Quantum Computing: Transforming the Digital Age

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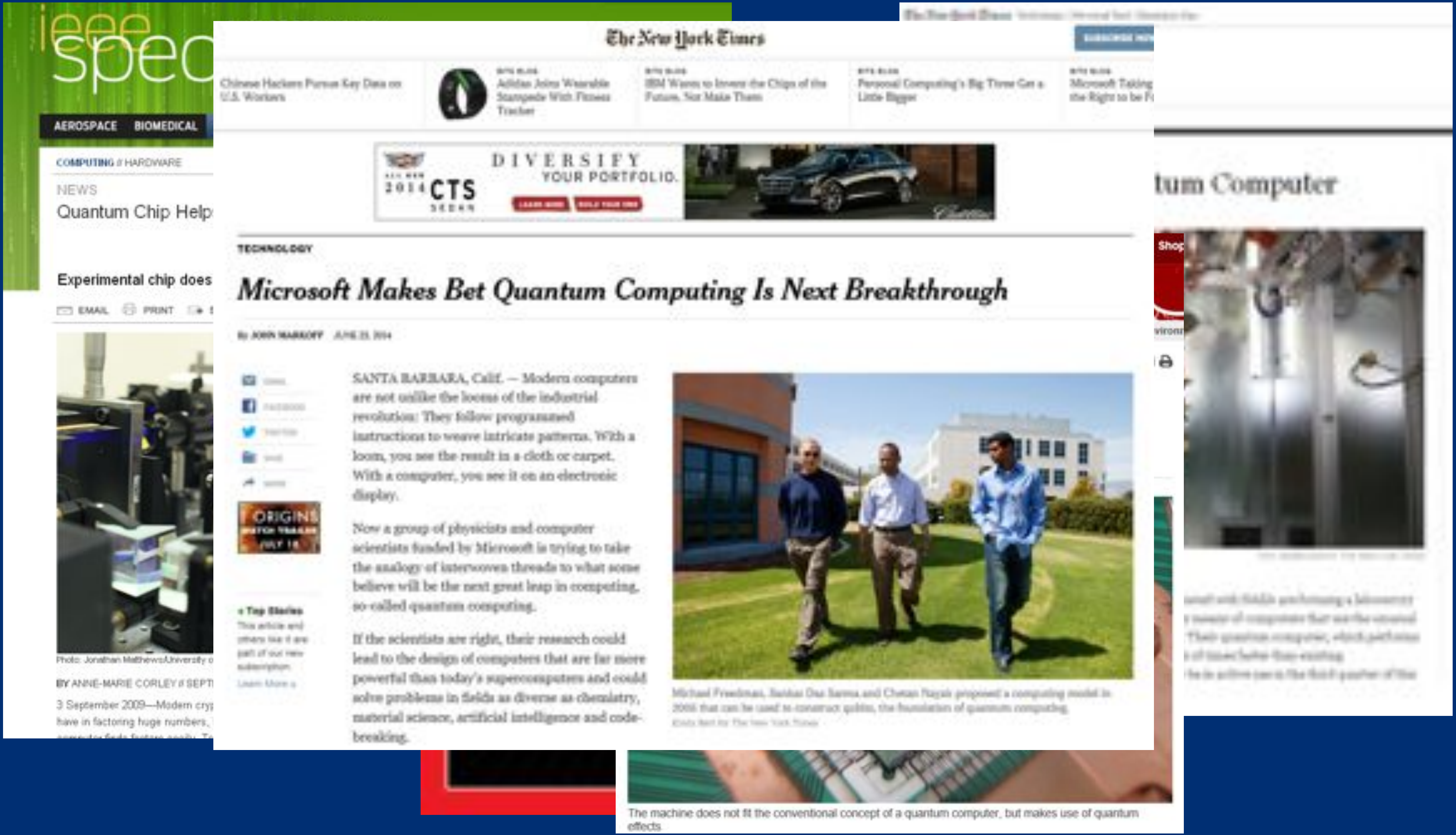
CRA Snowbird 2014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have in factoring huge numbers,
The New York Times
Chinese Hackers Pursue Key Data on U.S. Workers
Adidas Joins Wearable Stampede With Fitness Tracker
IBM Wants to Invent the Chips of the Future, Not Make Them
Personal Computing's Big Three Get a Little Bigger
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TECHNOLOGY
Microsoft Makes Bet Quantum Computing Is Next Breakthrough
By JOHN MARKOFF
SANTA BARBARA, Calif. — Modern computers are not unlike the looms of the industrial revolution: They follow programmed instructions to weave intricate patterns. With a loom, you see the result in a cloth or carpet. With a computer, you see it on an electronic display.
Now a group of physicists and computer scientists funded by Microsoft is trying to take the analogy of interwoven threads to what some believe will be the next great leap in computing, so-called quantum computing.
If the scientists are right, their research could lead to the design of computers that are far more powerful than today's supercomputers and could solve problems in fields as diverse as chemistry, material science, artificial intelligence and code-breaking.
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The machine does not fit the conventional concept of a quantum computer, but makes use of quantum effects

Computers have come a long way

Antikythera mechanism
(100 BC)

Babbage's Difference Engine
(proposed 1822)

ENIAC
(1946)

Sequoia
(2012)

Quantum
(2025?)

Thanks to Matthias Troyer

Success of Digital Computers and Moore’s Law

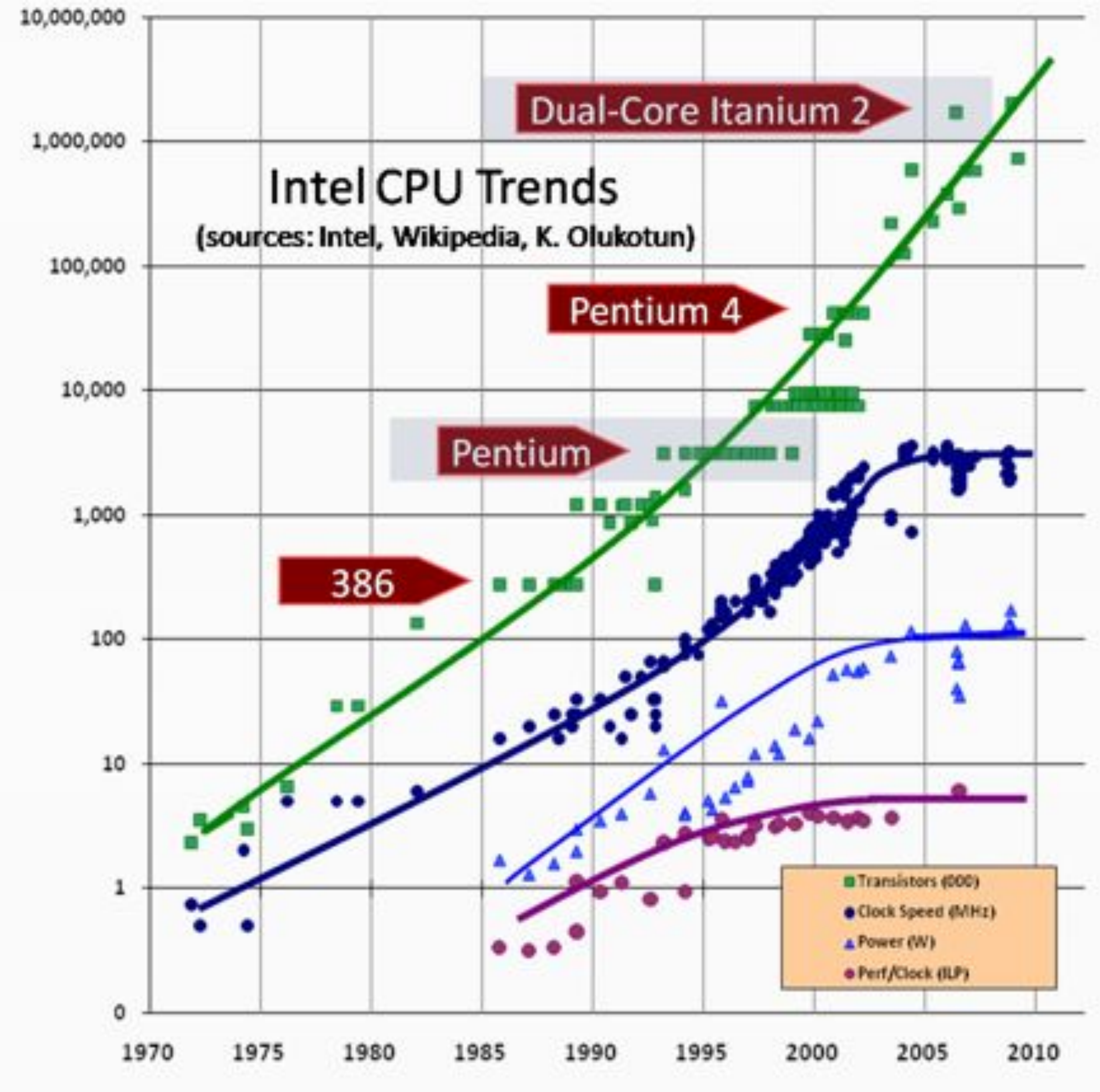
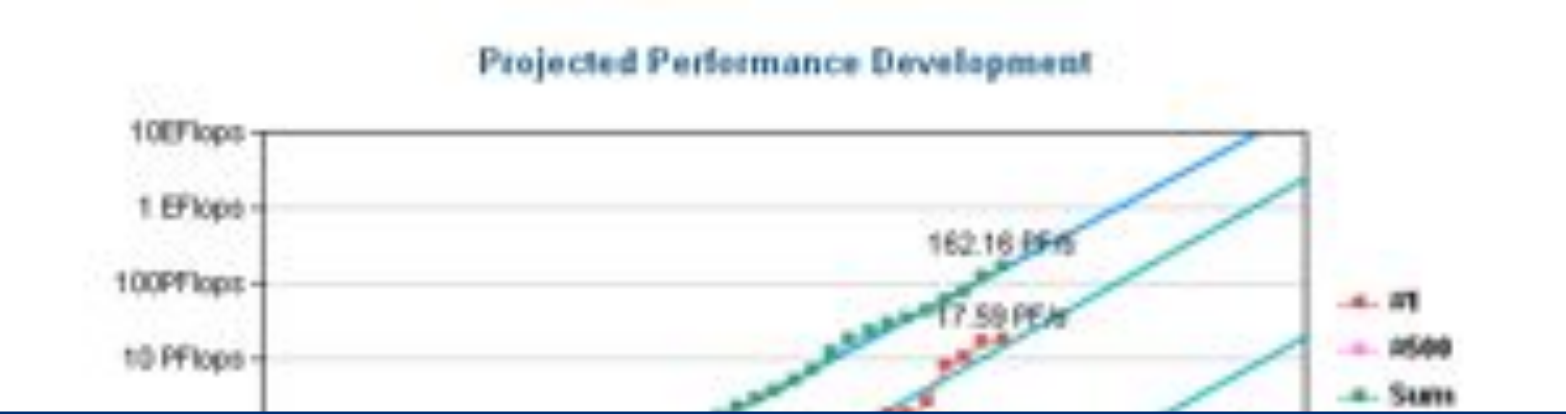
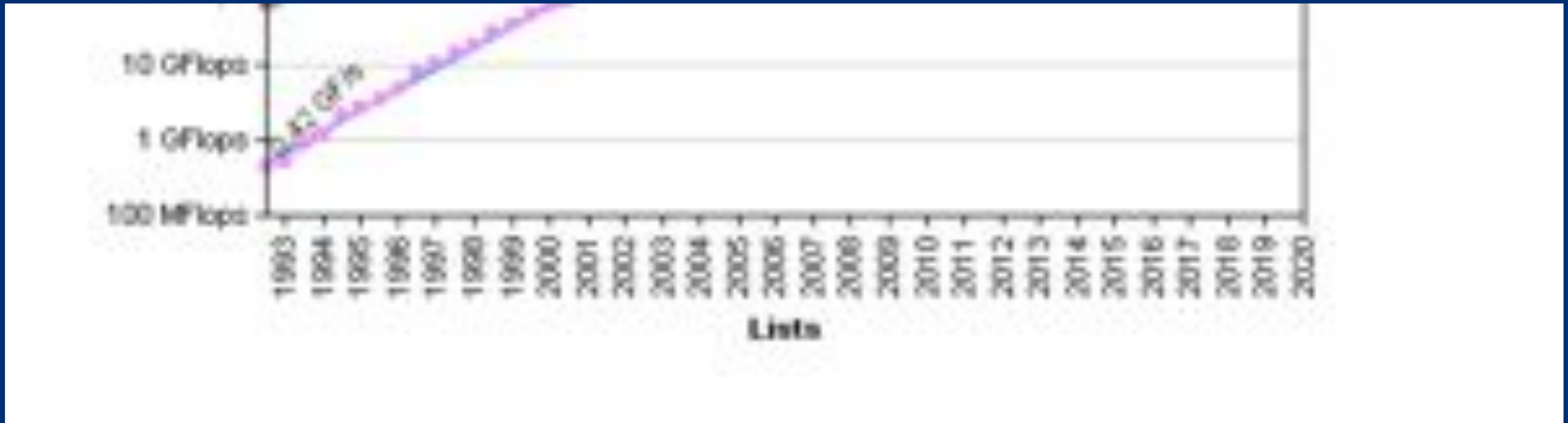


Figure 1: Intel CPU Introductions (graph updated August 2009; article text original from December 2004)

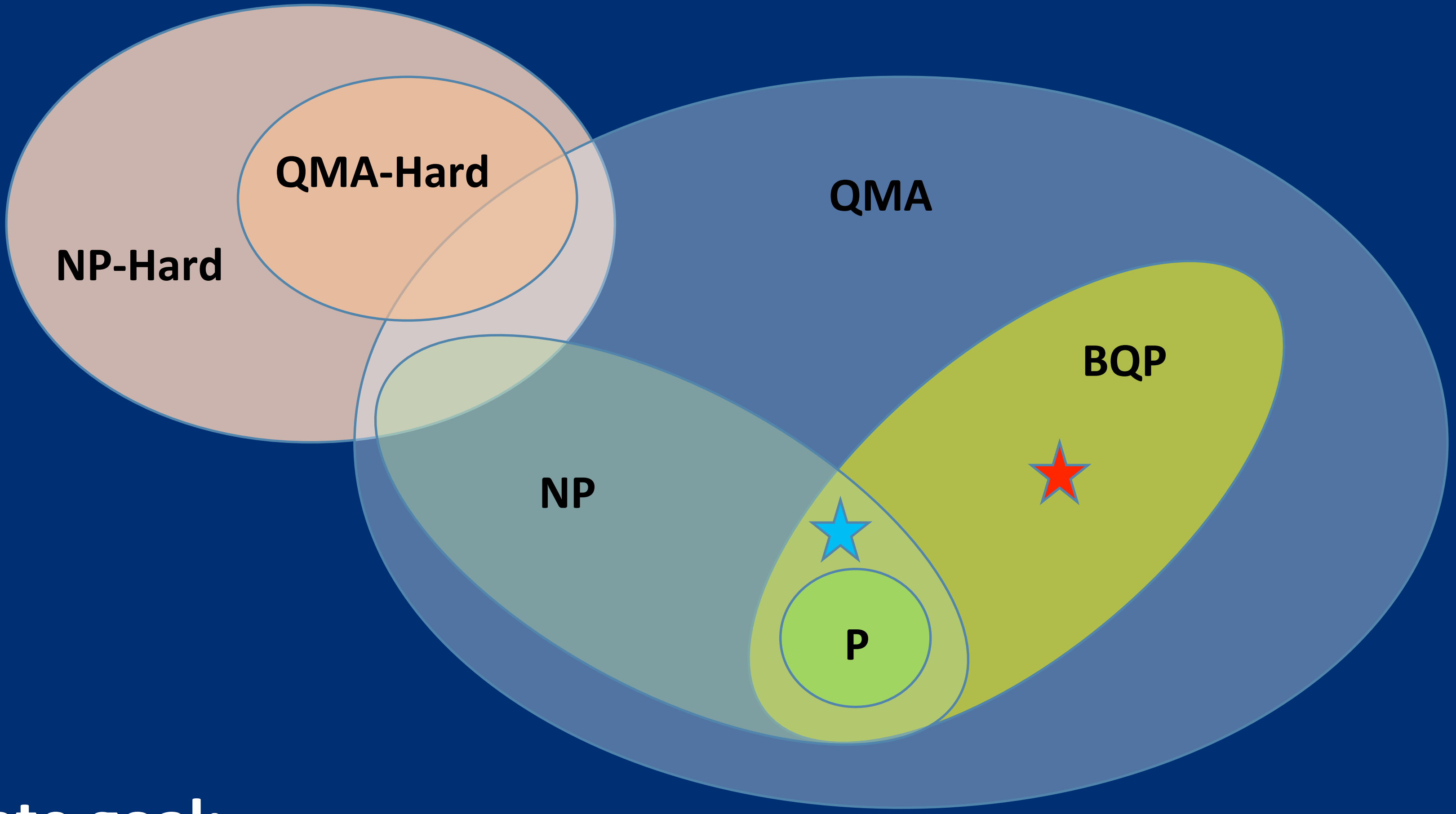
Success of Digital Computers and Moore’s Law



Is there anything we can’t solve on digital computers?



Some problems are hard to solve

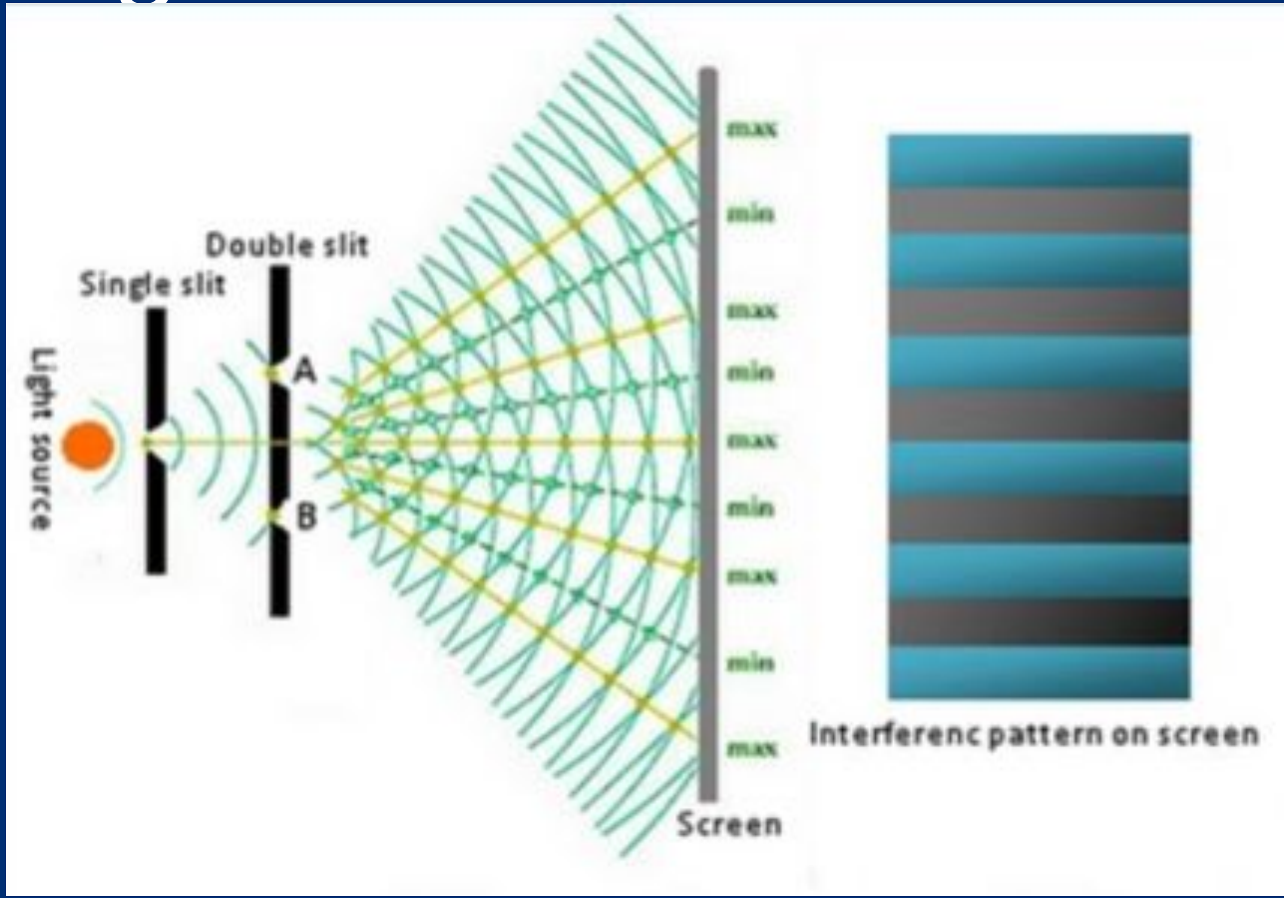


Ultimate goal:

Develop quantum algorithms whose complexity lies in BQP\P

Quantum Magic: Interference

source of particles



interference pattern = quantum coherence

Classical objects go ***either*** one way or the other.

Quantum objects (electrons, photons) go ***both*** ways.

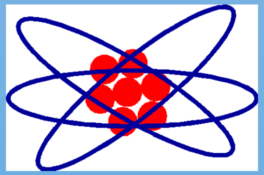
Gives a quantum computation an inherent type of parallelism!

Quantum Magic: Qubits and Superposition

$|0\rangle = |\quad\rangle = \downarrow$

$|1\rangle = |\quad\rangle =$

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



single atom

$|g\rangle = |\mathbf{0}\rangle$
$|e\rangle = |\mathbf{1}\rangle$

single spin

$|\downarrow\rangle = |\mathbf{0}\rangle$
$|\uparrow\rangle = |\mathbf{1}\rangle$

Information encoded in the state of a two-level quantum system

$|\psi\rangle =$

Thanks to Charlie Marcus

Input

P(1)

$+$ P(2)

⋮

$+$ P(2^n)

Output

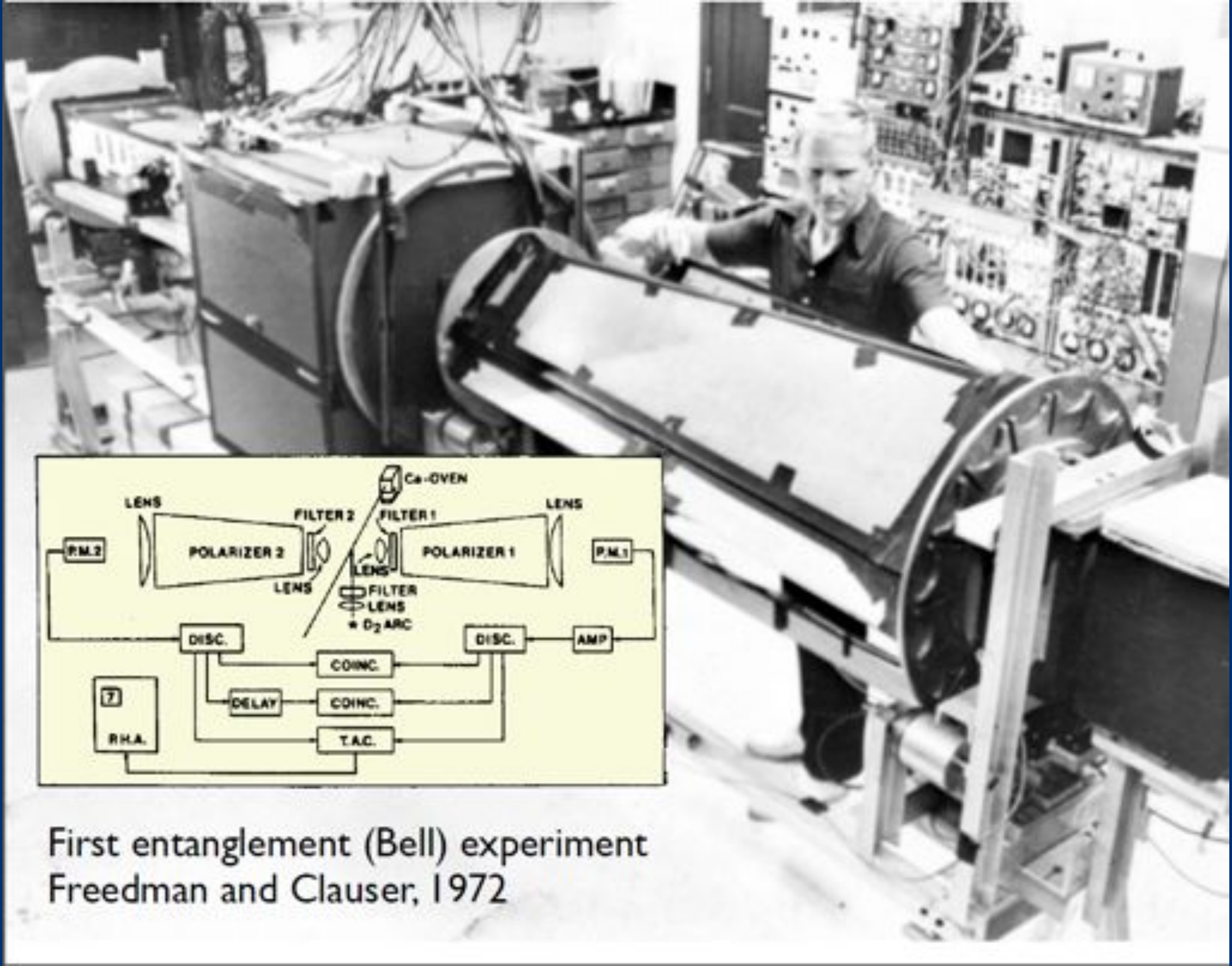
Q(1)

$+$ Q(2)

⋮

$+$ Q(2^n)

Quantum Magic: Entanglement

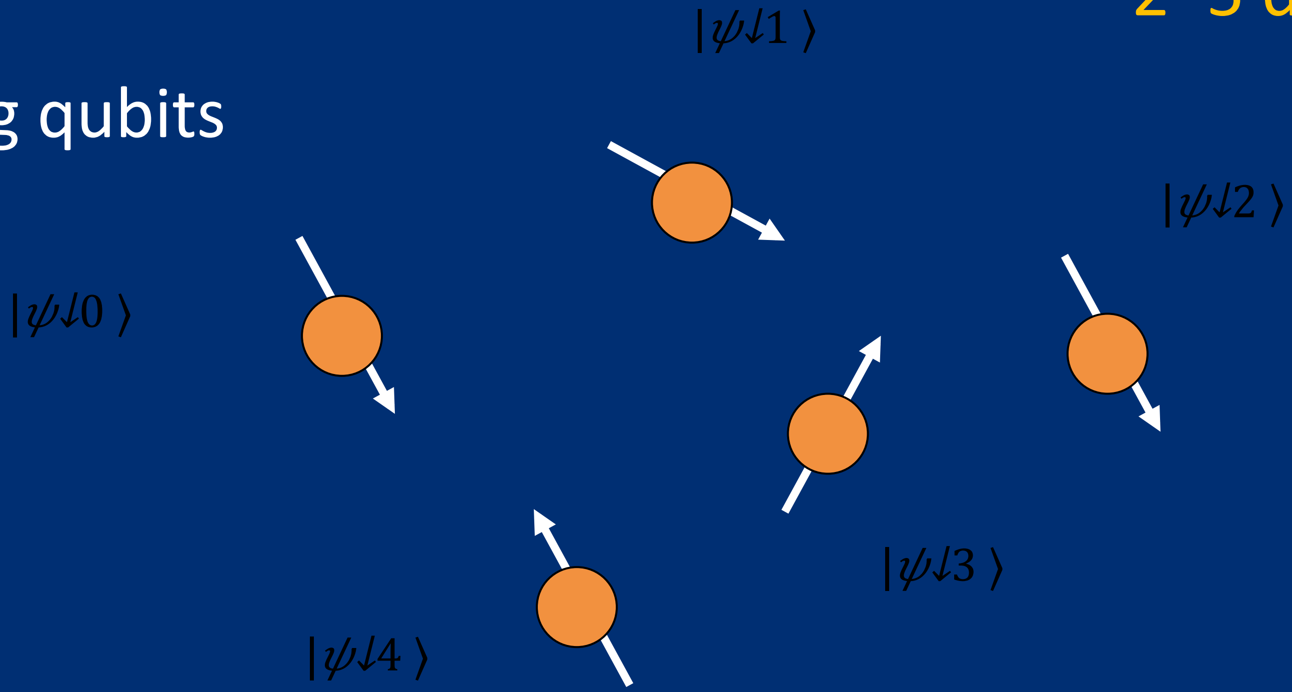


First entanglement (Bell) experiment
Freedman and Clauser, 1972

Quantum Magic: Entanglement

2*5 distinct amplitudes

N non-interacting qubits



$$|\psi_{total}\rangle = (\alpha_0|0\rangle+\beta_0|1\rangle)\otimes(\alpha_1|0\rangle+\beta_1|1\rangle)\otimes\ldots\otimes(\alpha_{N-1}|0\rangle+\beta_{N-1}|1\rangle)$$

State of N non-interacting qubits: ~ N bits of info

Thanks to Rob Schoelkopf

Quantum Magic: Entanglement

General state of N *interacting* qubits

32 distinct amplitudes!

$|\psi_1\rangle$ $|\psi_2\rangle$ $|\psi_4\rangle$

Simulating a 200-qubit interacting system requires ~ 10^{60} classical bits!

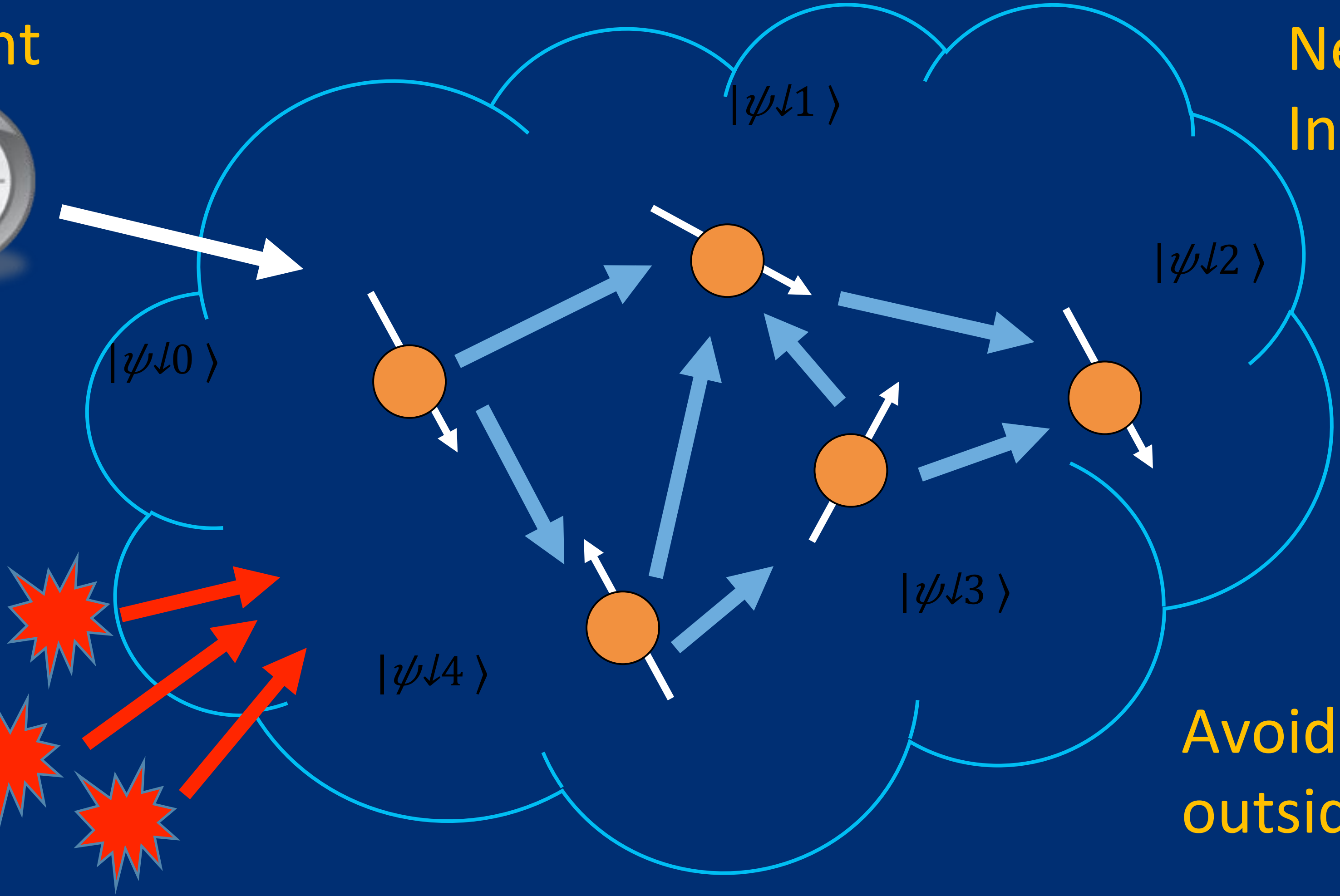
$$\boxed{|\psi_{total}\rangle = c_0|00\ldots0\rangle + c_1|00\ldots1\rangle + \ldots\ c_{2^N-1}|11\ldots1\rangle}$$

State of N interacting qubits: ~ 2^N bits of info!

Thanks to Rob Schoelkopf

Quantum Magic: What's the catch?

Need coherent control



Need strongly Interacting system

Decoherence and errors!

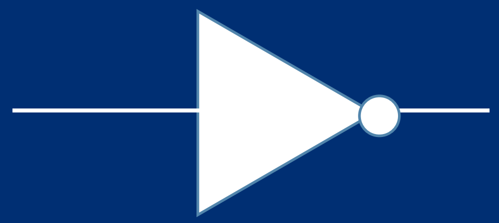
Avoid interaction with outside environment!

Thanks to Rob Schoelkopf

Quantum Gates: Digital quantum computation

Basic unit: **bit** = 0 or 1

Computing: **logical** operation



NOT

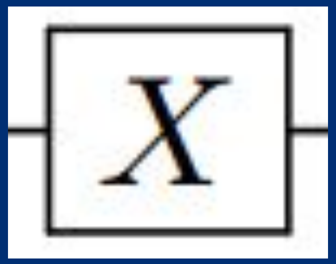
$0 \to 1$

$1 \to 0$

Basic unit: **qubit** = unit vector

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

Computing: **unitary** operation



NOT

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \beta \\ \alpha \end{bmatrix}$$

Quantum Gates: Digital quantum computation

Basic unit: **bit** = 0 or 1

Computing: **logical** operation

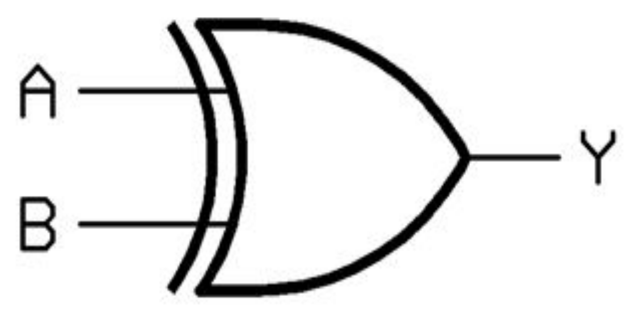
Description: **truth table**

Basic unit: **qubit** = unit vector

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

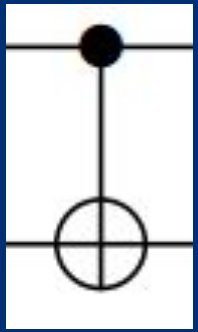
Computing: **unitary** operation

Description: **unitary matrix**



XOR gate

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

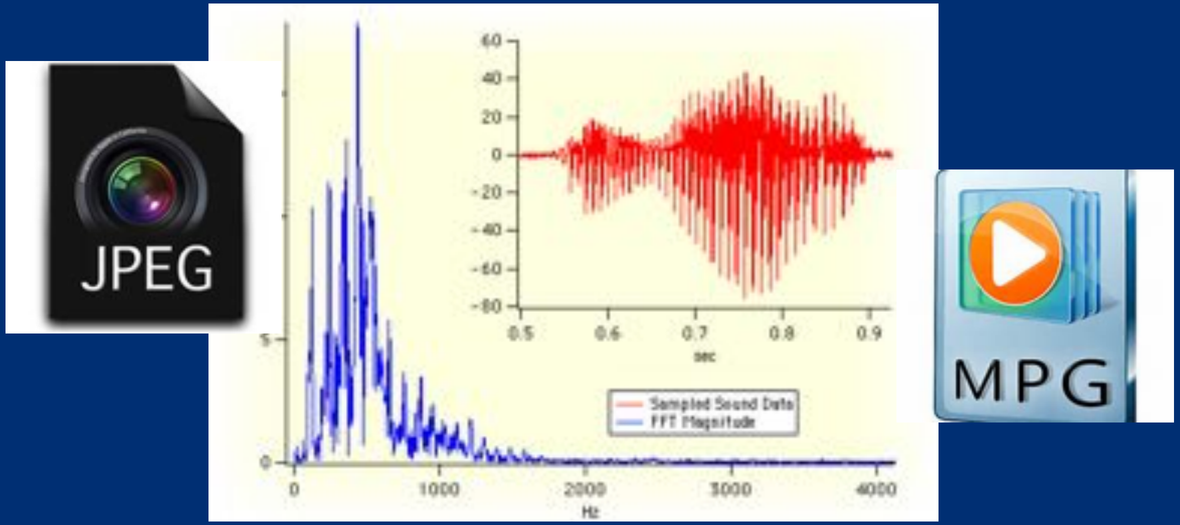


CNOT gate

[■1&0&0&0@0&1&0&0@0&0&0

Quantum power unleashed: super-fast FFT

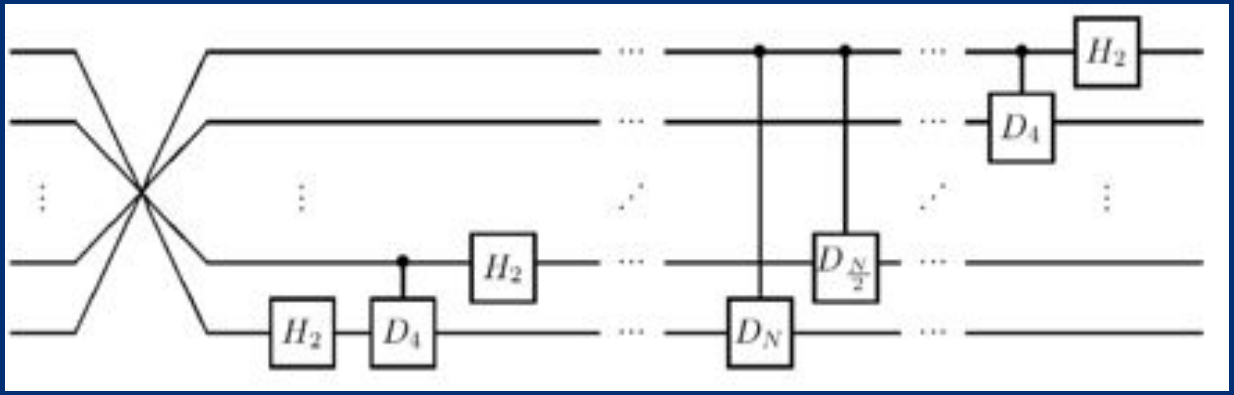
FFT



 # ops = N log N

Example:
1GB of data =
10 Billion ops

Quantum FFT



 # ops = log N

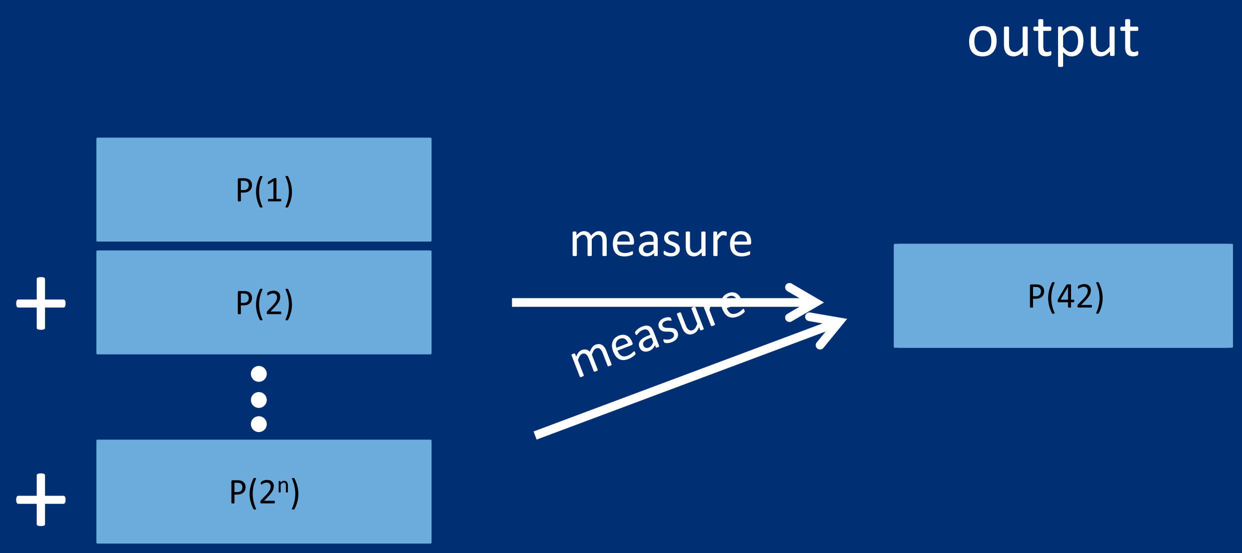
Example:
1GB of data =
27 ops (!!!)

Any other catches?

No-cloning principle

Quantum information cannot be copied

I/O limitations



Input: preparing initial state can be costly

Output: reading out a state is probabilistic

Requirements for Quantum Computation

Quantum Algorithms:

Design real-world quantum algorithms for small-, medium- and large-scale quantum computers

Quantum hardware architecture:

Architect a scalable, fault-tolerant, and fully programmable quantum computer

Quantum software architecture:

Program and compile complex algorithms into optimized, target-dependent (quantum and classical) instructions

Quantum Algorithm "Wins"

Shor's Algorithm (1994)

- Breaks RSA, elliptic curve signatures, DSA, El-Gamal
- Exponential speedups

Solving Linear Systems of Equations (2010)

- Applications shown for electromagnetic wave scattering
- Exponential speedups

Quantum simulation (1982)

- Simulate physical systems in a quantum mechanical device
- Exponential speedups

Cryptography

$$15 = \blacksquare \times \blacksquare$$

$$15 = 5 \times 3$$

$$1387 = \blacksquare \times \blacksquare$$

$$1387 = 19 \times 73$$

1807082088687
4048059516561
6440590556627
8102516769401
3491701270214
5005666254024
4048387341127
5908123033717
8188796656318
2013214880557

$=\blacksquare\times\blacksquare$

1807082088687
4048059516561
6440590556627
8102516769401

3968599 4553449
9459597 8646735

Example: (n=2048 bits)

classically ~7x10^{15} years

quantum ~100 seconds

5551572 9990445
43 99

Breaking RSA and elliptic curve signatures

Classical:

$O(\exp(n^{1/3}(\log n)^{2/3}))$

Quantum:

$O(n^2 \log n)$

OneDrive for Business

SharePoint

How does quantum factoring work? [Shor'94]

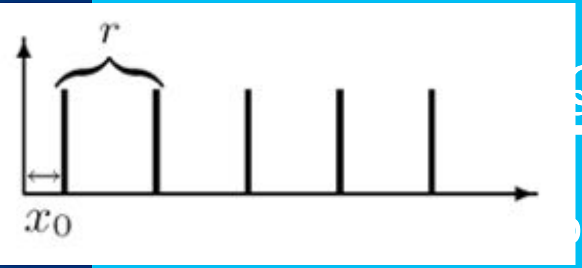
Prepare initial quantum distribution

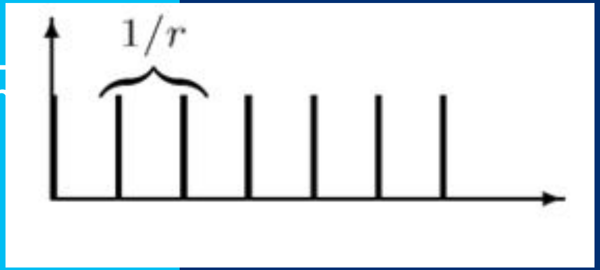
Use quantum superposition to exponentiate all inputs in parallel

Apply Fourier transform to obtain periodic state due to interference

Quantum measurement gives value close to the inverse period

Post-processing on a classical computer gives the period and a factor





Core idea: [Shor'94], [Kitaev'95]

Recent improvement: [Svore, Hastings, Freedman, QIC'1

Machine learning

Solving linear systems of equations

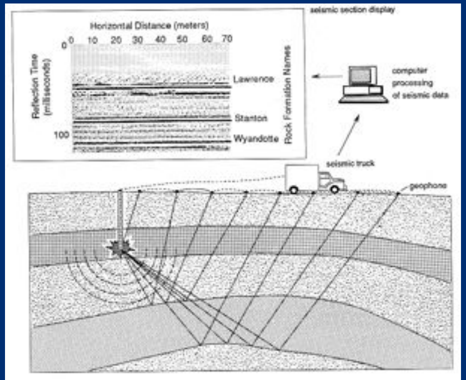
$$Ax = b$$

If is , then it requires time $O(N^3$

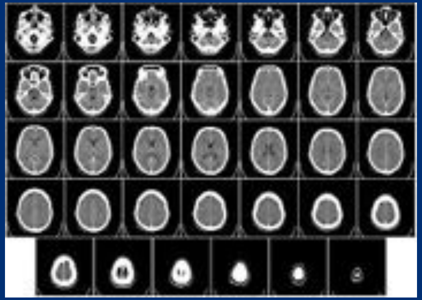
Matrix inversion can be expensive

Large inversion problems are expensive.

They are ubiquitous in science and engineering.



Seismic Processing



Tomography

If you have a billion pieces of data (and sparse *A*) roughly $10 \uparrow 18$ operations are required.

Quantum Matrix Inversion Algorithms: roughly $10{,}000$ operations.

How does the algorithm work

Steps for finding x [Harrow, Hassidim, Lloyd PRL'10]

$A=\sum_j \alpha_j \boldsymbol{v}_j \boldsymbol{v}_j^*$, where $\boldsymbol{v}_j$ are eigenvectors. Evolve $e^{-iAt}|b\rangle$.

Convert b to a quantum state

Find a quantum system that is equivalent to A

Simulate A to transform b into eigenbasis of A: $b=\sum_j \beta_j \boldsymbol{v}_j$

For each v_j, $\beta_j \mapsto \beta_j / \alpha_j$

Transform back to initial basis.

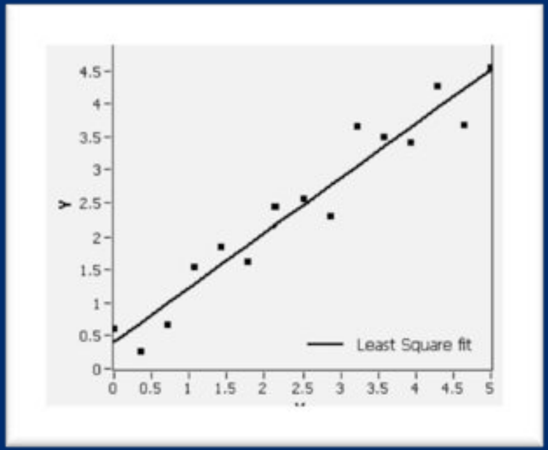
Quantum computers exponentially speed up the last 3 steps.

You can't always get what you want

Quantum computing doesn't give *x* efficiently, but allows you to sample from *x*.

Quantum least square fitting side steps this problem

(Wiebe, Braun, Lloyd 2012).



Electromagnetic scattering problems can be solved this way.

(Clader et al, 2013)

You have to know the right questions to ask a quantum computer.

Quantum Machine Learning Algorithms

Translating classical algorithms is usually not the best approach:

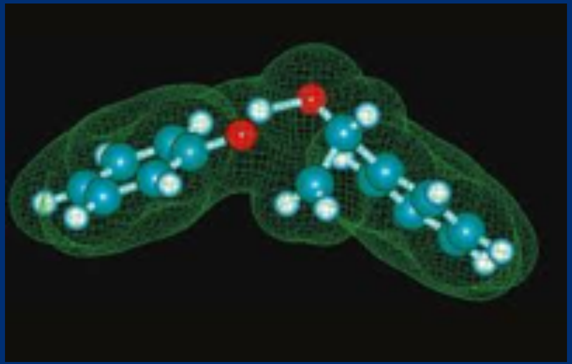
1. You have to load all the data (at least linear time)
2. You have to process the data (may be exponentially faster)
3. You get to read-out one number as an answer (which is probabilistic)
4. Want another answer? Go back to step 1

Quantum simulation

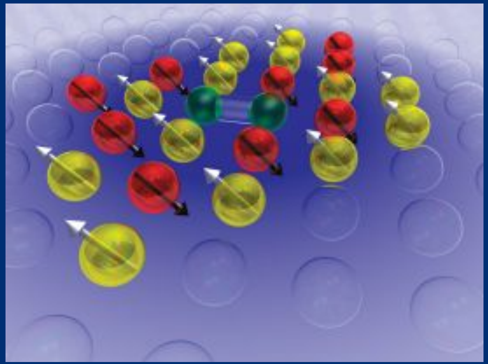
What does quantum simulation do?

Physical Systems

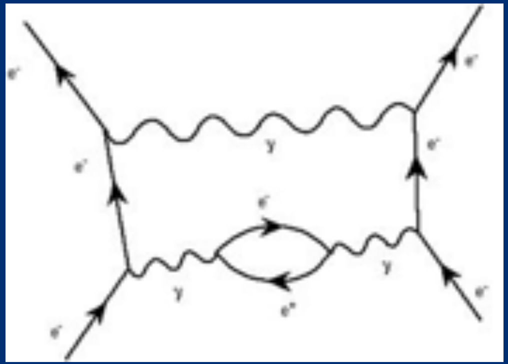
Quantum Chemistry



Superconductor Physics



Quantum Field Theory

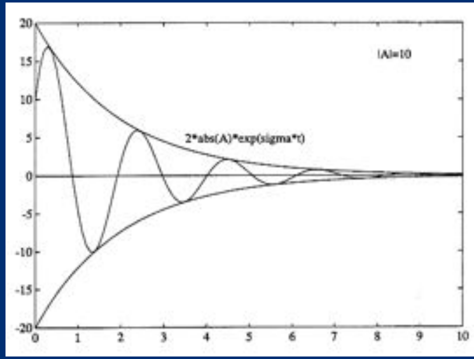


Computational Applications

Emulating Quantum Computers

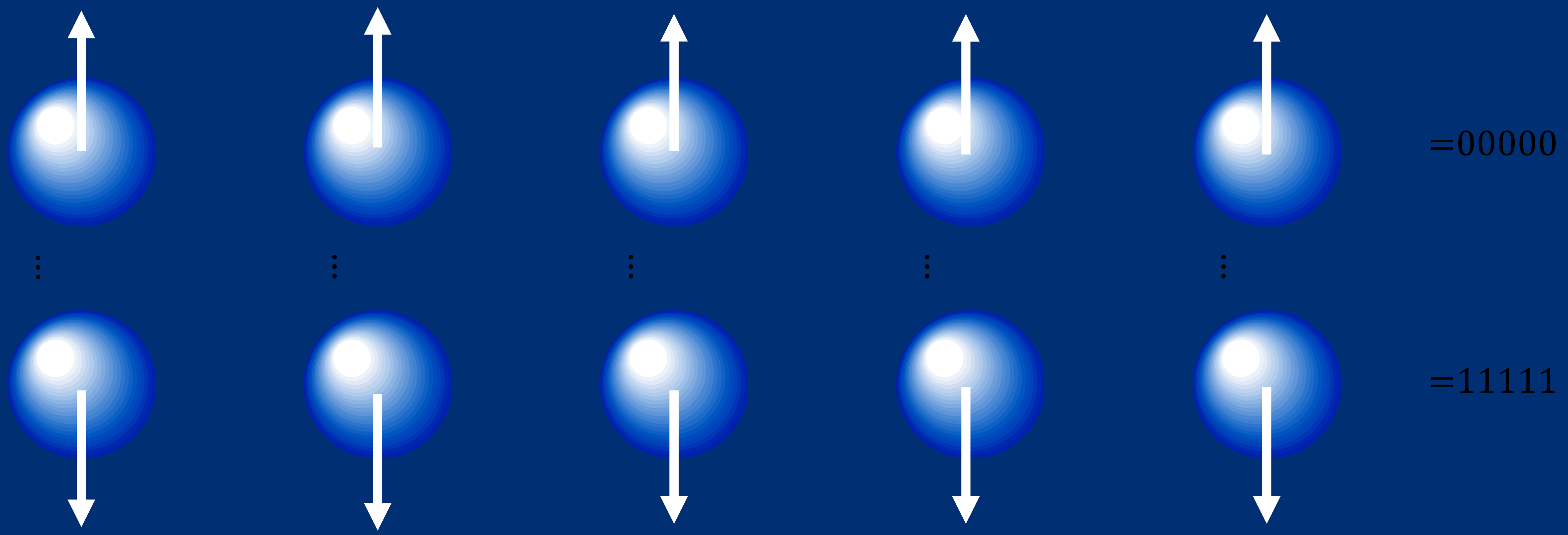
Linear Algebra

Differential Equations



Quantum simulation

Particles can either be spinning clockwise (down) or counterclockwise (up)



There are $2 \uparrow 5$ possible orientations in the quantum distribution.

Cannot store this in memory for 100 particles.

How does simulation work? [Lloyd Science'96]

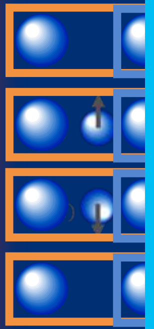
Prepare initial quantum distribution.

Decompose Interaction into a sum of simple ones.

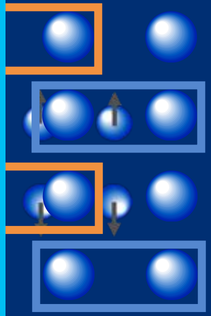
Use quantum superposition to evolve under each simple interaction.

Rapidly switch between each simple evolution.

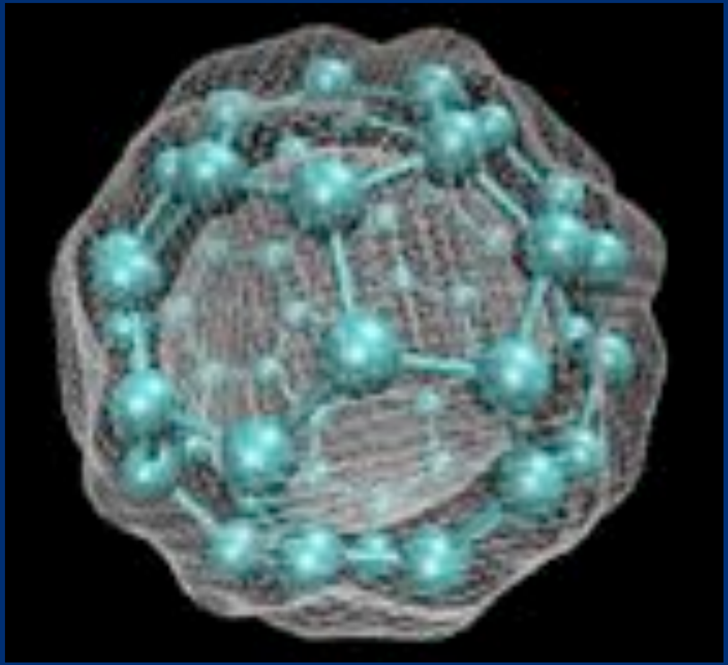
Measure resulting quantum distribution.



Quantum computers exponentially speed up third step.



Quantum Simulation for Quantum Chemistry



Ultimate problem:

Simulate molecular dynamics of *larger* systems or to *higher accuracy*

Want to solve system *exactly*

Current solution:

33% supercomputer usage dedicated to chemistry and materials modeling

Requires simulation of exponential-size Hilbert space

Limited to 50-70 spin-orbitals classically

Quantum solution:

Simulate molecular dynamics using *quantum simulation*

Scales to 100s spin-orbitals using only 100s qubits

Runtime recently reduced from $O(N^{11})$ to $O(N^{4})-O(N^{6})$

Quantum Chemistry

$H=\sum_{pq} h_{pq} a_p^\dagger a_q + 1/2 \sum_{pqrs} h_{pqrs} a_p^\dagger$

Can quantum chem
computer: Dave We
Hastings, Matthias T

As quantum
with a sma
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quantum c
application
systems, a
materials.
for one of t
quantum c
find the gro
classical c
problem re
over curren
that can be
This suggest
quantum chemistry p \cite{WBCH13a,HWBT14a} which relied on exponentially costly classical exact simulation.
be needed.

The Trotter Step Size Required for Accurate Quantum Simulation of Quantum Chemistry
David Poulin, M. B. Hastings, Dave Wecker, Nathan Wiebe, Andrew C. Doherty, Matthias

m Chemistry: M. B.

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error at given
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timestep. All of
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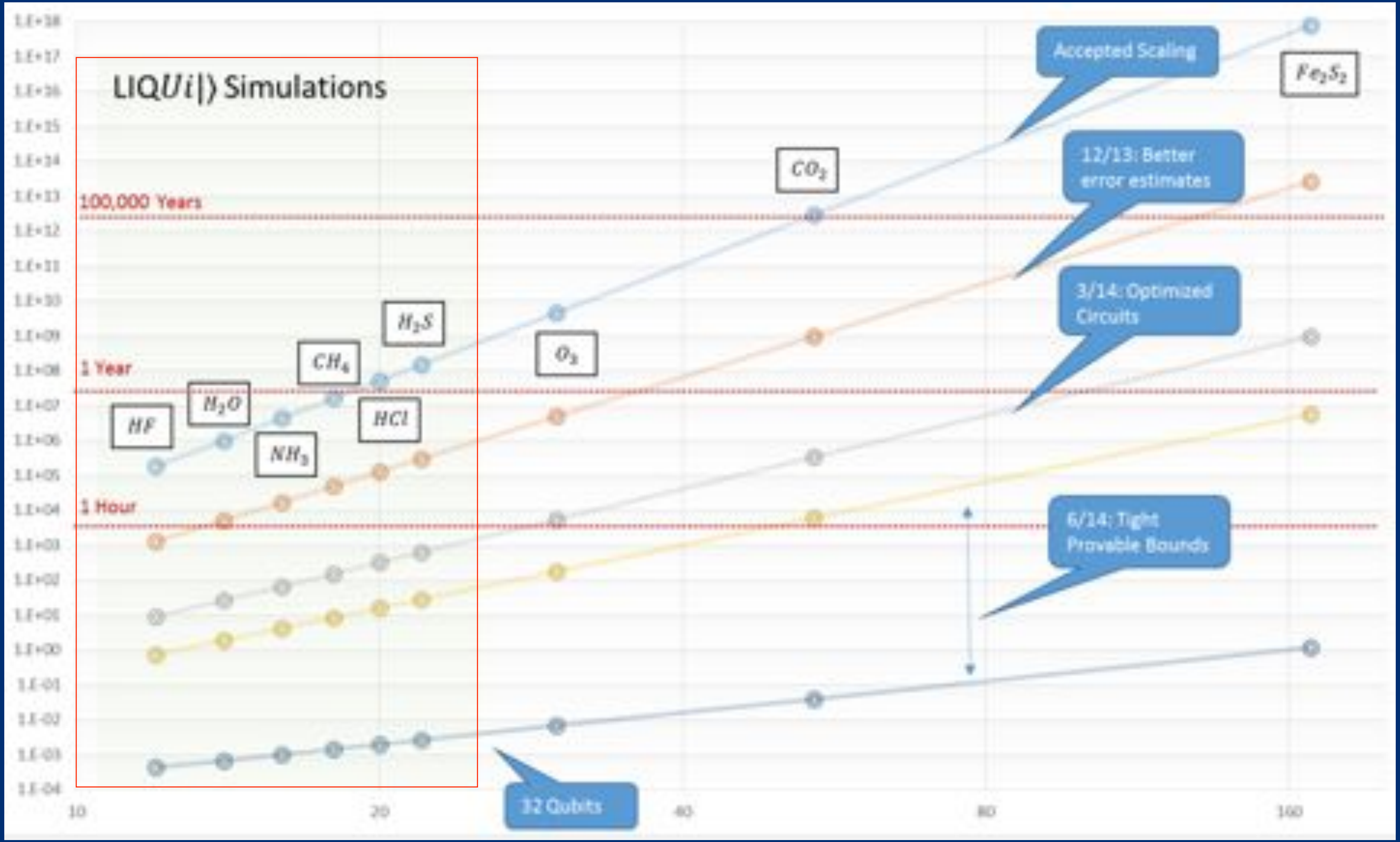
Ferredoxin ($Fe_2 S_2$) used in many metabolic reactions including energy transport in photosynthesis

- *Intractable on a classical computer*
- *First paper: ~300 million years to solve*
- *Second paper: ~30 years to solve (10^7 reduction)*
- *Third paper: ~300 seconds to solve (another 10^3 reduction)*

http://arxiv.org/abs/1406.4920

Quantum Chemistry

$H=\sum_{pq} h_{pq} a_p^\dagger a_q + 1/2 \sum_{pqrs} h_{pqrs} a_p^\dagger$



Application: Nitrogen Fixation

Ultimate problem:

Find catalyst to convert nitrogen to ammonia at room temperature

Reduce energy for conversion of air to fertilizer

Current solution:

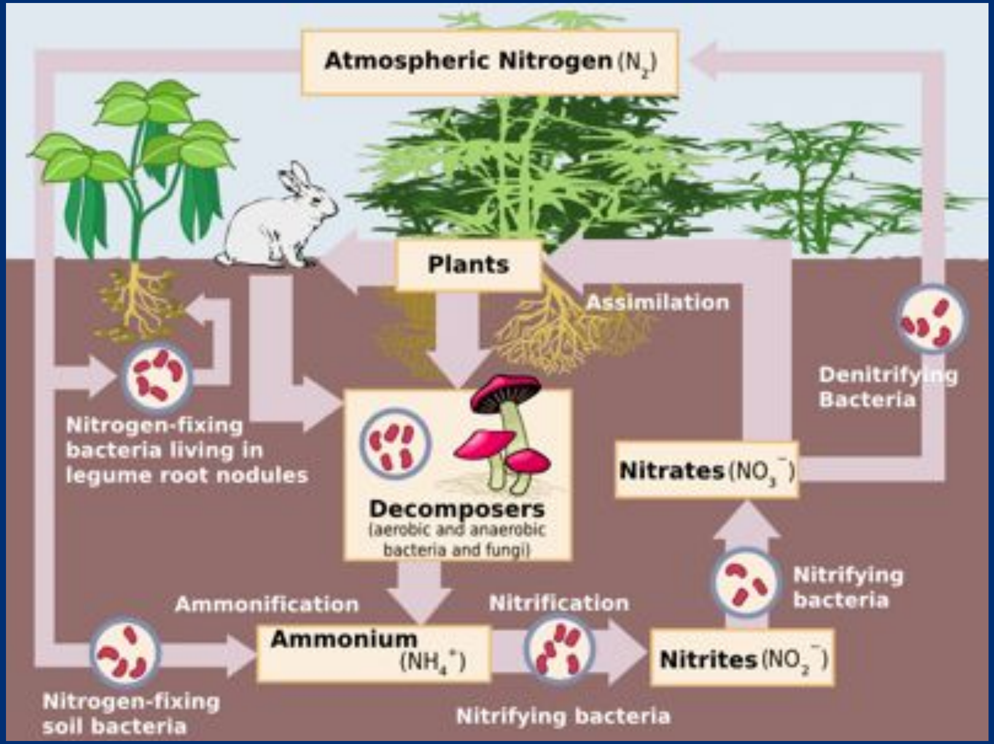
Uses Haber process developed in 1909

Requires high pressures and temperatures

Cost: 3-5% of the worlds natural gas production (1-2% of the world's annual energy)

Quantum solution:

~ 100-200 qubits: Design the catalyst to enable inexpensive fertilizer production



Application: Carbon Capture

Ultimate problem:

Find catalyst to extract carbon dioxide from atmosphere

Reduce 80-90% of emitted carbon dioxide

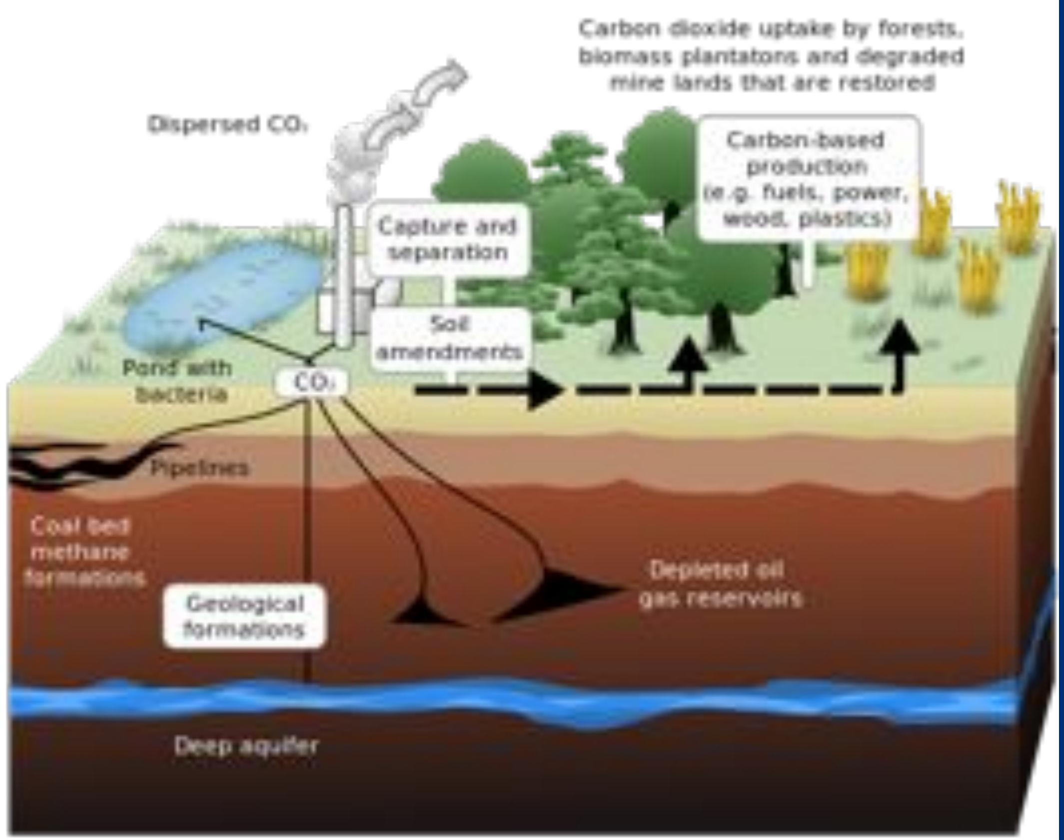
Current solution:

Capture at point sources

Results in 21-90% increase in energy cost

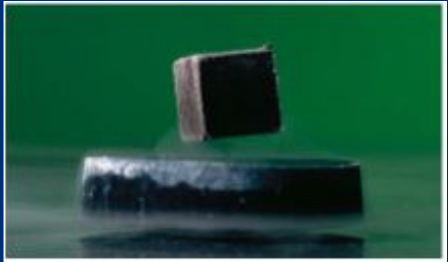
Quantum solution:

~ 100-200 qubits: Design a catalyst to enable carbon dioxide extraction from air



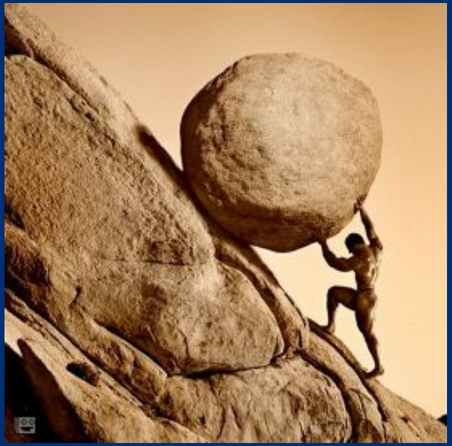
How much faster is it?

Imagine you have 100 interacting electrons in a superconductor.



Quantum computing makes testing models of high-temperature superconductivity conceivable.

Supercomputer simulation requires roughly $10\uparrow 34$ operations.



Quantum simulation requires roughly $10\uparrow 10$ operations.
[Wiebe,Berry, Hoyer, Sanders, JPA’11]
[Wiebe,Childs, QIC’12]

Exact gate counts can be found using [Raeisi, Wiebe, Sanders NJP’12], [Wecker, Bauer, Clark, Hastings, Troyer arXiv’14].

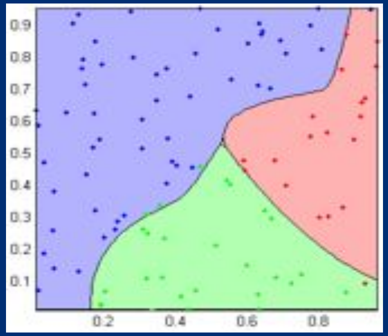
Quantum Algorithm Opportunities

Quantum simulation

- Extend q. chem. method to solid state materials
- E.g., high temp. superconductivity
- ~ 2000 qubits; linear or quad. scaling

Machine learning

- Clustering, regression, classification
- Polynomial speedups to date
- Can we harness interference to produce better inference models?

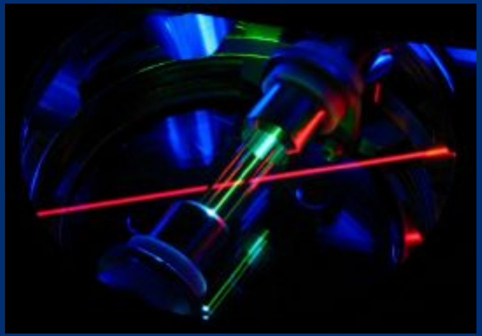


Cryptography

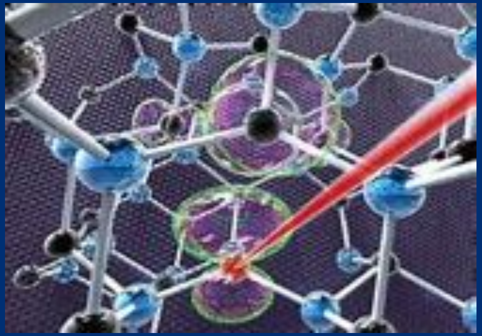
- RSA, DSA, elliptic curve signatures, El-Gamal
- What questions should we pose to a quantum computer?

Quantum Hardware Technologies

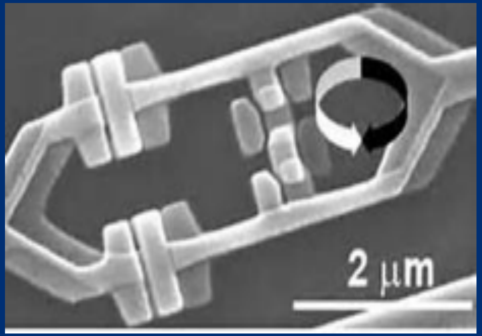
Ion traps



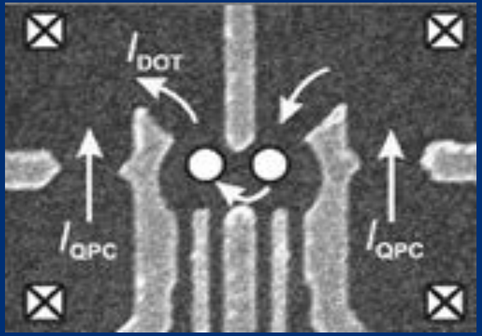
NV centers



Super-
conductors

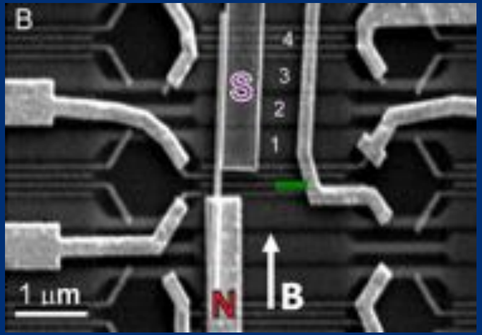


Quantum
dots



Linear optics

Topological



Ages of Quantum Computing

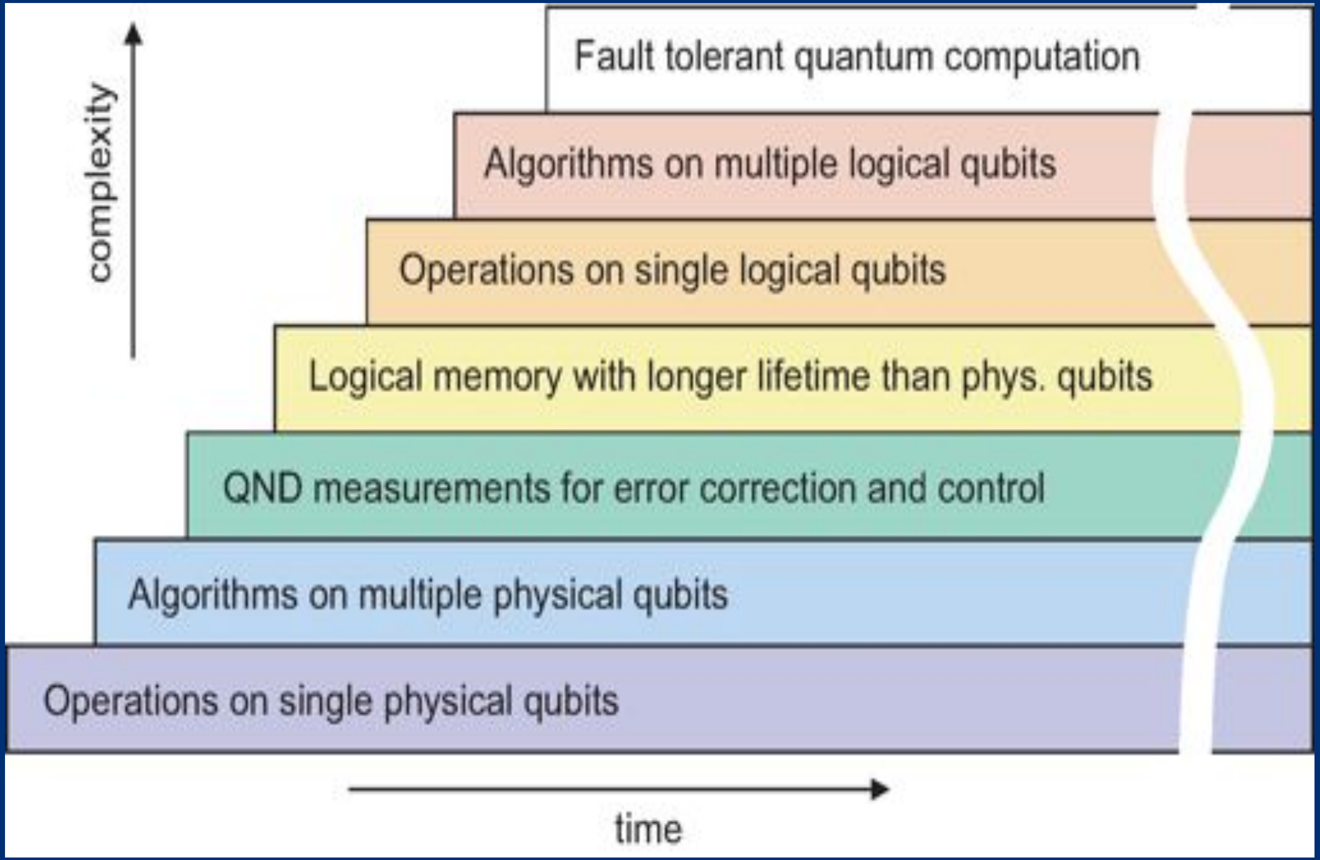
"Age of Qu. Error Correction"

"Age of Qu. Feedback"

"Age of Measurement"

"Age of Entanglement"

"Age of Coherence"

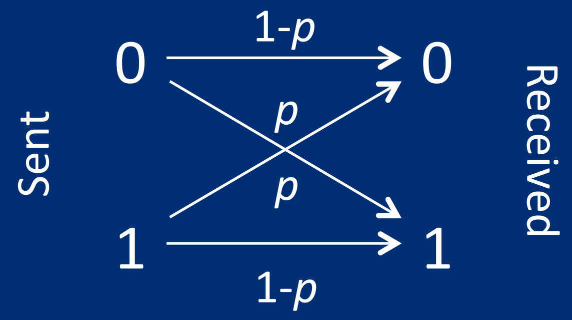


"We" are ~ here

M. Devoret and R. Schoelkopf, Science (2013)

Thanks to Rob Schoelkopf

Classical Error Correction



Probability p of having a bit flipped

Repetition code: redundantly encode, majority voting

$0 \rightarrow 000$

$1 \rightarrow 111$

Reduces classical error rate to $3p^2 - 2p^3$

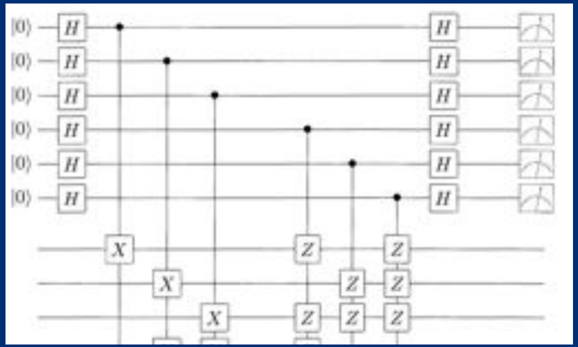
Can we do this for quantum computing? Some reasons to think **no**:

- "No cloning" theorem
- Errors are continuous (or are they?)
- Measurements change the state

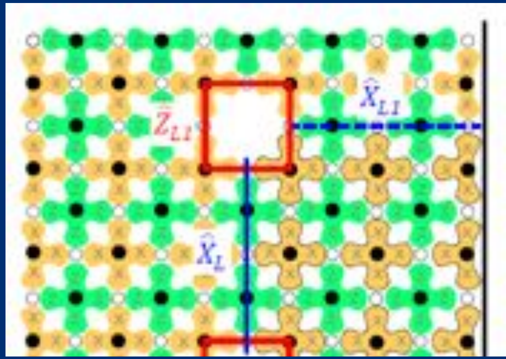
Thanks to Rob Schoelkopf

Different Error Correction Architectures

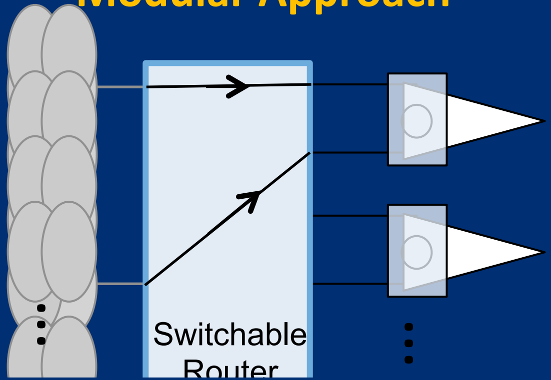
Standard QEC



Surface Code



Modular Approach



Overhead required in known schemes:

1,000 – 10,000 actual qubits for every logical!!

(+ concatenation!)

- threshold ~ 10^{-4}
- many ops., syndromes per QEC cycle

- threshold ~ 1%
- large system to see effects?

- good local gates (10^{-4}?) remote gates fair (90%?)
- then construct QEC as software layer?

Thanks to Rob Schoelkopf

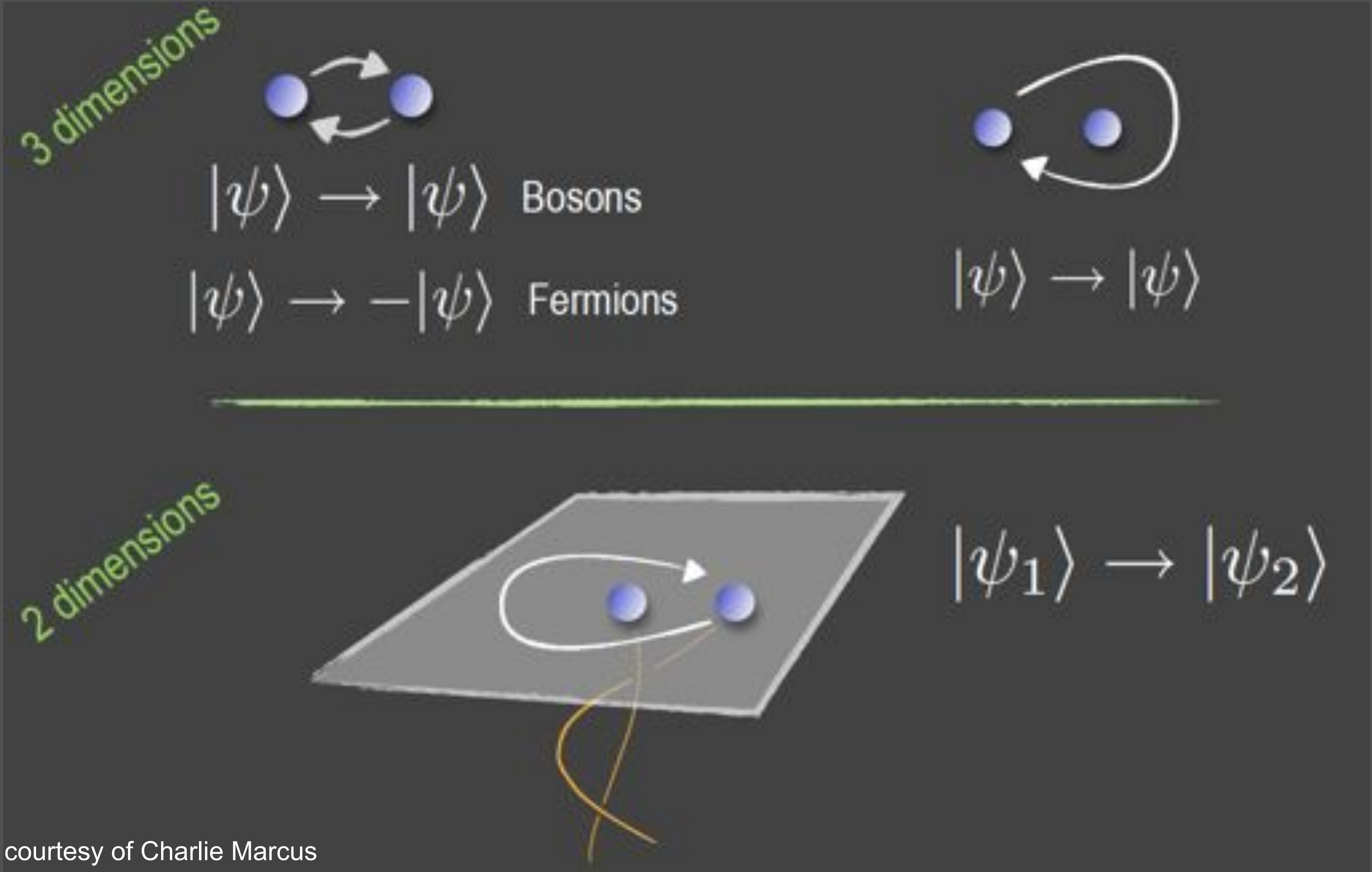


Image courtesy of Charlie Marcus

The man and his particle

Chi l'ha visto?

Ettore Majorana ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

1938

Image courtesy of Leo Kouwenhoven

Majorana fermions

(particle) $\gamma^\dagger = \gamma$ (anti-particle)

→ Electric charge is zero
→ Energy is zero
→ Everything is zero (except mass)

How to measure the "niks" particle?

→ That's why it was not yet detected!

Image courtesy of Leo Kouwenhoven

New directions in the pursuit of Majorana fermions in solid state systems

Jason Alicea[1]

[1] *Department of Physics and Astronomy, University of California, Irvine, California 92697*

(Dated: February 8, 2012)

Topology provides natural immunity to noise!

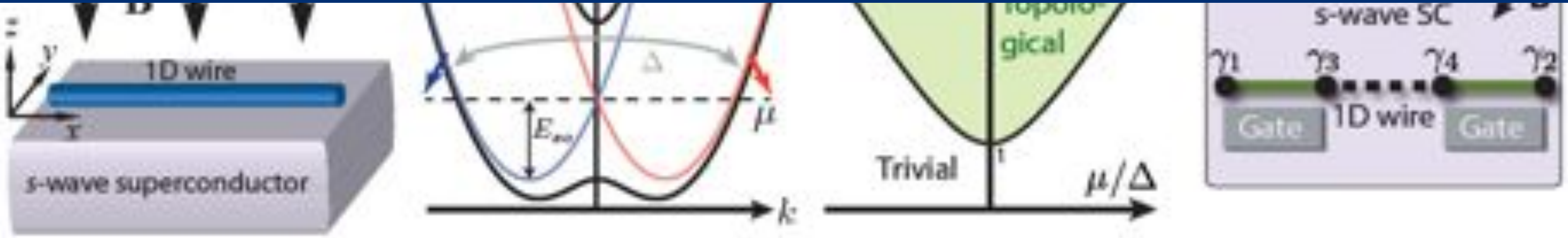


FIG. 6. (a) Basic architecture required to stabilize a topological superconducting state in a 1D spin-orbit-coupled wire. (b) Band structure for the wire when time-reversal symmetry is present (red and blue curves) and broken by a magnetic field (black curves). When the chemical potential lies within the field-induced gap at $k = 0$, the wire appears 'spinless'. Incorporating the pairing induced by the proximate superconductor leads to the phase diagram in (c). The endpoints of topological (green) segments of the wire host localized, zero-energy Majorana modes as shown in (d).

nature physics

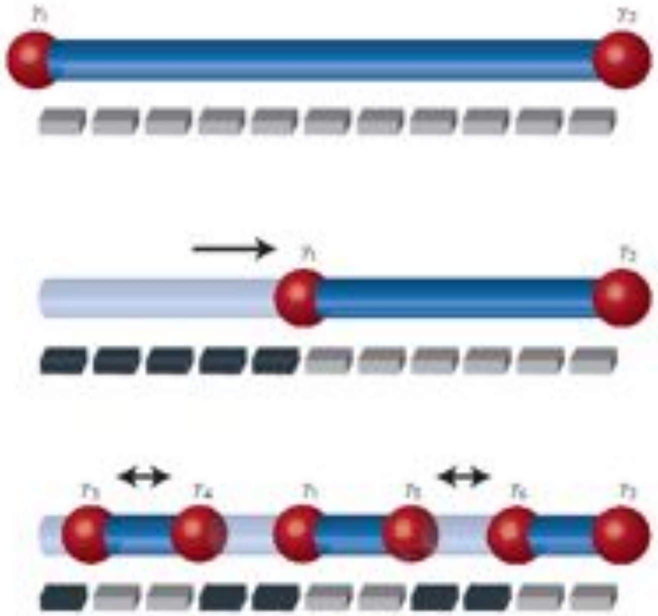
ARTICLES

PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI: 10.1038/NPHYS1915

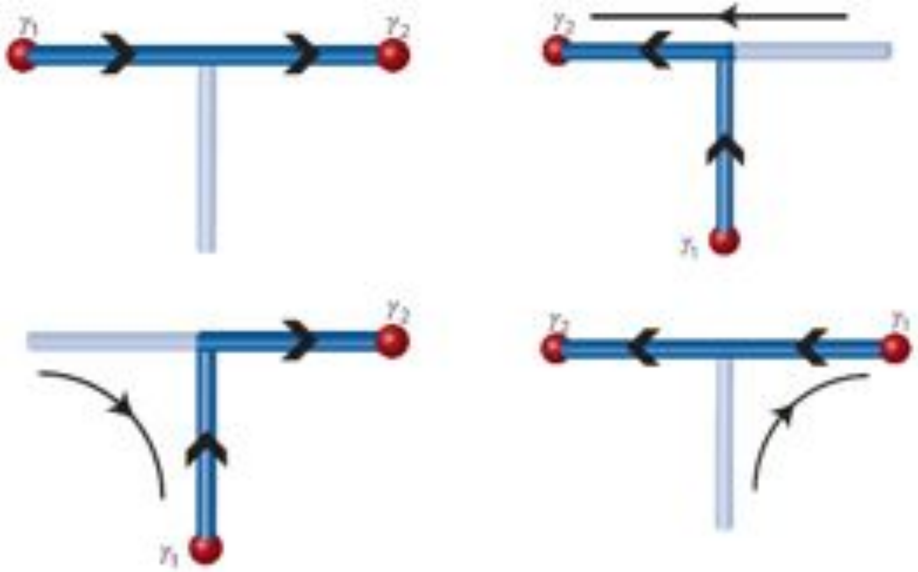
Non-Abelian statistics and topological quantum information processing in 1D wire networks

Jason Alicea[1]*, Yuval Oreg[2], Gil Refael[3], Felix von Oppen[4] and Matthew P. A. Fisher[3,5]

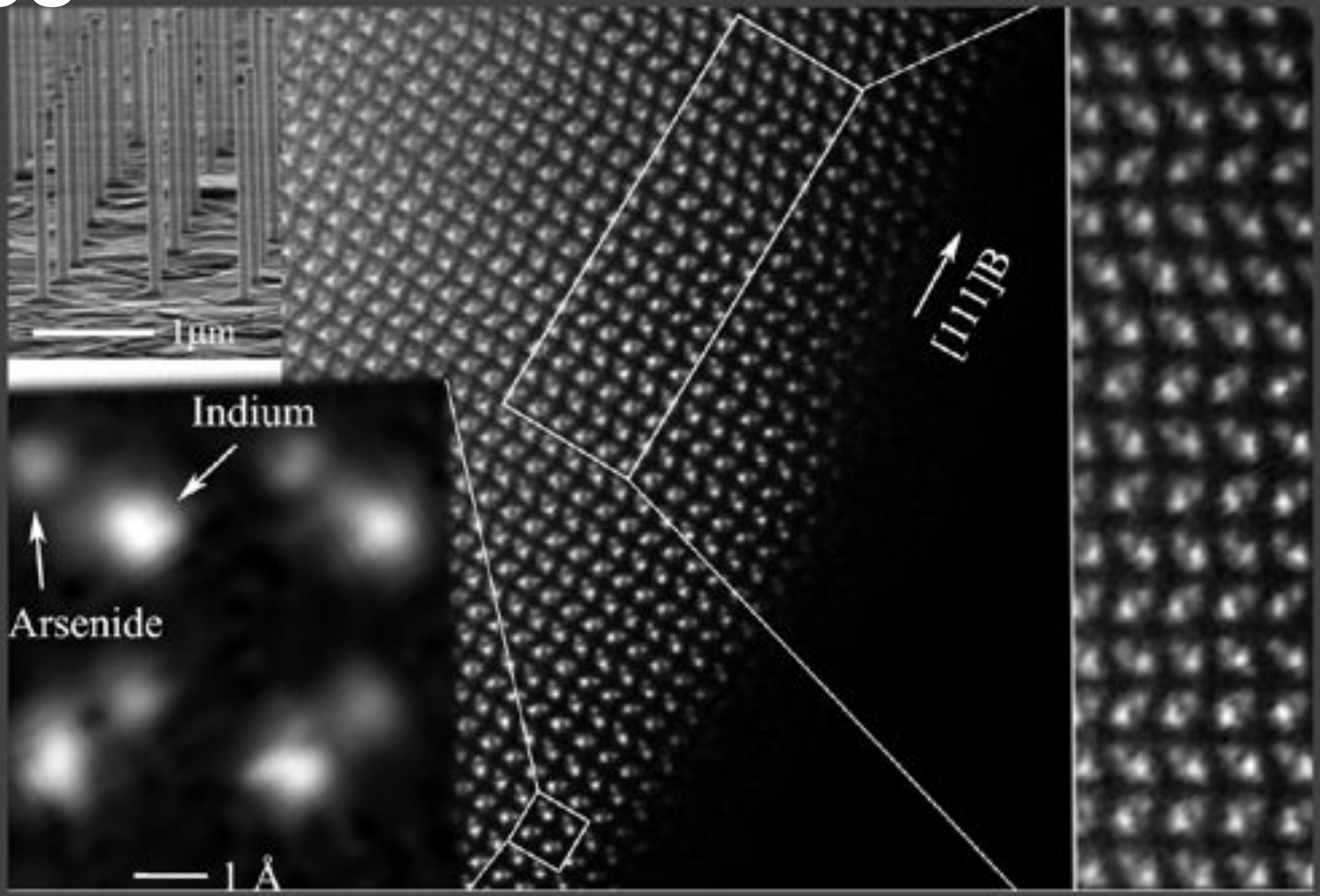
creation and movement



braiding



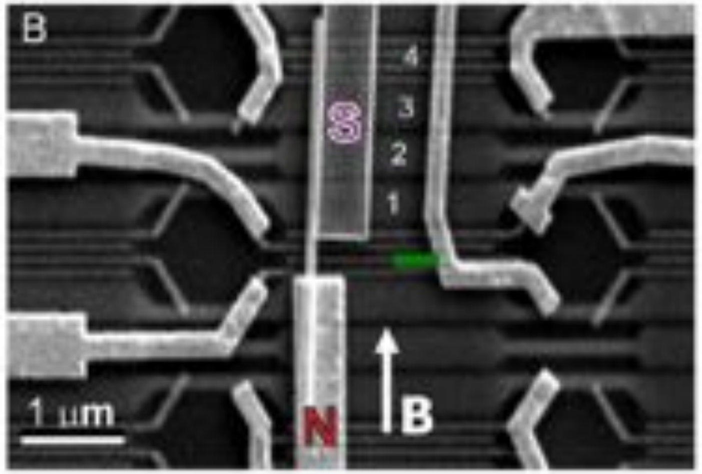
Epitaxial growth of InAs (or InSb) nanowires



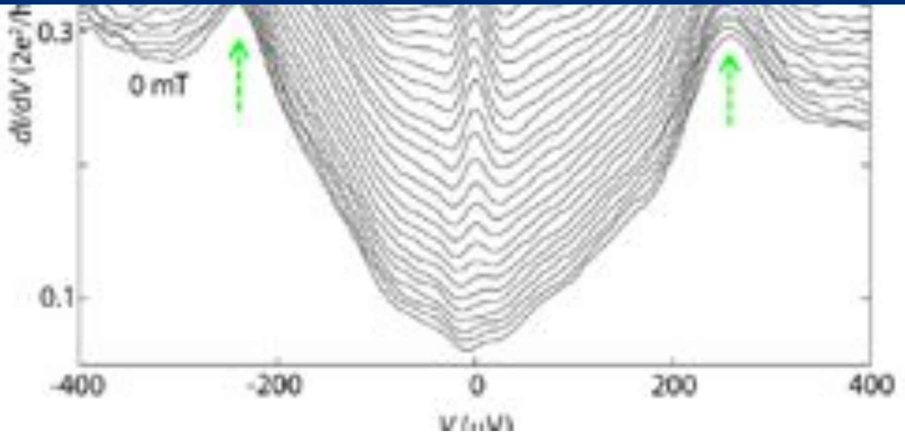
P. Krogstrup, J. Nygård, Univ. of Copenhagen

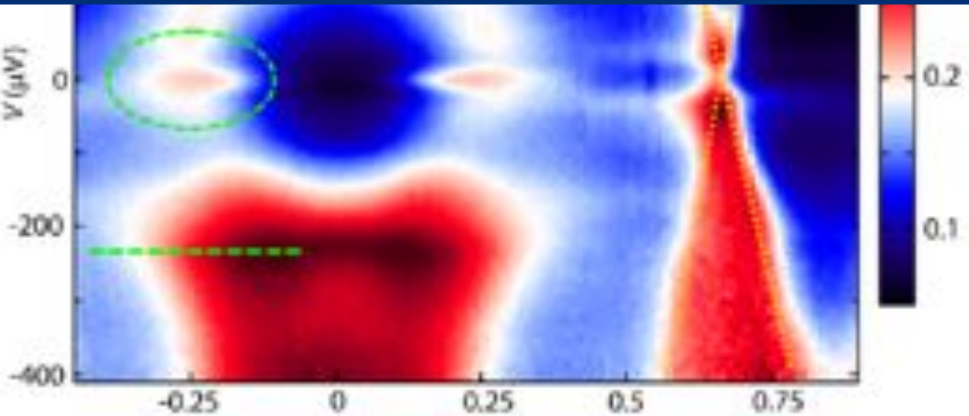
Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1*] K. Zuo,[1*] S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†



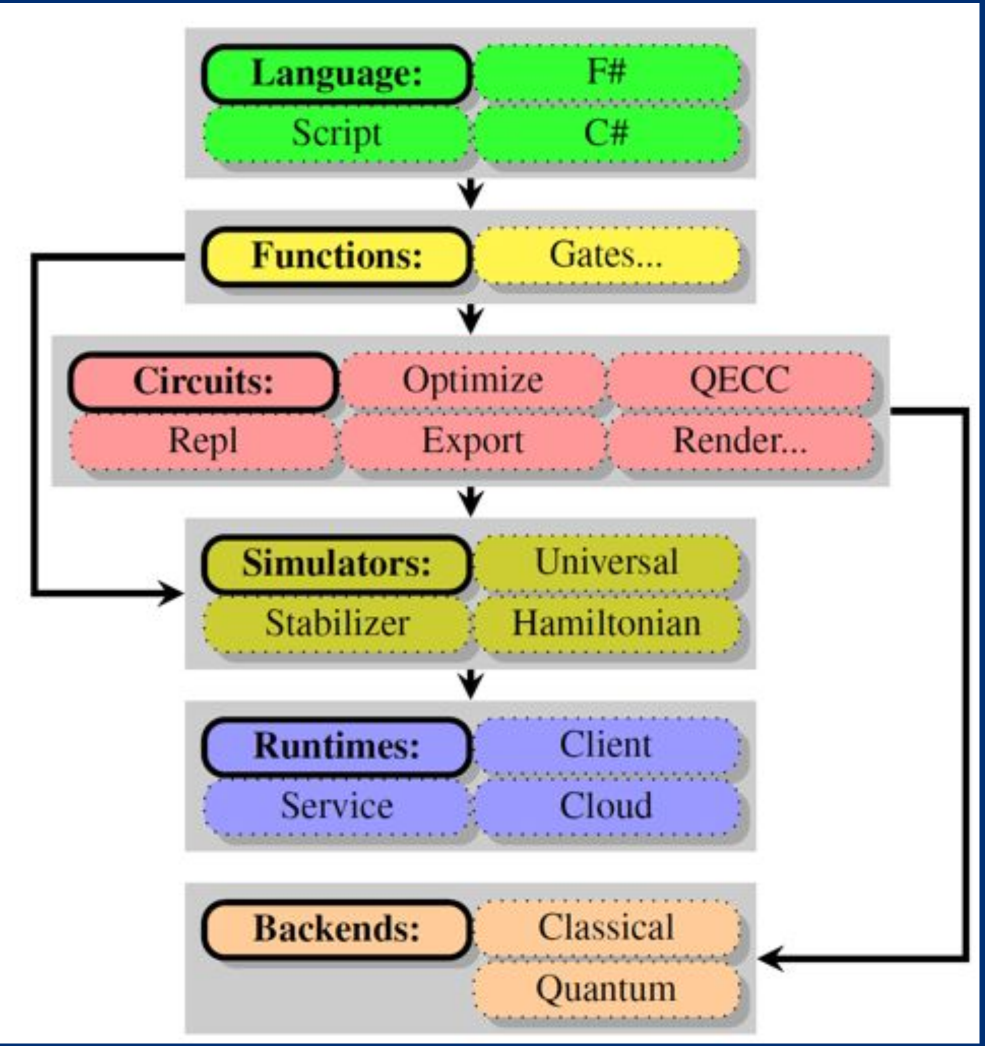
Hardware provides error correction: Only ~10-100s for every logical???





LIQ$Ui|\rangle$: Quantum Software Architecture

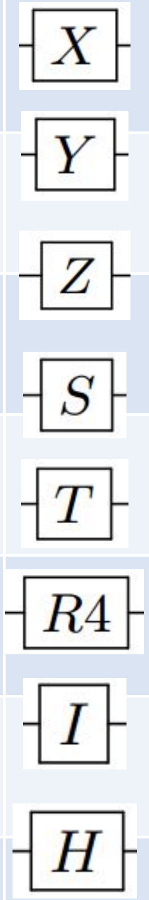
- Enables easy programming and simulation of complex quantum circuits
- Allows retargeting of circuits for various purposes: simulation, rendering, optimization, noise modeling, and export
- Provides state-of-the-art quantum circuit simulation tools

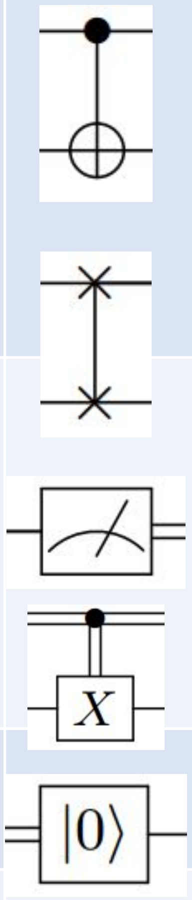


The LIQ$Ui|\rangle$ *platform*
[Wecker, Svore, 2014]

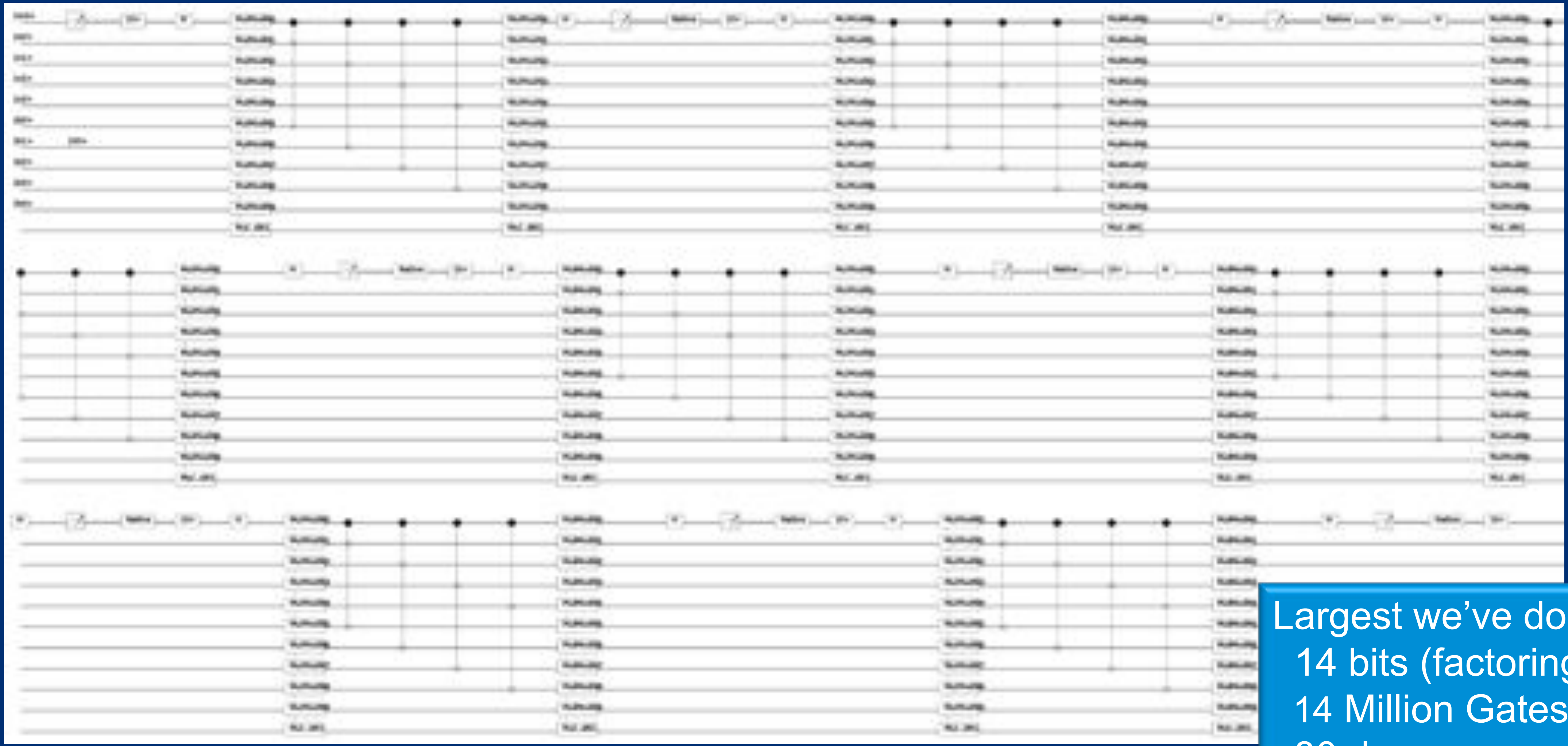
Quantum Gates

Evolution: $|\psi\uparrow' \rangle=U|\psi\rangle$, this may be realized by a Hamiltonian $H=\ln(U)\,/\Delta t$

Type	Basis	U	Name	Sym
Pauli	{|0⟩,|1⟩}	[■0&1@1&0]	X	
	{|0⟩,|1⟩}	[■0&−i@i&0]	Y	
Z Rotation	{|0⟩,|1⟩}	[■1&0@0&−1]	Z	
$e\uparrow i\pi/2$	{|0⟩,|1⟩}	[■1&0@0&i]	S	
	{|0⟩,|1⟩}	[■1&0@0&e↑iπ/4]	T	
	{|0⟩,|1⟩}	[■0&1@1&e↑iπ/8]	R4	
Identity	{|0⟩,|1⟩}	[■1&0@0&1]	I	
	{|0⟩,|	1/√2		

Type	Basis	U	Name	Sym
Controlled Not	{■|00⟩,|01⟩, |10⟩,|11⟩}	[■1&0&0&0@0&1&0&0@0&0&0&1@0&0&1&0]	CNOT (CX)	
	{■|00⟩,|01⟩, |10⟩,|11⟩}	[■1&0&0&0@0&0&1&0@0&1&0&0@0&0&0&1]	SWAP	
Measure	{|0⟩,|1⟩}	Qubit to Bit	M	
Binary Control	{|0⟩,|1⟩}	Conditional Application	BC	

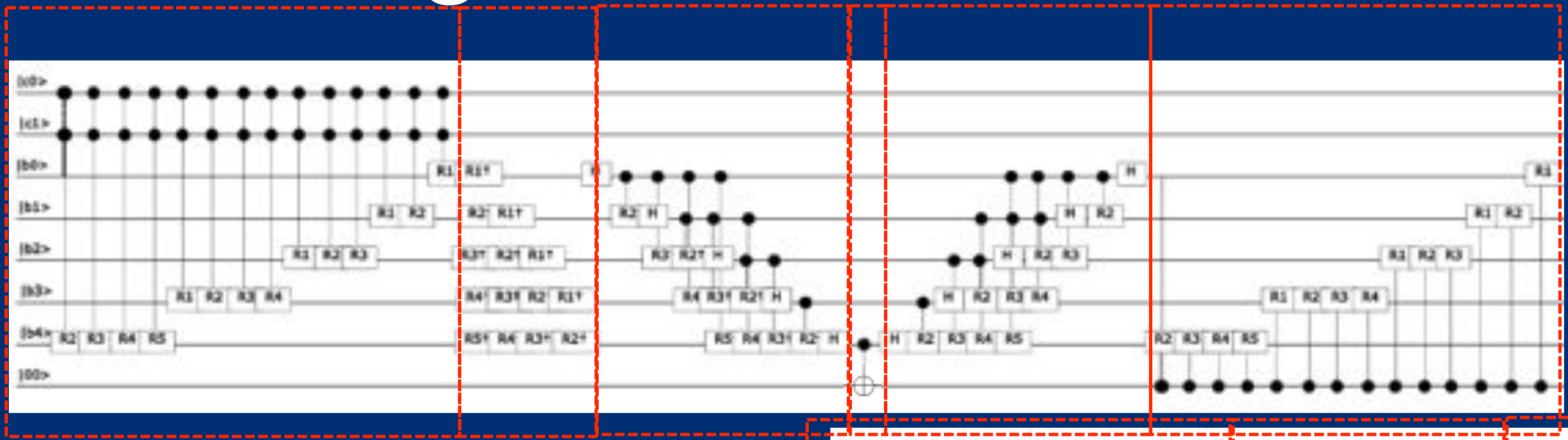
Shor’s algorithm: 4 bits ≅ 8200 gates

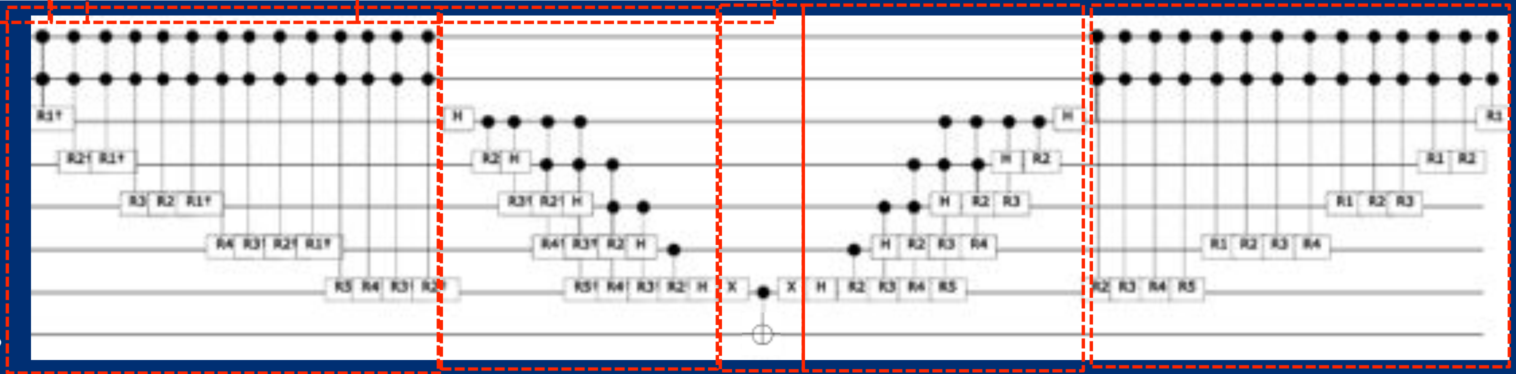


Circuit for Shor’s algorithm using 2n+3 qubits – Stéphane Beauregard

Largest we’ve done:
14 bits (factoring 8193)
14 Million Gates
30 days

Shor’s algorithm: Modular Adder

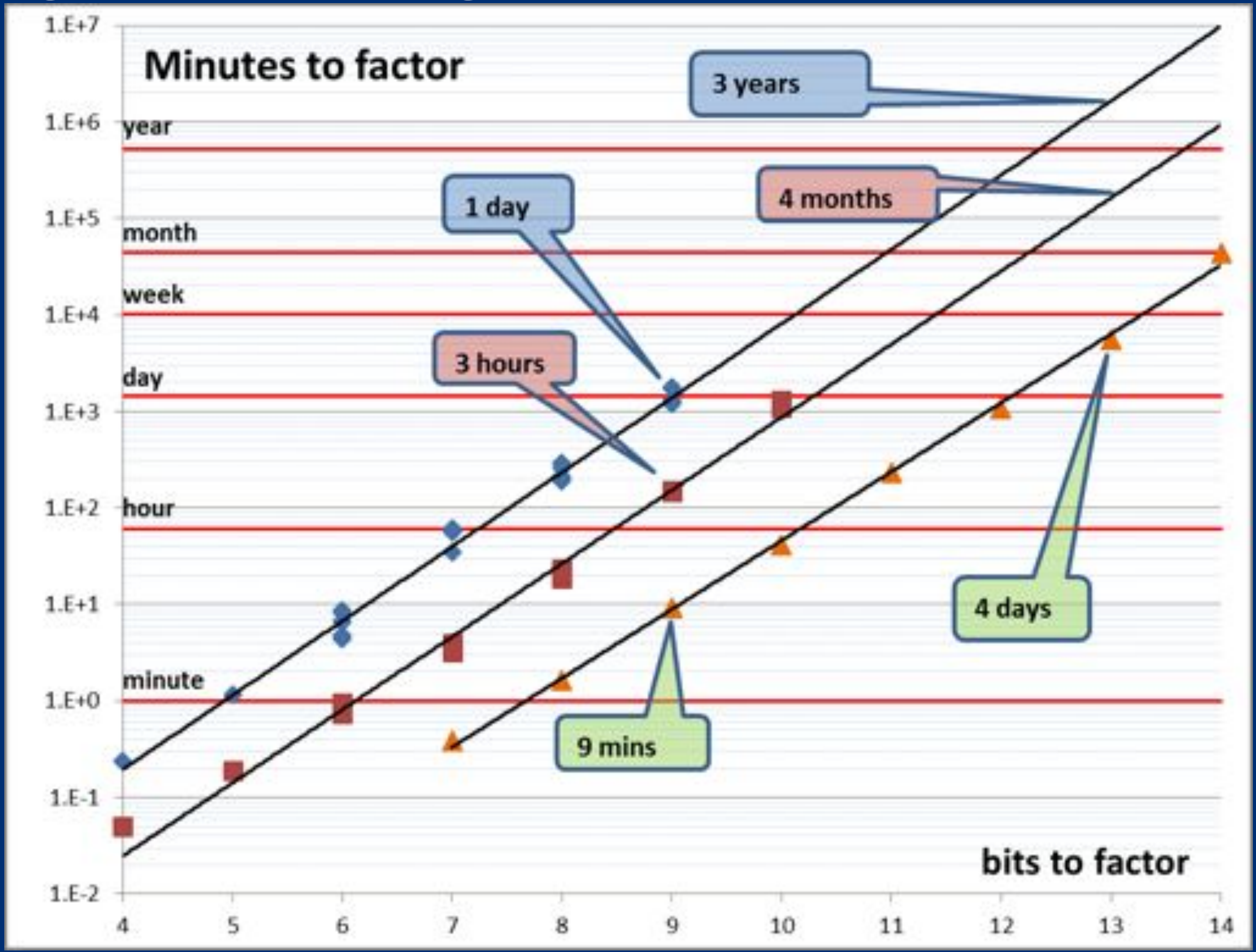




As defined in:
Circuit for Shor’s algorithm using 2n+3 qubits
– Stéphane Beauregard

```
let op (qs:Qubits) =
    CCAdd a cbs              // Add a to Φ|b⟩
    AddA' N bs               // Sub N from Φ|a+b⟩
    QFT' bs                  // Inverse QFT of Φ|a+b−N⟩
    CNOT [bMx;anc]           // Save top bit in Ancilla
    QFT bs                   // QFT of a+b-N
    CAddA N (anc :: bs)      // Add back N if negative
    CCAdd' a cbs             // Subtract a from Φ|a+b mod N⟩
    QFT' bs                  // Inverse QFT
    X [bMx]                  // Flip top bit
    CNOT [bMx;anc]           // Reset Ancilla to |0⟩
    X [bMx]                  // Flip top bit back
    QFT bs                   // QFT back
    CCAdd a cbs              // Finally get Φ|a+b mod N⟩
```

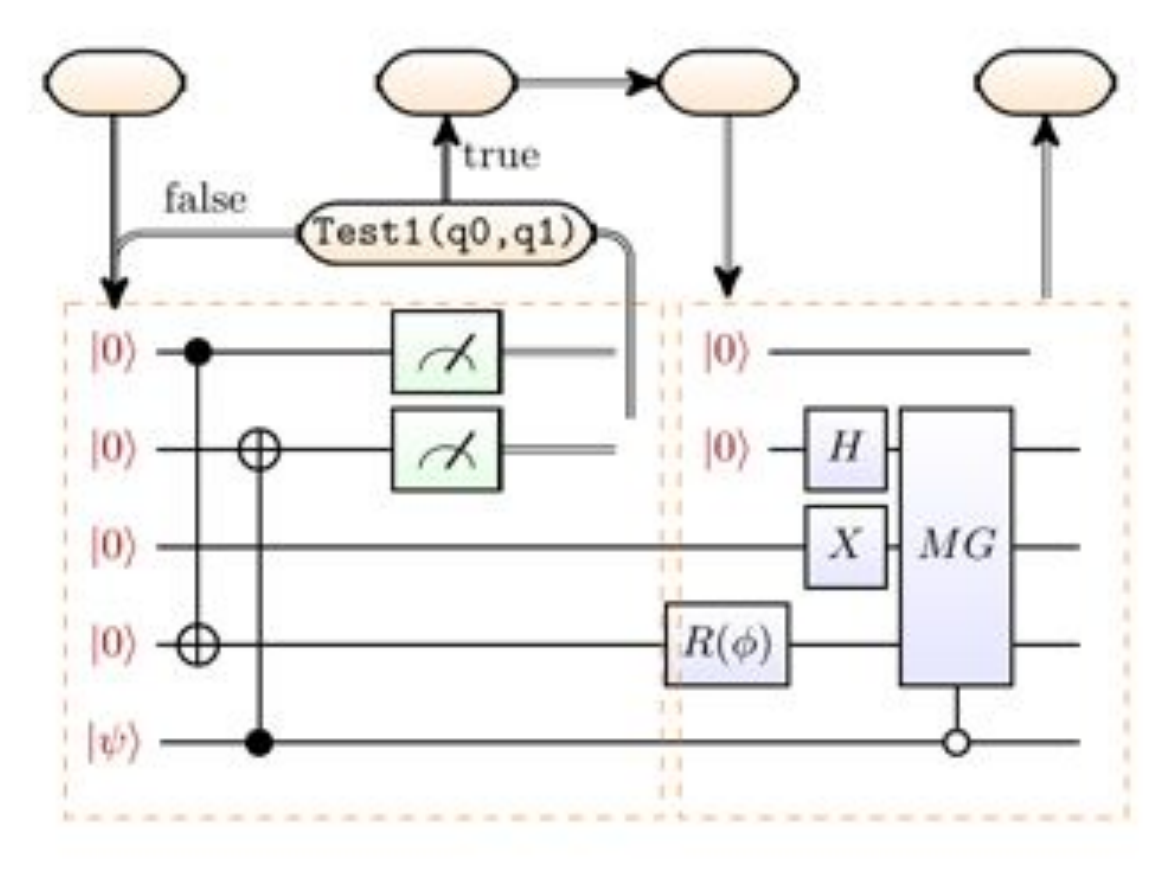
Simulating Shor's Algorithm



LIQ$Ui|\rangle$ for Compilation onto Hardware

```
let QFT (qs : Qs)
    let n = qs.Length - 1
    for i = 0 to n do
    let q = qs.[i]
    H q
    for j = (i + 1) to n do
        let theta = 2.0 * Math.PI /
        float(1 <<< (j - i + 1))
        CRz theta qs.[j] q
    for i = 0 to ((n - 1) / 2) do
    SWAP qs.[i] qs.[n - i]

let QftOp  = compile QFT
let QftOp' = adjoint QftOp
```

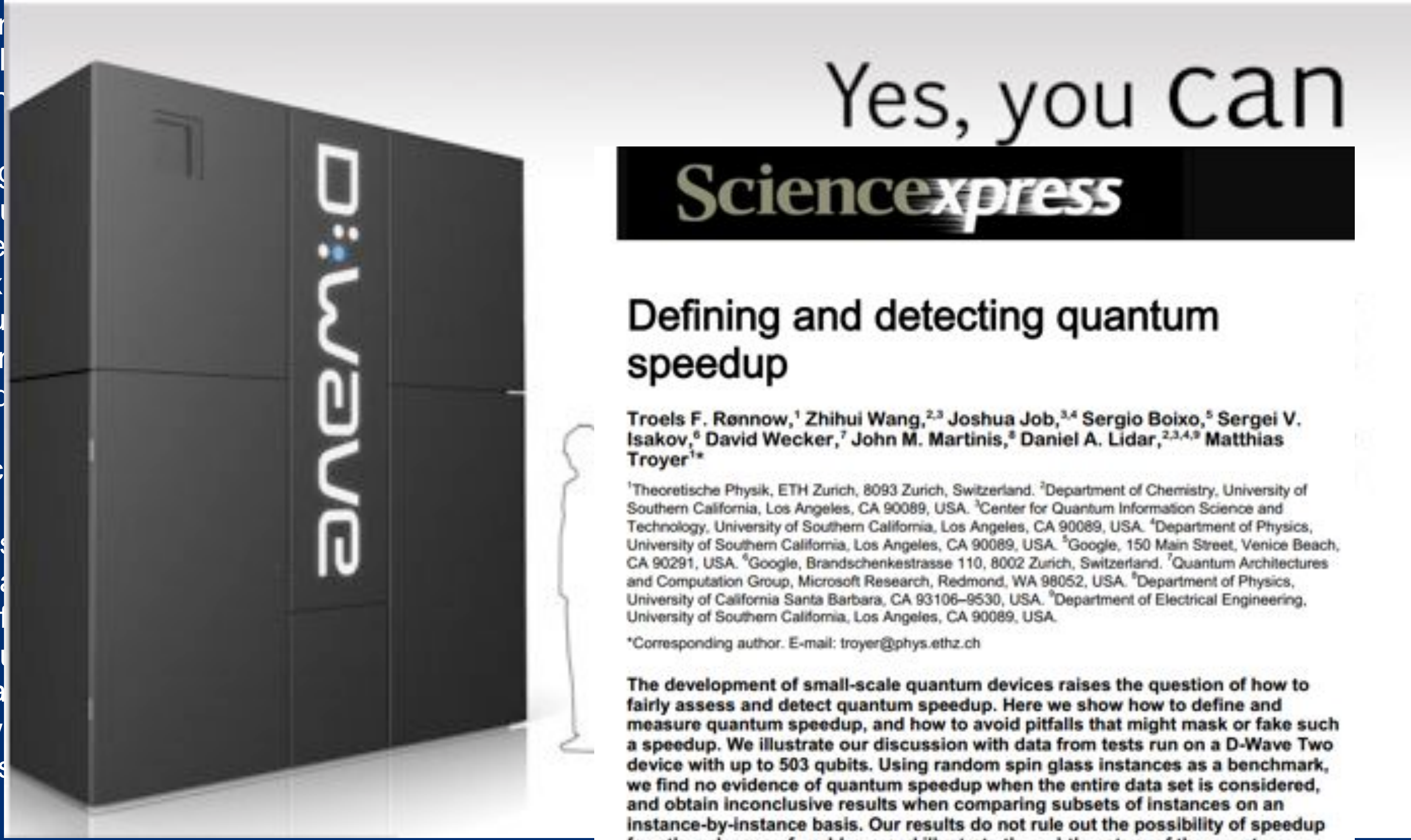


Spin-Glass Models

$H(t)=\Gamma(t)\sum_{i=1}^{N}\Delta_i\,\sigma_i^x+\Lambda(t)(\sum_{i=1}^{N}h_i\,\sigma$

Quantum annealir
Sergio Boixo, Troel
David Wecker, Dan

Quantum technolog
devices, such as qu
random number ge
with capabilities ex
annealer, in particu
evolving a known ir
towards the ground
problem. Here, we
D-Wave One devic
strong correlations
annealer, in contras
and classical annea
that the device perf
evidence for quant
level crossings cha
computational pow
classical algorithms



Sciencexpress

Defining and detecting quantum speedup

Troels F. Rønnow,[1] Zhihui Wang,[2,3] Joshua Job,[3,4] Sergio Boixo,[5] Sergei V. Isakov,[6] David Wecker,[7] John M. Martinis,[8] Daniel A. Lidar,[2,3,4,9] Matthias Troyer[1*]

[1]Theoretische Physik, ETH Zurich, 8093 Zurich, Switzerland. [2]Department of Chemistry, University of Southern California, Los Angeles, CA 90089, USA. [3]Center for Quantum Information Science and Technology, University of Southern California, Los Angeles, CA 90089, USA. [4]Department of Physics, University of Southern California, Los Angeles, CA 90089, USA. [5]Google, 150 Main Street, Venice Beach, CA 90291, USA. [6]Google, Brandschenkestrasse 110, 8002 Zurich, Switzerland. [7]Quantum Architectures and Computation Group, Microsoft Research, Redmond, WA 98052, USA. [8]Department of Physics, University of California Santa Barbara, CA 93106–9530, USA. [9]Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA.

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The development of small-scale quantum devices raises the question of how to fairly assess and detect quantum speedup. Here we show how to define and measure quantum speedup, and how to avoid pitfalls that might mask or fake such a speedup. We illustrate our discussion with data from tests run on a D-Wave Two device with up to 503 qubits. Using random spin glass instances as a benchmark, we find no evidence of quantum speedup when the entire data set is considered, and obtain inconclusive results when comparing subsets of instances on an instance-by-instance basis. Our results do not rule out the possibility of speedup for other classes of problems and illustrate the subtle nature of the quantum speedup question.

F. Rønnow, Zhihui
David Wecker, John

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posed.

401.2910

Conclusions

Quantum computers exploit interference and superposition to solve problems.

How big/fast does a quantum computer have to be to have an advantage?

[Boixo, Ronnow et al ’13]
[Wecker, Bauer et al ’14]

What are the right questions to ask a quantum computer?

[Wiebe, Braun, Lloyd ’12]
[Wiebe, Grenade et al ‘13]

Exponential speedups for *certain* simulation, cryptography, linear algebra problems.

How do you compile, test, and debug quantum algorithms?

[Wiebe, Kliuchnikov’13]
[Bocharov, Gurevich, Svore’13]
[Wecker, Svore Geller’ 14]

What other problems does a quantum computer solve better or faster?

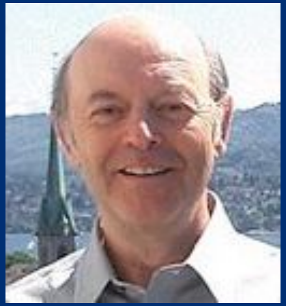
QuArC

Doug Carmean

Vadym Klichnikov

Alex Bocharov

Yuri Gurevich



Alan Geller

Dave Wecker

Krysta Svore

Ken Reneris

Martin Roetteler

Burton Smith

Nathan Wiebe

Station Q

Maissam Barkeshli

Michael Freedman

Chetan Nayak

Bela Bauer

Matthew Hastings

Kevin Walker

Parsa Bonderson

Roman Lutchyn

Zhenghan Wang

Meng Cheng

Mike Mulligan

Jon Yard

University Partners

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Reilly
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NBI

Leo
Kouwenhoven
Delft

Amir
Yacoby
Harvard

Dale
Van Harlingen
UIUC

Mike
Manfra
Purdue

Chris
Palmstrom
UCSB

Bert
Halperin
Harvard

Sankar
Das Sarma
U Maryland

Matthias
Troyer
ETH Zurich

Outlook

Training of students

Encourage more funding

Need research at all levels and in many areas

Support of quantum computing as "quantum computer science"

Not just as physics

Field is becoming a merging and now entering age to be treated as a computer science

We have qubits, we have algorithms, now we need the computer science and corresponding software infrastructure

Need more students in quantum algorthms --- appification of quantum computing!

http://research.microsoft.com/groups/quarc/

http://research.microsoft.com/en-us/labs/stationq/

ksvore@microsoft.com