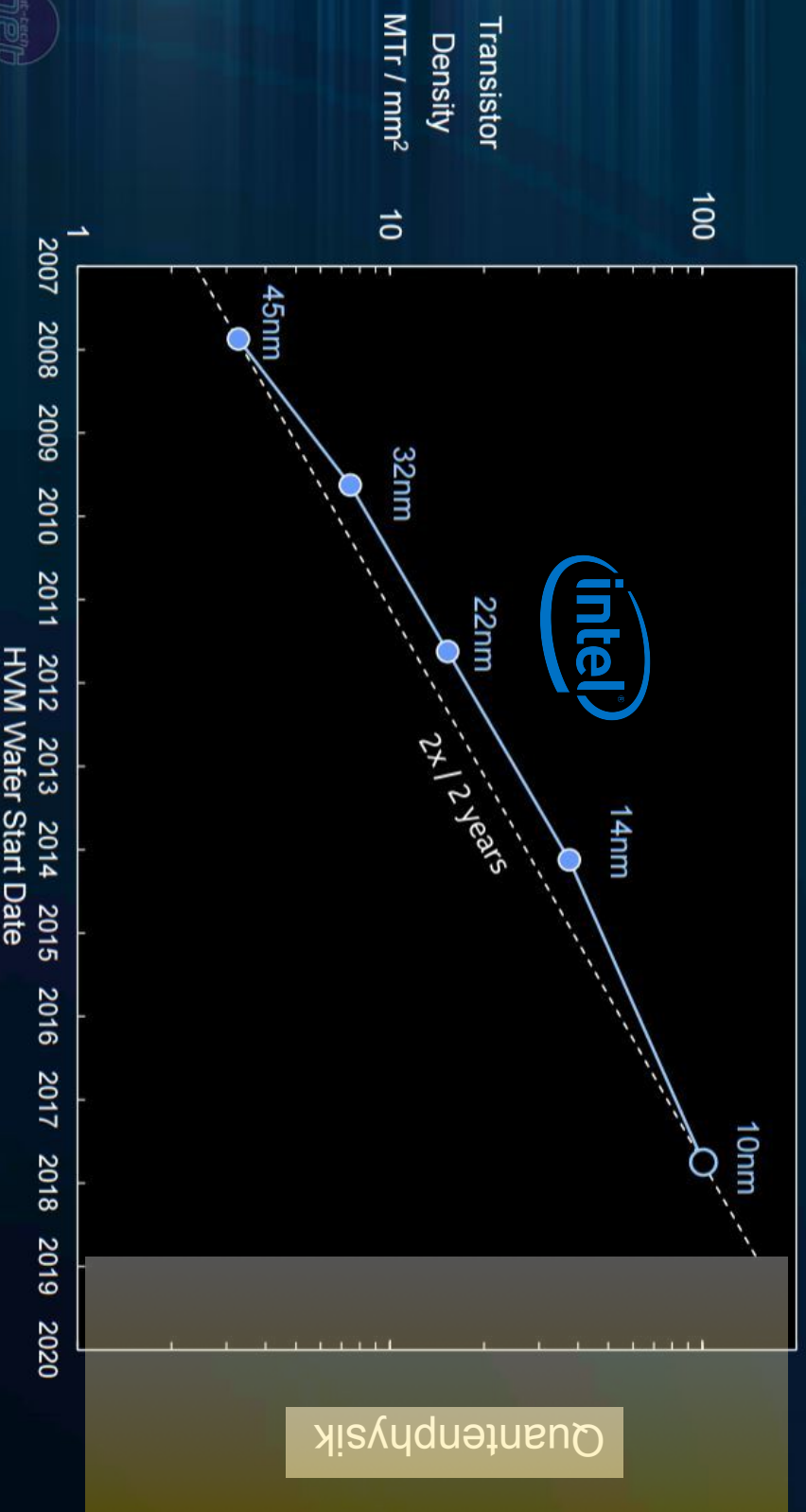
winter term 2022/23

2 SWS

0. Introduction

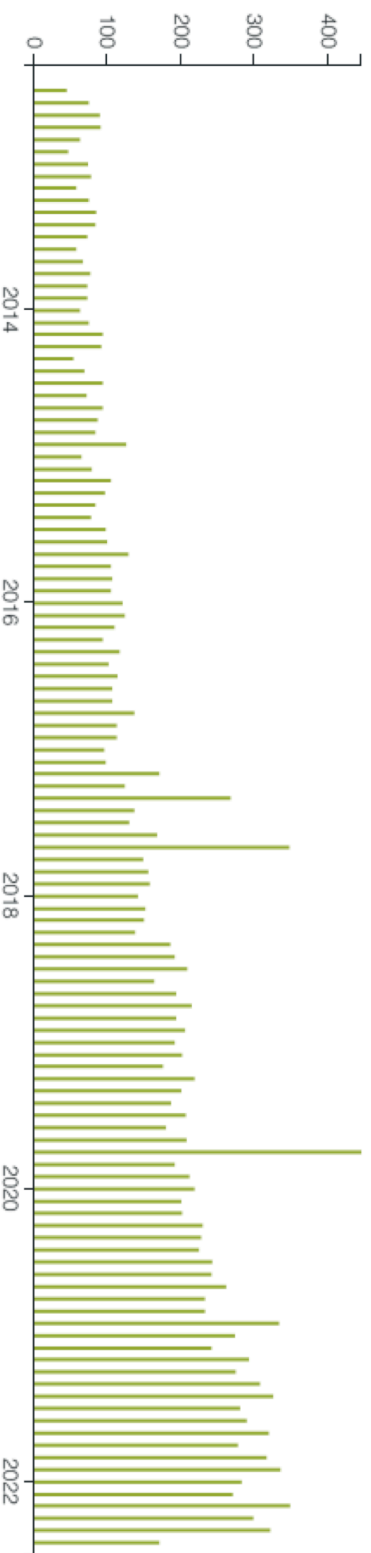
Michael Fleischhauer

LOGIC TRANSISTOR DENSITY



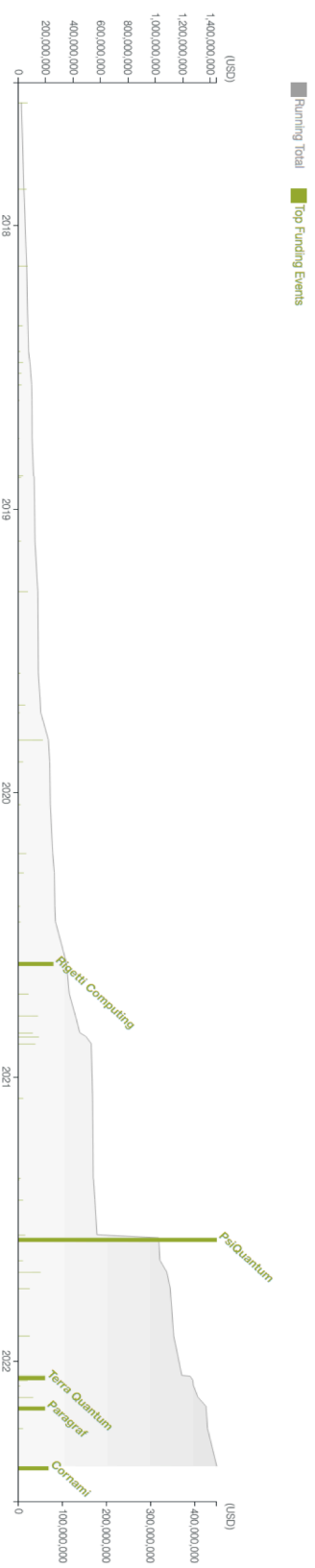
Publications & Venture Capital Investments

Publications over time



Venture Capital

48 funding events from the past 5 years



a bit of history:

- 1980 P. Benioff: first ideas of a quantum Turing Machine
- 1981/82 R. Feynmann: „*Simulating Physics with Computers*“
- 1985 D. Deutsch: formal concept of quantum Turing machines
- 1994 P. Shor: algorithm to factorize integers into primes
- 1996 L. Grover: search algorithm
- 1998 I. Chuang, N. Gershenfeld, M Kubinec: two-qubit quantum computer

...

2010's

commercial interest takes off

McKinsey & Co: „...investment dollars are pouring in, and quantum-computing start-ups are proliferating“.

Dec. 2021

D-Wave One

11.05.2011



Quantenrechner auf dem Prüfstand

17.03.2014 | News

Von: Fabio Bergamin

Eine neuartige Rechenmaschine erregt in der Fachwelt Aufsehen. Handelt es sich dabei um den ersten künstlichen Quantencomputer? Ein Team unter der Leitung von ETH-Professor Matthias Troyer bestätigt nun, dass die Maschine Quanteneffekte nutzt. Schneller als ein herkömmlicher Computer ist sie aber nicht.



Ist dies der erste künstliche Quantencomputer? Im Bild die aktuelle 512-Qubits-Version von D-Wave. (Bild: Courtesy of D-Wave Systems Inc.)

NATURE | NEWS

D-Wave upgrade: How scientists are using the world's most controversial quantum computer

Scepticism surrounds the ultimate potential of D-wave machines, but researchers are already finding uses for them.

Elizabeth Gibney

24 January 2017

nature

International weekly journal of science

31.05.2013

D-WAVE

Blick in die Zukunft

Die Firma D-Wave Systems will den ersten kommerziellen Quantencomputer-„gekauft haben. Grundlagenforschung ist skeptisch. Nun haben externe Experten das System getestet.“
von Robert Gast



Fachbereich  Physik



Article

Quantum supremacy using a programmable superconducting processor

<https://doi.org/10.1038/s41586-019-1666-5>

Received: 22 July 2019

Accepted: 20 September 2019

Published online: 23 October 2019



Frank Arute¹, Kunal Arya¹, Ryan Babbush¹, Dave Bacon¹, Joseph C. Bardin^{1,2}, Rami Berends¹, Rupak Biswas³, Sergio Boixo¹, Fernando G. S. L. Brandao^{4,5}, David A. Buell¹, Brian Burkett¹, Yu Chen¹, Zijun Chen¹, Ben Chiaro⁵, Roberto Collins¹, William Courtney¹, Andrew Dunsworth¹, Edward Farhi¹, Brooks Foxen^{1,2}, Austin Fowler¹, Craig Gidney¹, Marissa Gustafina¹, Rob Graff¹, Keith Guerin¹, Steve Habegger¹, Matthew P. Harrigan¹, Michael J. Hartmann^{1,6}, Alan Ho¹, Markus Hoffmann¹, Trent Huang¹, Travis S. Humble¹, Sergei V. Isakov¹, Evan Jeffrey¹, Zhang Jiang¹, Dvir Kafri¹, Kostyantyn Kechedzhii¹, Julian Kelly¹, Paul V. Klimov¹, Sergey Knysh¹, Alexander Korotkov^{1,6}, Fedor Kostin¹, David Landhuis¹, Mike Lindmark¹, Erik Lucero¹, Dmitry Lyakh¹, Salvatore Mandrà^{1,10}, Jarrod R. McClean¹, Matthew McEwen¹, Anthony Megrant¹, Xiao Mi¹, Kristel Michielsen^{1,11}, Masoud Mohseni¹, Josh Mutus¹, Ofer Naaman¹, Matthew Neeley¹, Charles Neill¹, Murphy Yuezhen Niu¹, Eric Ostby¹, Andre Petukhov¹, John C. Platt¹, Chris Quintana¹, Eleanor G. Rieffel¹, Pedram Roushan¹, Nicholas C. Rubin¹, Daniel Sank¹, Kevin J. Satzinger¹, Vadim Smelyanskiy¹, Kevin J. Sung^{1,12}, Matthew D. Trevithick¹, Amit Vainsencher¹, Benjamin Villalonga¹, Theodore White¹, Z. Jamie Yao¹, Ping Yeh¹, Adam Zalcman¹, Hartmut Neven¹ & John M. Martinis^{1,13}



Jetzt auch offiziell: Googles Quantencomputer beweist "Quantum Supremacy"

23.10.2019 13:04 Uhr

Ein Google-Quantencomputer hat – ab heute auch offiziell – mit 53 Qubits eine Berechnung ausgeführt, für die der stärkste Supercomputer 10.000 Jahre bräuhete.

Quantum Supremacy – IBM widerspricht Googles Beweis

Beweis

24.10.2019 12:15 Uhr

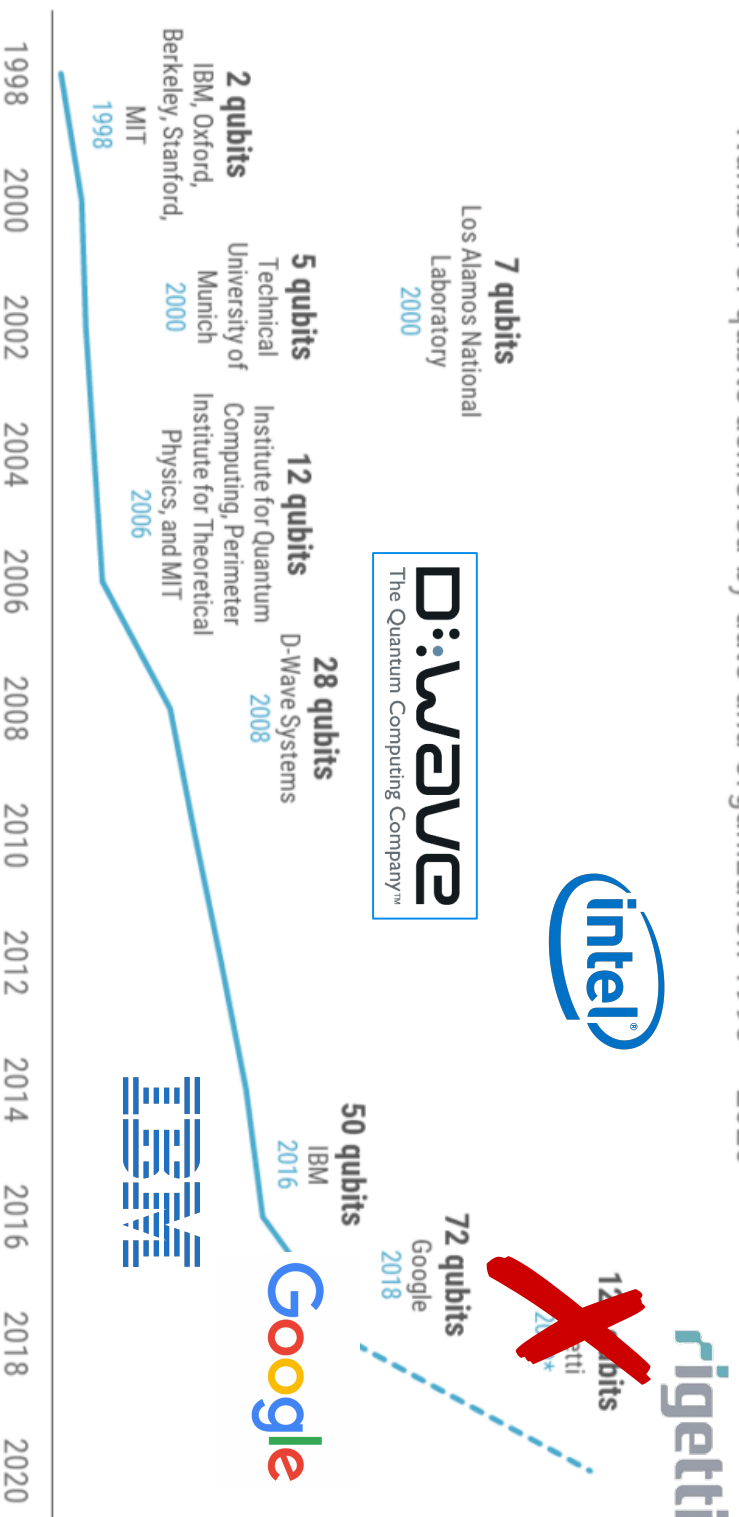
War der Beweis für die Quantencomputer-Überlegenheit durch Google ein Schnellschuss? IBM sagt, ein Supercomputer könne das Problem in 2,5 Tagen lösen.





Quantum computers are getting more powerful

Number of qubits achieved by date and organization 1998 – 2020*



Source: MIT, Qubit Counter. *Rigetti quantum computer expected by late 2019.

CBINSIGHTS

COMPUTING

Google's Quantum Computer Achieves Chemistry Milestone

A downsized version of the company's Sycamore chip performed a record-breaking simulation of a chemical reaction

By Neil Savage on September 4, 2020

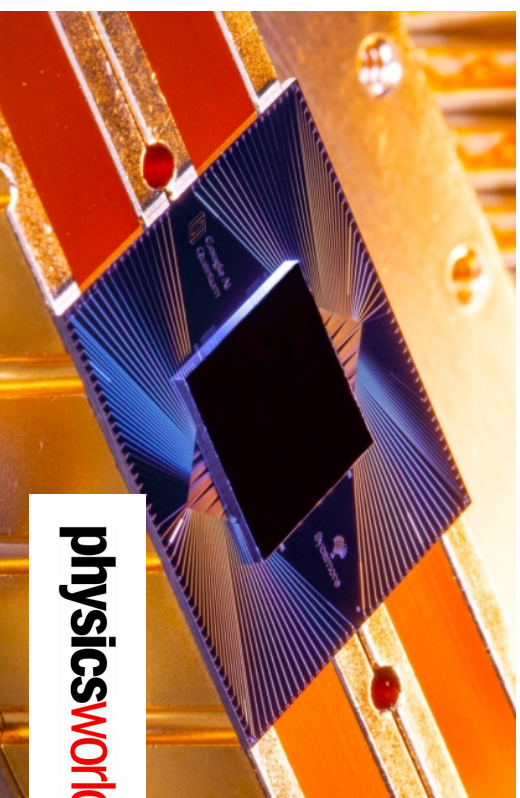
SCIENTIFIC
AMERICAN™

Fachbereich
Physik

QUANTUM COMPUTING RESEARCH UPDATE

Molecule's electronic structure is simulated on a quantum computer

05 Sep 2020



Chemistry set: Google's Sycamore processor. (Courtesy: Erik Lucero/Google)

physics
world

TECHNISCHE UNIVERSITÄT
KAISERSLAUTERN

NEWS | 17 November 2020

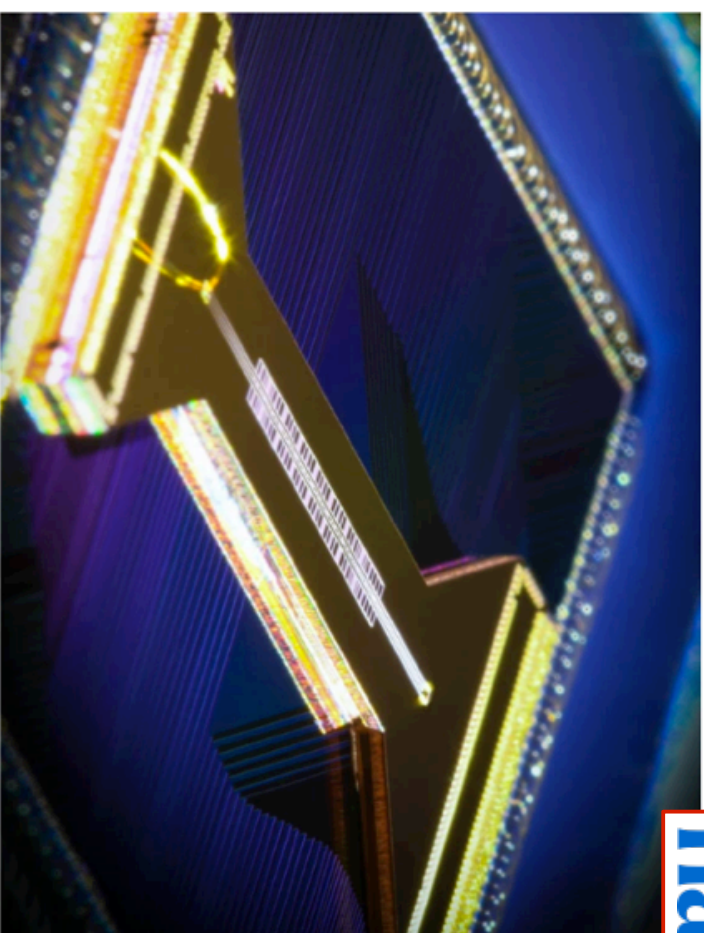
Quantum computer race intensifies as alternative technology gains steam

Trapped ion systems are gaining momentum in the quest to make a commercial quantum computer.

[Elizabeth Gibney](#)



nature



An ion trap from Honeywell's quantum computer. Credit: Honeywell Quantum Solutions

NEWS | 19 November 2021

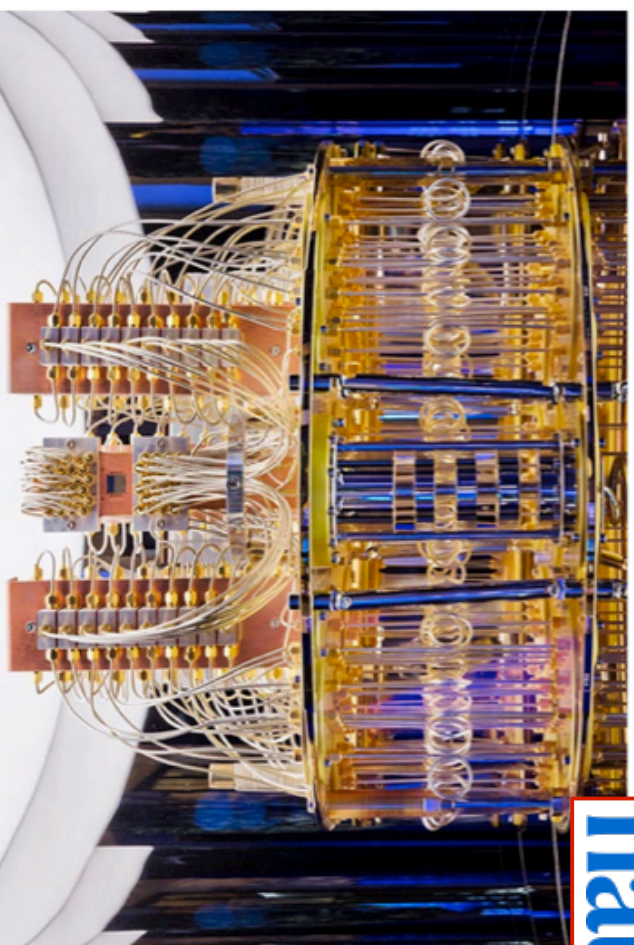
First quantum computer to pack 100 qubits enters crowded race

But IBM's latest quantum chip and its competitors face a long path towards making the machines useful.

[Philip Ball](#)



nature



The innards of an IBM quantum computer show the tangle of cables used to control and read out its qubits. Credit: IBM

but:



$H^{\otimes n}$

Quantum Bullshit Detector

@BullshitQuantum

Often correct albeit not infallible
-Scott Aaronson

📅 Seit März 2019 bei Twitter

394 Folge ich 13.012 Follower

Folgen

Why Quantum-Computing ?



Taxi
Company



Anna



Betty



Chris



Taxi 0



Taxi 1



Taxi 0



Taxi 1

additional information



optimization goal





Taxi 0



Anna



Betty



Taxi 1



Chris

0	0	1
---	---	---

A B C

A B C

0	0	1
0	1	0
1	0	0
0	1	1
1	0	1
1	1	0
1	1	1
0	0	0

$$8 = 2 \times 2 \times 2 = 2^3$$

A	B	C	rating
0	0	1	-1
0	1	0	-1
1	0	0	+1
0	1	1	+1
1	0	1	-1
1	1	0	-1
1	1	1	-1
0	0	0	-1

Betty



Chris



maximum number of friends
in one car

Betty



Anna



minimum number of enemies
in one car

Anna



Chris

rating of configuration =

friendly pairs in a car

- # enemy pairs in a car

A B C rating

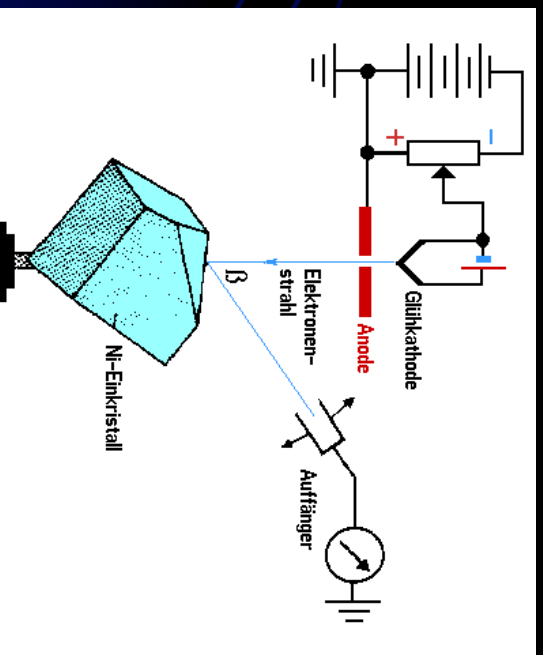
0	0	1	-1
0	1	0	-1
1	0	0	+1
0	1	1	+1
1	0	1	-1
1	1	0	-1
1	1	1	-1
0	0	0	-1

... now quantum physics
enters the stage

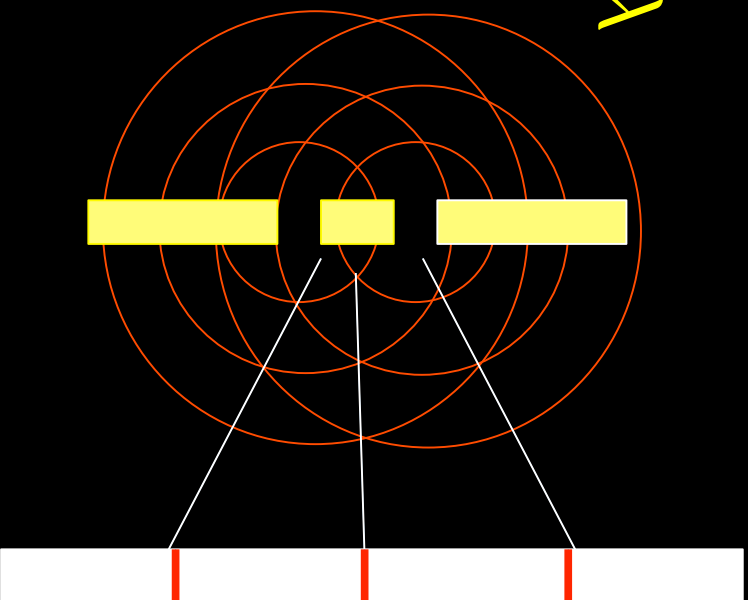
- **Davission & Germer 1925**

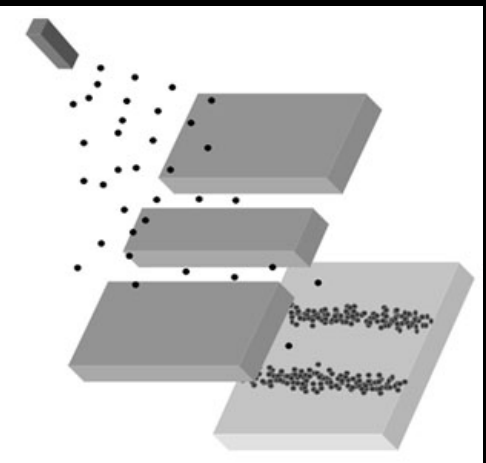


refraction of electrons
at a cristal



γ

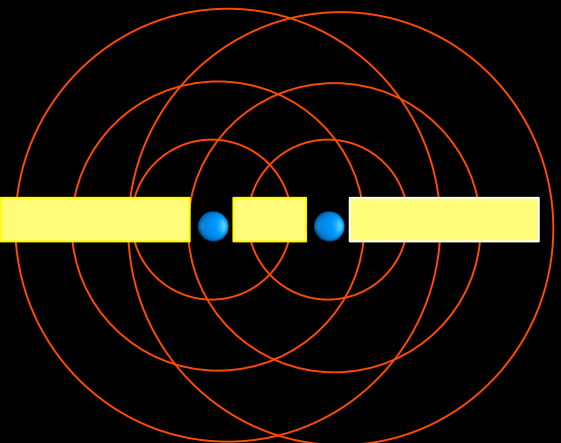


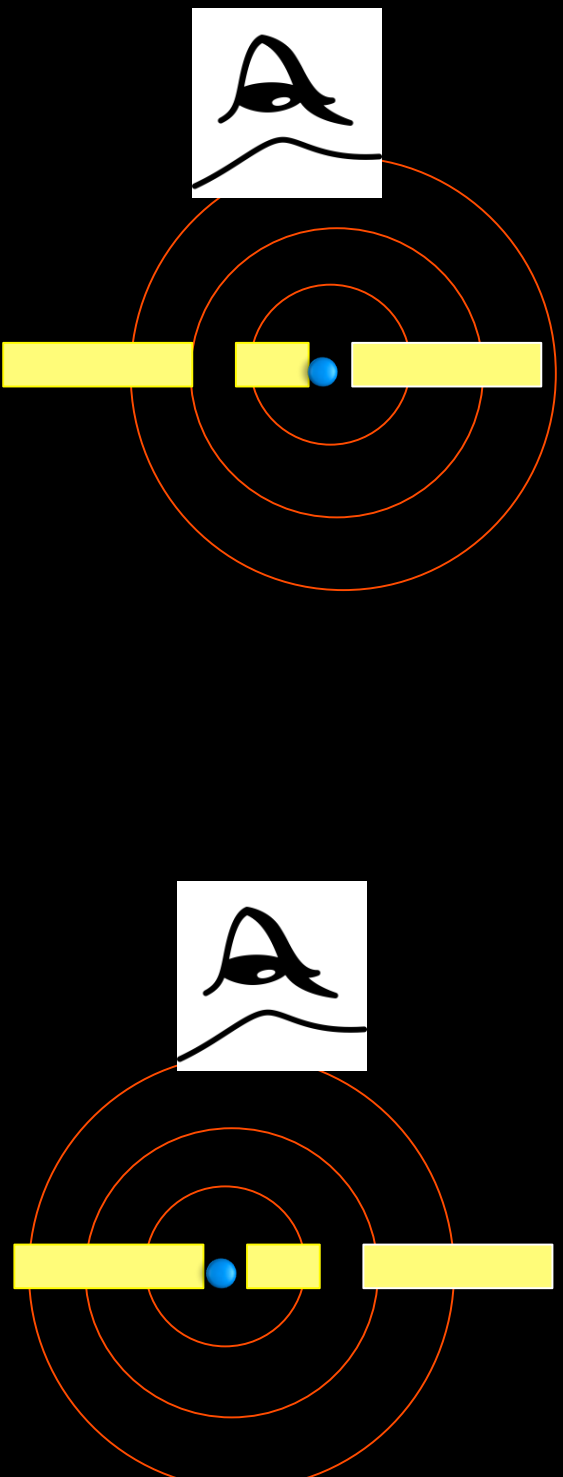


Every particle traverses both slits
at the same time!

Superposition

$$|\phi\rangle \sim |0\rangle \pm |1\rangle$$





but: if a quantum particle is observed
it is either up or down

$$|\phi\rangle \sim |0\rangle \pm |1\rangle$$

$$|\phi\rangle \sim |1\rangle$$

$$|\phi\rangle \sim |0\rangle$$

50%

50%

Bit

0

1

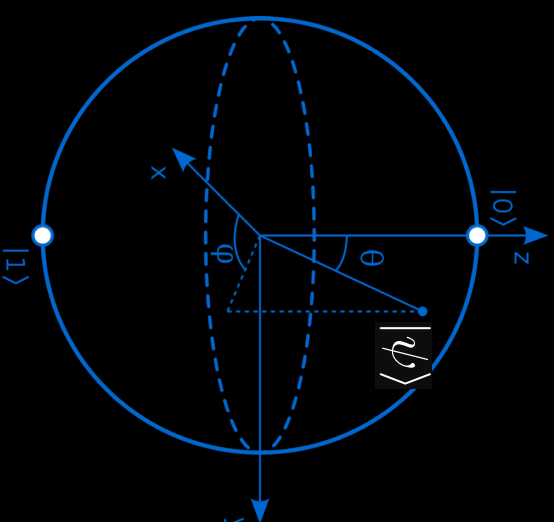
Qubit

$|0\rangle$

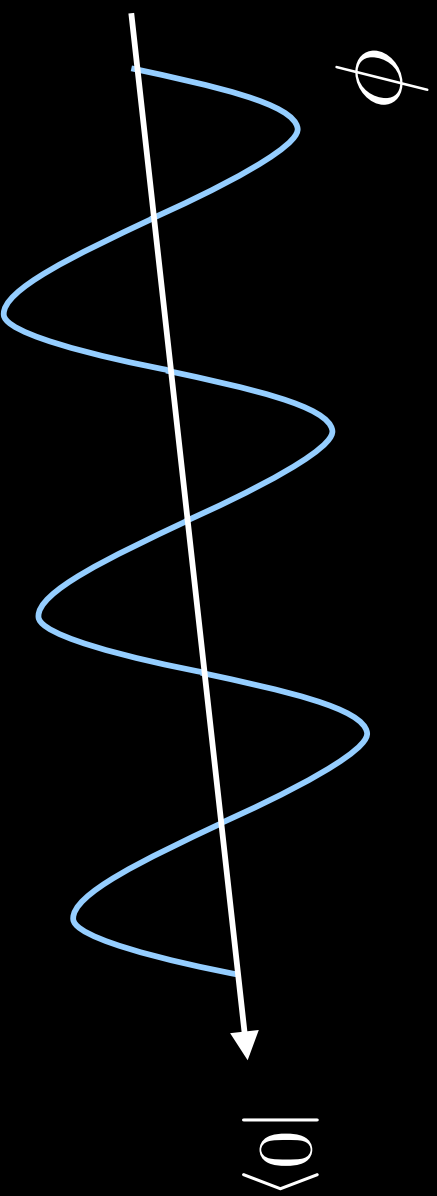
$|1\rangle$

$$|\psi\rangle = \cos \theta |0\rangle + \sin \theta e^{i\phi} |1\rangle$$

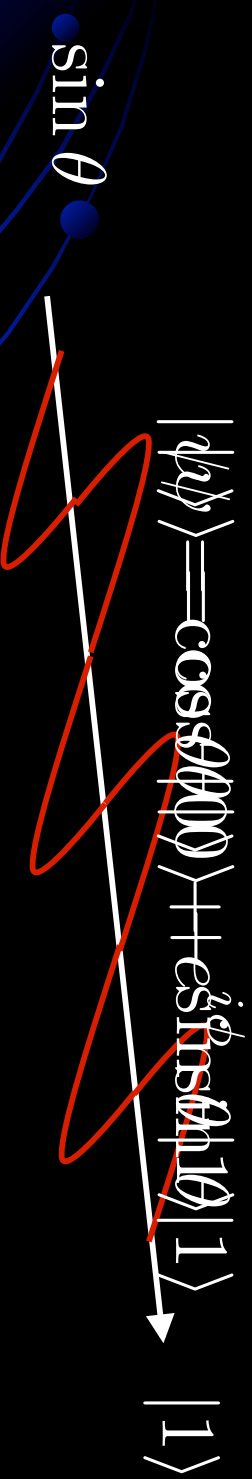
Superposition !



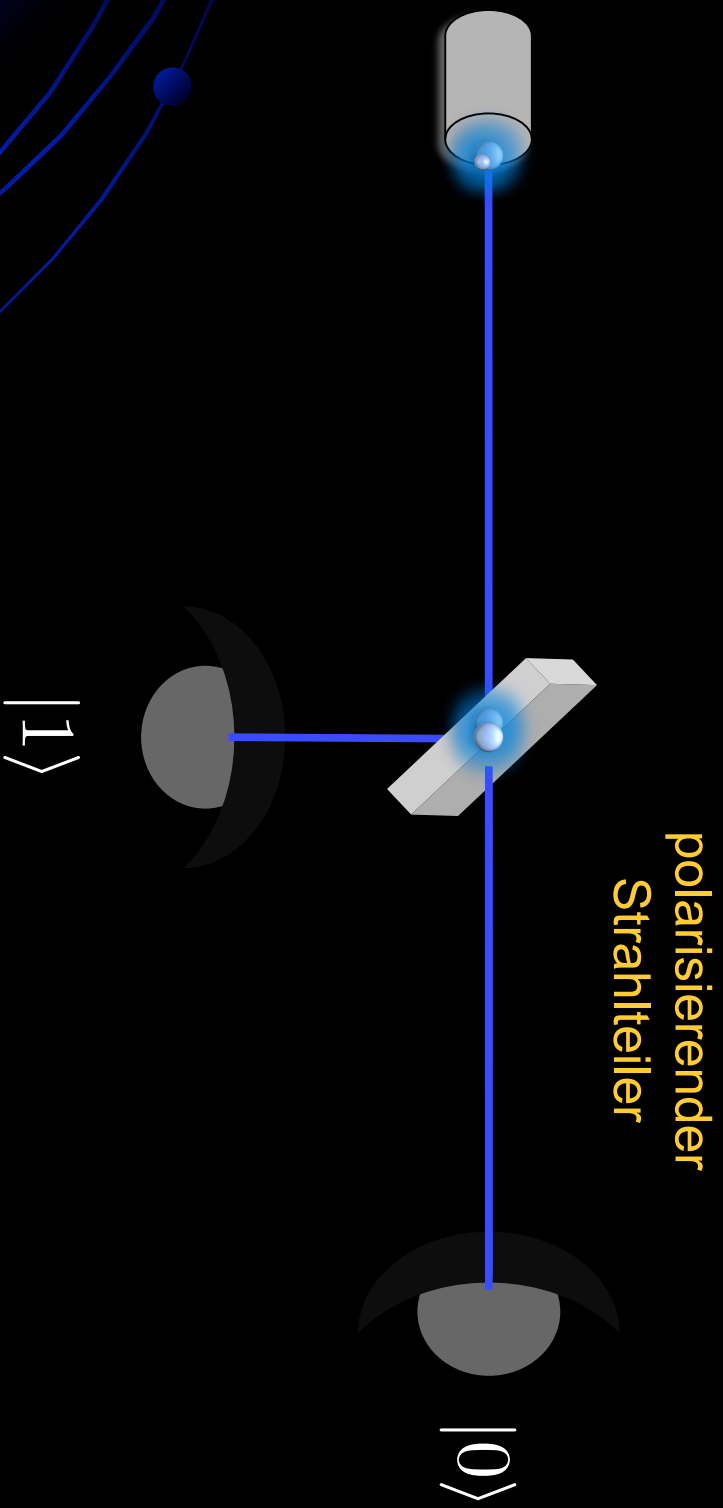
Qubit: Photon



+



Qubit: Photon



Superposition of many-particle states: entanglement

$$|\psi_A\rangle$$

$$(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$$

qubits

not correlated

$$|\psi_B\rangle$$

$$(|0\rangle - |1\rangle)(|0\rangle - |1\rangle)$$

Superposition:

$$|\psi_A\rangle - |\psi_B\rangle$$

$$|1\rangle|0\rangle + |0\rangle|1\rangle$$

measurement of qubit 1

fixes value of qubit 2

Bertlmann's socks



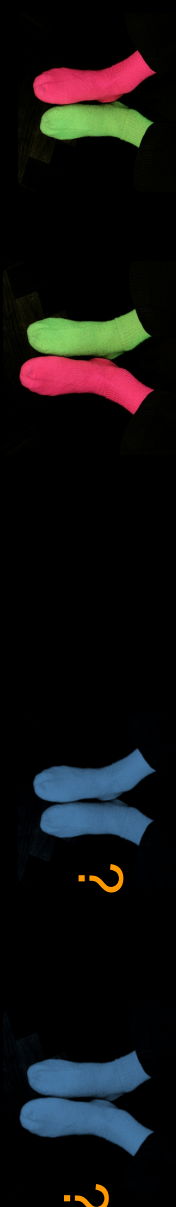
Reinhold Bertlmann



→ What is different here from the classical world ?

Quantum correlations are stronger than classical ones

$$|1\rangle|0\rangle + |0\rangle|1\rangle = |+\rangle|-\rangle + |-\rangle|+\rangle$$



$$|+\rangle = |0\rangle + |1\rangle \quad |-\rangle = |0\rangle - |1\rangle$$

For entangled states
quantum correlations can violate classical bounds

Bell inequalities

John Bell 1928–1990





NOBELPRISET I FYSIK 2022 THE NOBEL PRIZE IN PHYSICS 2022

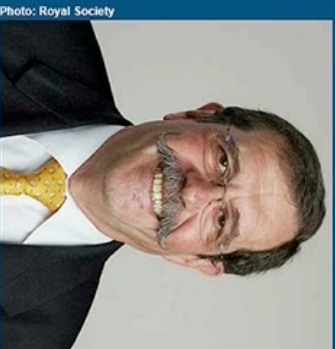


Photo: Royal Society

Alain Aspect

Université Paris-Saclay &
École Polytechnique, France



Photo: Peter Lyons

John F. Clauser

J.F. Clauser & Assoc.,
USA

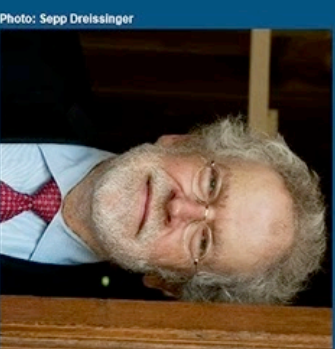


Photo: Sepp Dreissinger

Anton Zeilinger

University of Vienna,
Austria

*"för experiment med sammanflätade fotoner som påvisat brott mot Bell-olikheter och
banat väg för kvantinformationsvetenskap"*

*"for experiments with entangled photons, establishing the violation of Bell inequalities and
pioneering quantum information science"*

#nobelpize



$$(|0\rangle + |1\rangle)(|0\rangle + |1\rangle) = |0\rangle|0\rangle + |0\rangle|1\rangle + |1\rangle|0\rangle + |1\rangle|1\rangle$$

$$|\phi\rangle \sim |0\rangle \pm |1\rangle$$



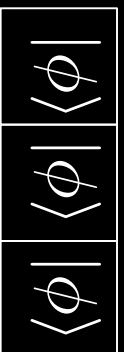
Anna



Betty



Chris



all 2^3 combinations



Taxi 0



Taxi 1

	A	B	C
0	0	0	1
0	1	1	0
1	0	0	0
1	1	1	1
0	1	0	1
1	1	1	0
1	1	1	1
0	0	0	0

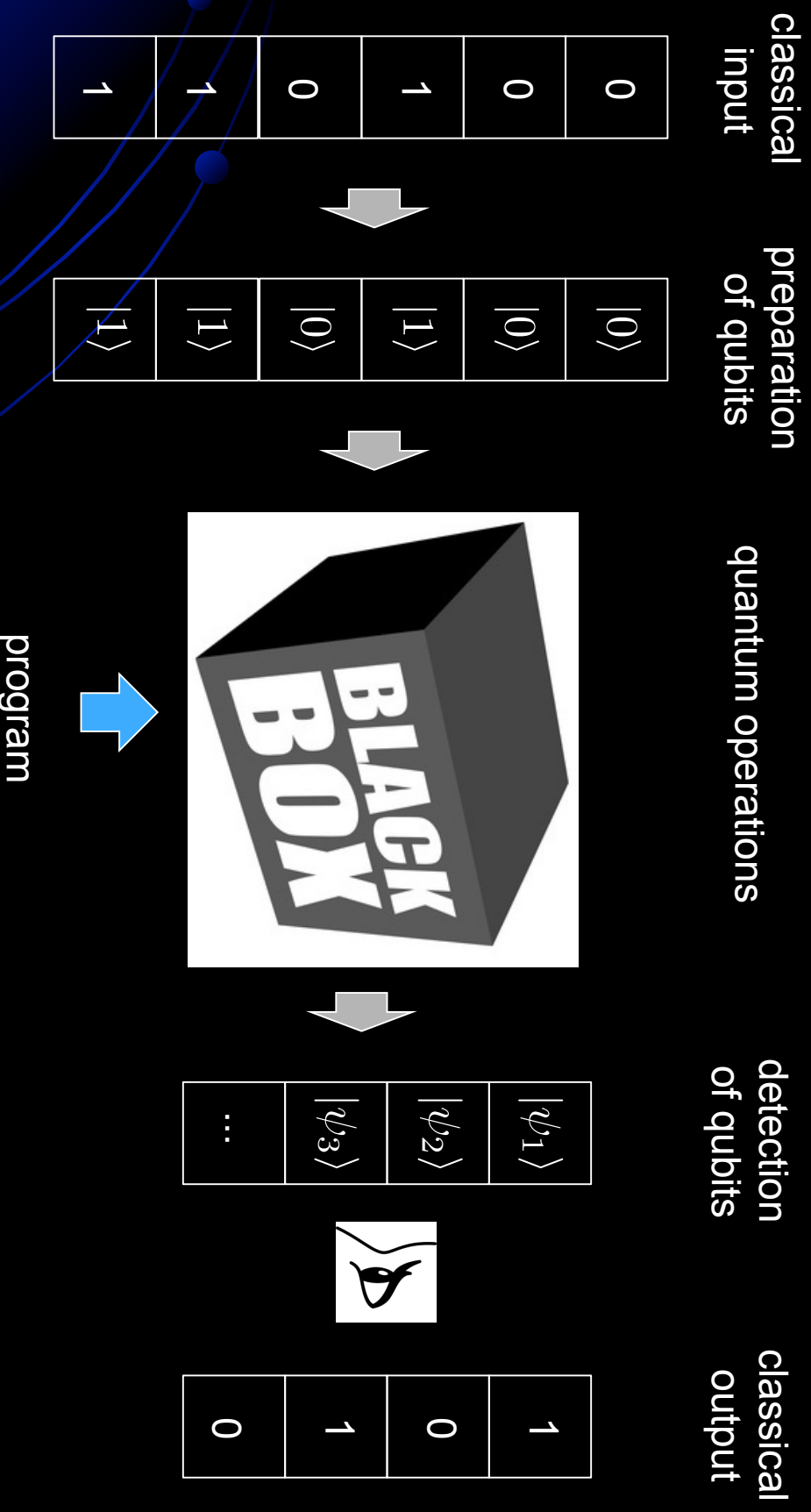


Wertung

-1
-1
+1
+1
-1
-1
-1
-1



General principle of a quantum computer



Quantum computer can do more
than classical ones
but not everything!

Deutsch-Josza algorithm



valid

invalid



Deutsch-Josza algorithm

$$f : \{0,1\} \rightarrow \{0,1\}$$

front back head tail

$$\begin{array}{ll} f(0) = 0 & f(0) = 1 \\ f(1) = 0 & f(1) = 1 \end{array}$$

constant (invalid)

$$\begin{array}{ll} f(0) = 0 & f(0) = 1 \\ f(1) = 1 & f(1) = 0 \end{array}$$

balanced (valid)

To find out if f constant or balanced
two inquiries needed!

Deutsch-Josza algorithm

$$|0\rangle|1\rangle \longrightarrow \left(|0\rangle + |1\rangle\right)\left(|0\rangle - |1\rangle\right)$$

f encoded in unitary transfo

$$U_f : |x\rangle|y\rangle \longrightarrow |x\rangle|y \oplus f(x)\rangle$$

$$U_f|x\rangle(|0\rangle + |1\rangle) = \begin{cases} |x\rangle(|0\rangle + |1\rangle) & \text{constant} \\ -|x\rangle(|0\rangle - |1\rangle) & \text{balanced} \end{cases}$$

A single inquiry sufficient!

Shor's factorization

$$3 \times 7 = ?$$

Shor's factorization

$$3 \times 7 = 21$$

Shor's factorization

$$3 \times 7 = 21$$

$$17 \times 112 = 1904$$

How about the inverse problem ?

$$33 = 3^2 \times 11?$$

$$29083 = 127 \times 229$$

Shor's factorization

$$3 \times 7 = 21$$

$$17 \times 112 = 1904$$

How about the inverse problem ?

$$33 = 3 \times 11$$

simple

$$29083 = 127 \times 229$$

hard

NP

hard problem

Shor's factorization

$$N = p \times q$$

best known classical algorithm

$$\exp \left\{ \mathcal{O}(\log N)^{1/3} (\log \log N)^{2/3} \right\}$$

Shor's algorithm

$$\mathcal{O}((\log N)^3) \quad \text{exponential speedup!}$$

example: (2010) factorization 768-bit integer:

hundreds of computer in 2 years; 10^{20} operations

2000-bit Zahl factorizable in 3×10^{11} operations

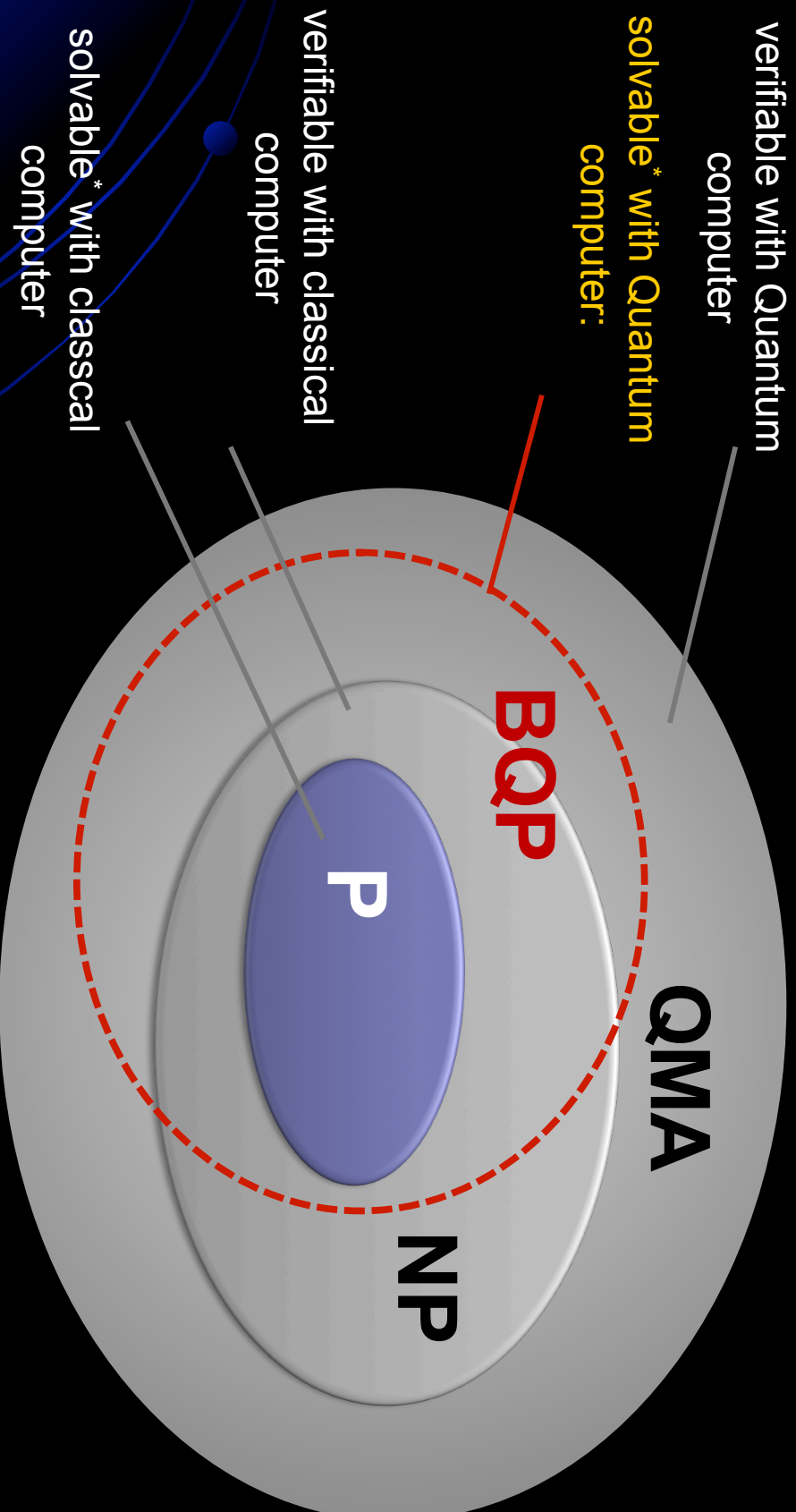
Grover's search algorithm



classical: $\sim N/2 \sim \exp(\log(N))$ inquiries needed

Grover: $\sim \sqrt{N} \sim \exp(\frac{1}{2} \log(N))$ inquiries needed

Mathematical problems:



The challenge: Error correction

The challenge: Error correction

entanglement is fragile

$$|0\rangle|0\rangle|0\rangle|0\rangle + |1\rangle|1\rangle|1\rangle|1\rangle$$

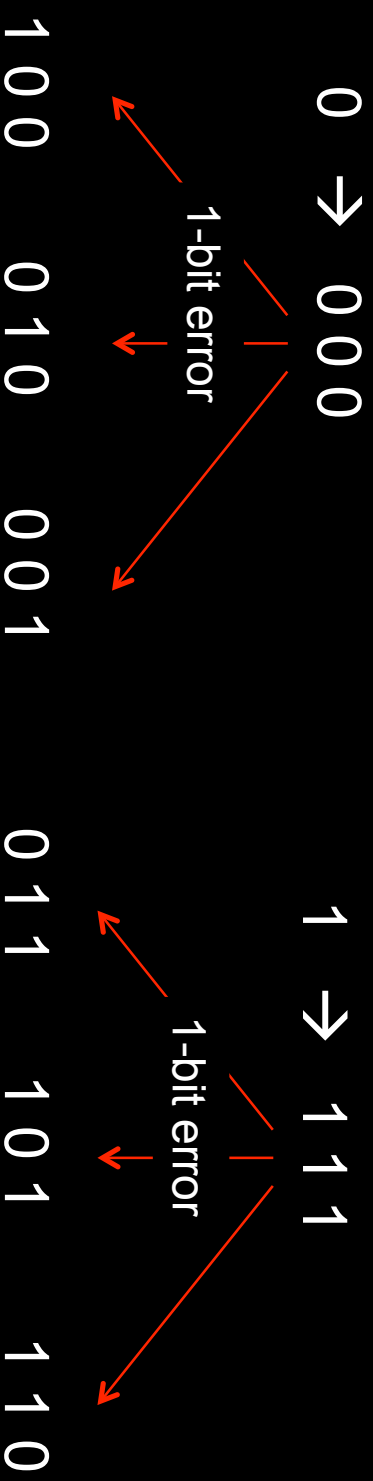
$$|0\rangle|0\rangle|0\rangle|0\rangle$$

$$|1\rangle|1\rangle|1\rangle|1\rangle$$

Measurement of only one particle destroys entanglement!

Error correction

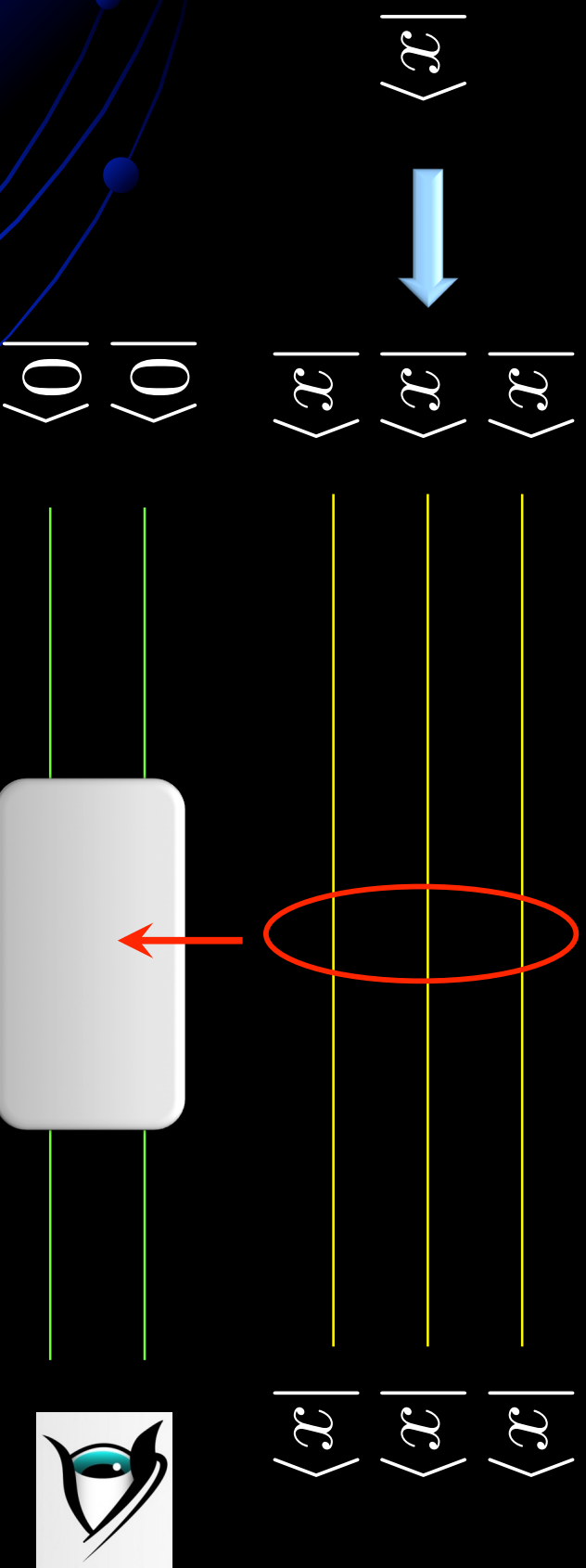
- redundancy makes less susceptible → code



- Error detection: partial checksum ...
- Error correction

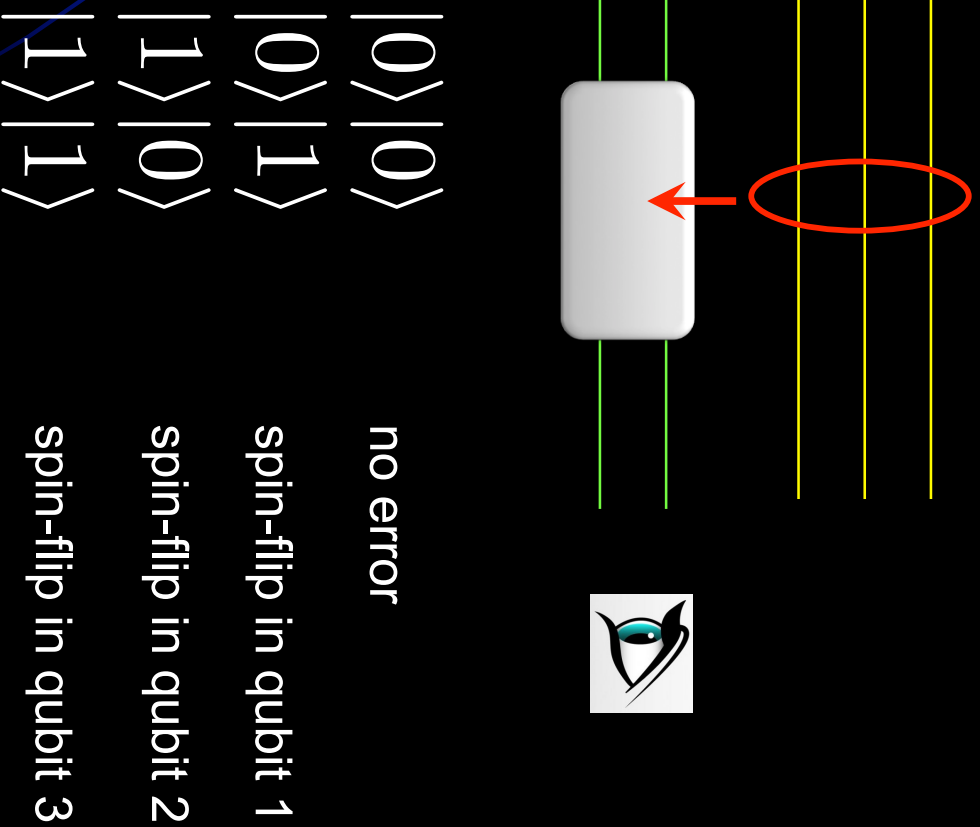
Quantum error correction

- Measurements on qubits destroys entanglement !!



- Interaction with ancilla qubits
- Measurement of ancilla qubits

Quantum error correction



Quantum error correction

- 3 different elementary qubit errors

$$\begin{array}{lll} |1\rangle \leftrightarrow |0\rangle & |0\rangle \leftrightarrow -|0\rangle & |1\rangle \leftrightarrow -|0\rangle \\ & |1\rangle \leftrightarrow -|1\rangle & \end{array}$$

- coding, error-detection and correction introduce new errors

→ fault-tolerant Quantum computing requires enormous overhead

Example: **surface code**

1-qubit error $p < 0,1\%$ → **10.000 – 100.000 physical qubits**
per logic qubit

..... So, is all only a hype after all ?

Noisy Intermediate-Scale Quantum simulations



John Preskill, CalTech

Quantum Computer with 50 – 100 logic qubits
w/o error correction in near future

This will be sufficient for some applications

Potential use cases outside science:

- **Optimization**
 - Automotive: Optimizing autonomous fleets
 - Energy: Utilization predictions; grid optimization;
 - Weather forecast
 - Finance: automated trading; risk analysis; portfolio optimization
 - fraud detection
 - Logistics: Route & traffic optimization; supply-chain optimization
- **Material research**
 - Chemical industry: catalysis
 - Drug research
- **Cryptography & data security**

Data clustering

data-set $\mathbf{x}_j$ in high-dimensional space

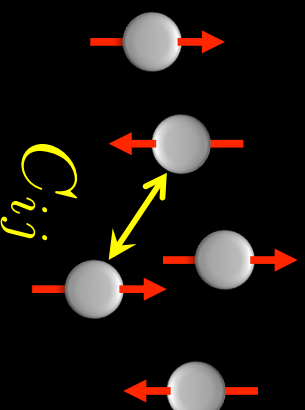
$\mathbf{x}_j = (\text{eye color, width of nose,}) \leftrightarrow \text{label } s_j = \pm 1$

C_{ij} distance (dissimilarity) of $\mathbf{x}_i$ and $\mathbf{x}_j$

data clustering = minimization of cost function

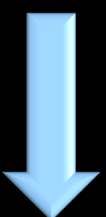
$$H = \sum_{ij} C_{ij} s_i s_j$$

- energetically lowest state of a system of interacting magnets

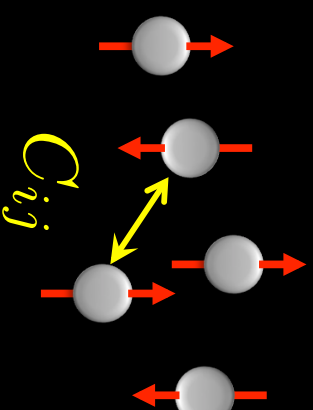
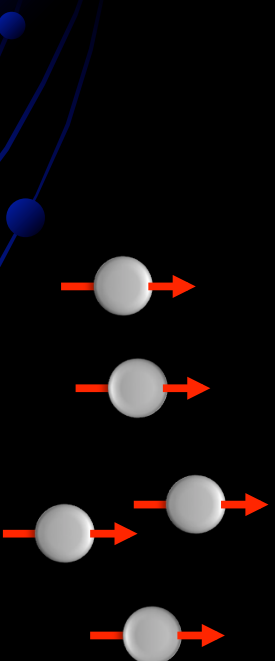


Quantum-Annealer

$$H = - \sum_{ij} s_i s_j$$



$$H = \sum_{ij} G_{ij} s_i s_j$$



Quantum Approximate Optimization

General optimization problem NP hard!

Probably also a quantum computer will not solve this !

E. Farhi, J. Goldstone, S. Gutmann (2014):
efficient *Approximation* using Quantum algorithm

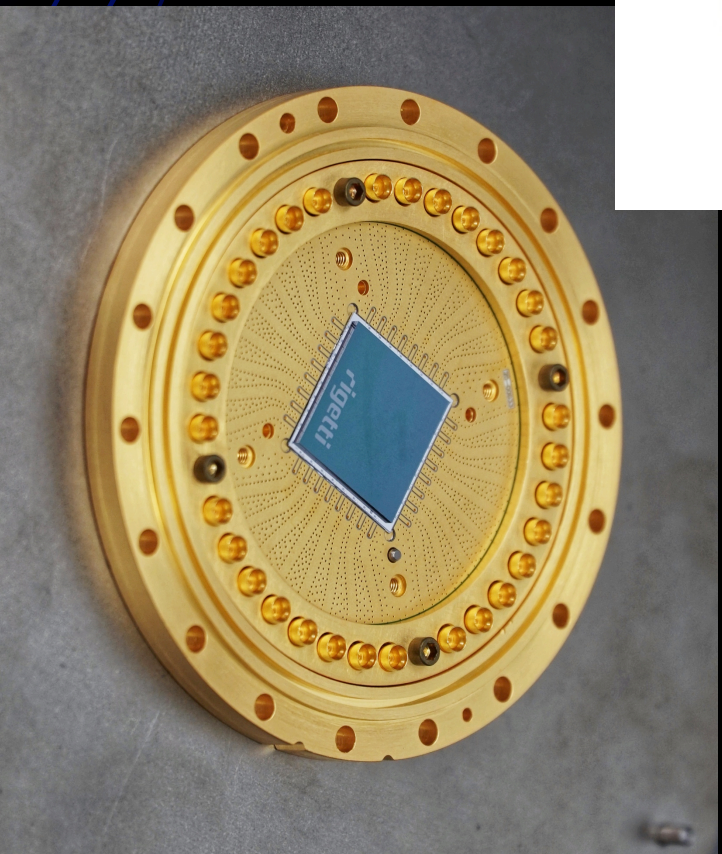
Example: QAO on 19 qubit QComputer

arXiv: 1712.05771

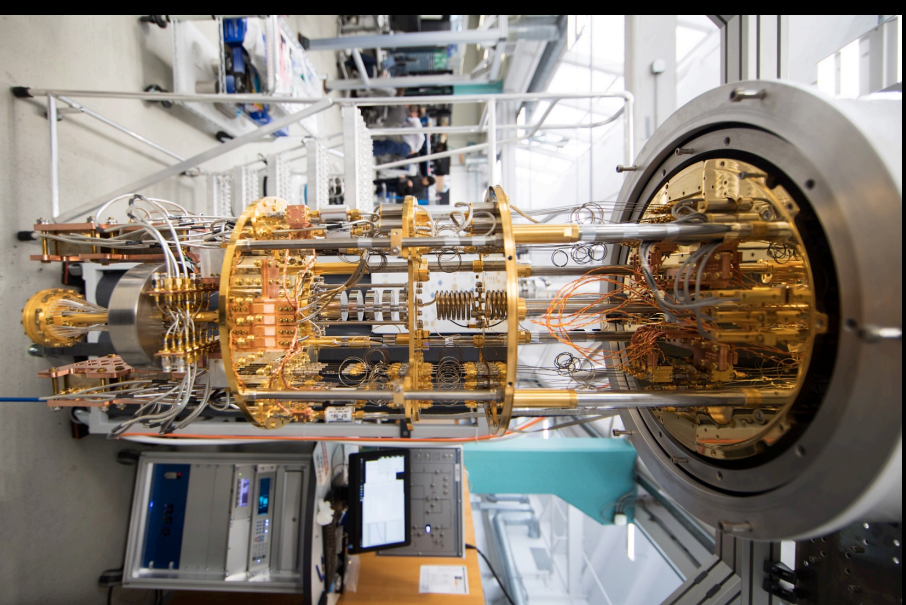
Unsupervised Machine Learning on a Hybrid Quantum Computer

J. S. Otterbach, R. Manenti, N. Aldoust, A. Bestwick, M. Block, B. Bloom, S. Caldwell, N. Didier, E. Schuyler Fried, S. Hong, P. Karalekas, C. B. Osborn, A. Papageorge, E. C. Peterson, G. Prawiroatmodjo, N. Rubin, Colm A. Ryan, D. Scarabelli, M. Scheer, E. A. Sete, P. Sivarajah, Robert S. Smith, A. Staley, N. Tezak, W. J. Zeng, A. Hudson, Blake R. Johnson, M. Reagor, M. P. da Silva, and C. Rigetti
Rigetti Computing, Inc., Berkeley, CA
(Dated: December 16, 2017)

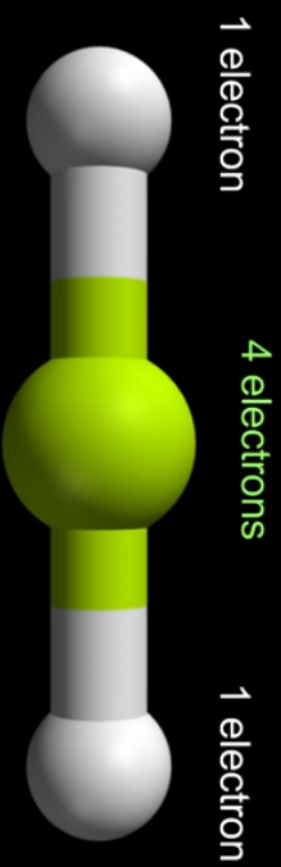
rigetti



19 qubits



Simulation of molecules



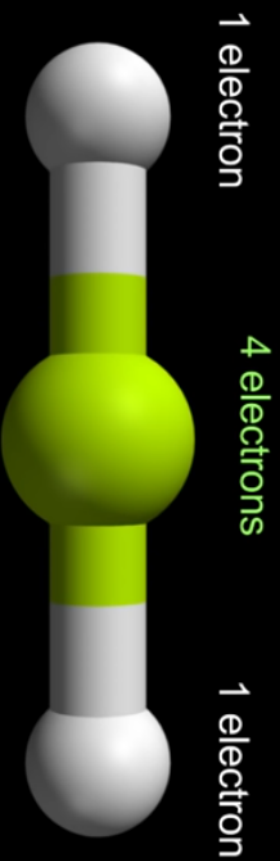
fully quantum mechanical solution requires diagonalization of

400.000 x 400.000 Matrix

$$\begin{pmatrix} c_{1,1} & c_{1,2} & \dots & c_{1,40000} \\ c_{2,1} & c_{2,2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ c_{40000,1} & \dots & \dots & c_{40000,40000} \end{pmatrix}$$



Simulation of molecules



LETTER

242 | NATURE | VOL 549 | 14 SEPTEMBER 2017

doi:10.1038/nature23879

Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets

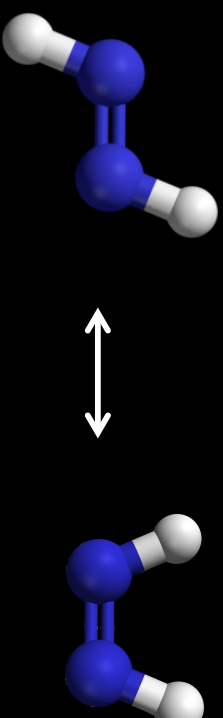
Abhinav Kandala^{1*}, Antonio Mezzacapo^{1*}, Kristan Temme¹, Maika Takita¹, Markus Brink¹, Jerry M. Chow¹ & Jay M. Gambetta¹



7 – qubit quantum computer

42 | NATURE | VOL 549 | 14 SEPTEMBER 2017

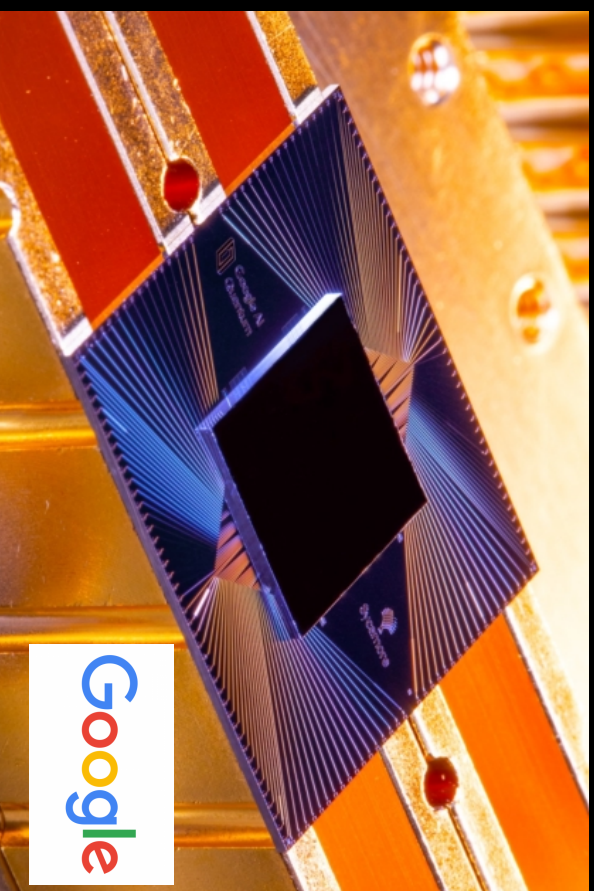
Simulation of molecules



Simulation of Isomerisation of Diazene^{*}

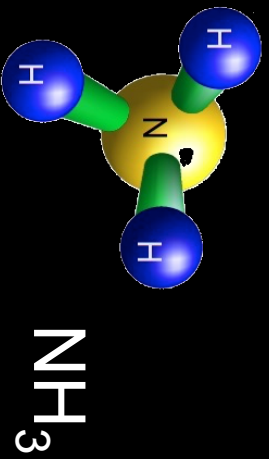


Sycamore quantum chip
53 qubits
Science, 08/2020



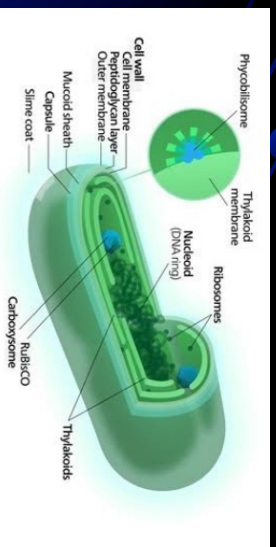
^{*} but: ... not really an interesting problem

Simulation of molecules



Thyssen

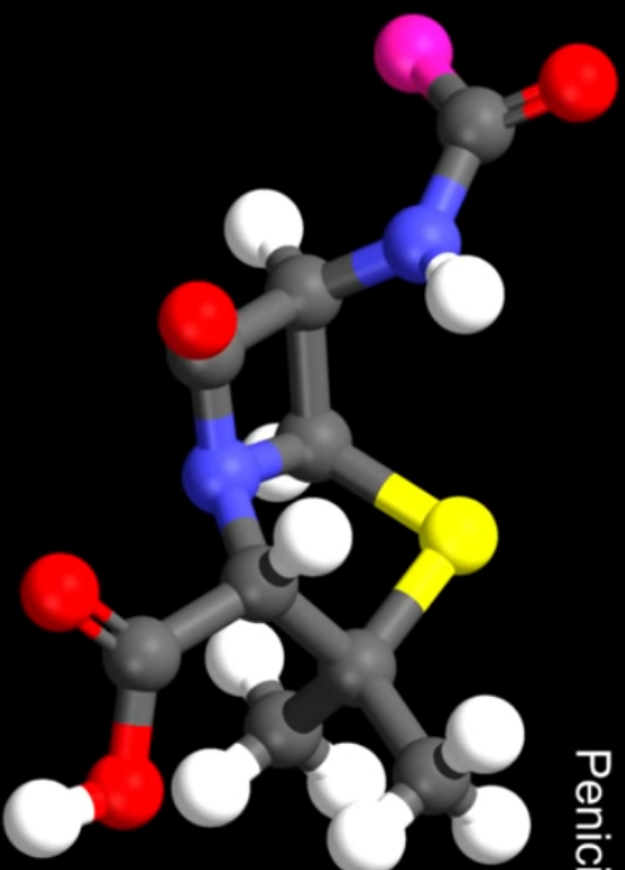
Ammonia synthesis central for fertilizer production
(Haber Bosch)



- high temperatures / high pressure
- 2% of World energy consumption

more efficiently ??

Cyano bacterium



Penicillin

COMPUTING | OPINION

Quantum Computing May Be Closer Than You Think

Five new quantum information science centers will marry the R&D strengths of academia, industry and U.S. national laboratories

By Dario Gil on September 1, 2020

SCIENTIFIC
AMERICAN™

..... SO, we need to have experts !