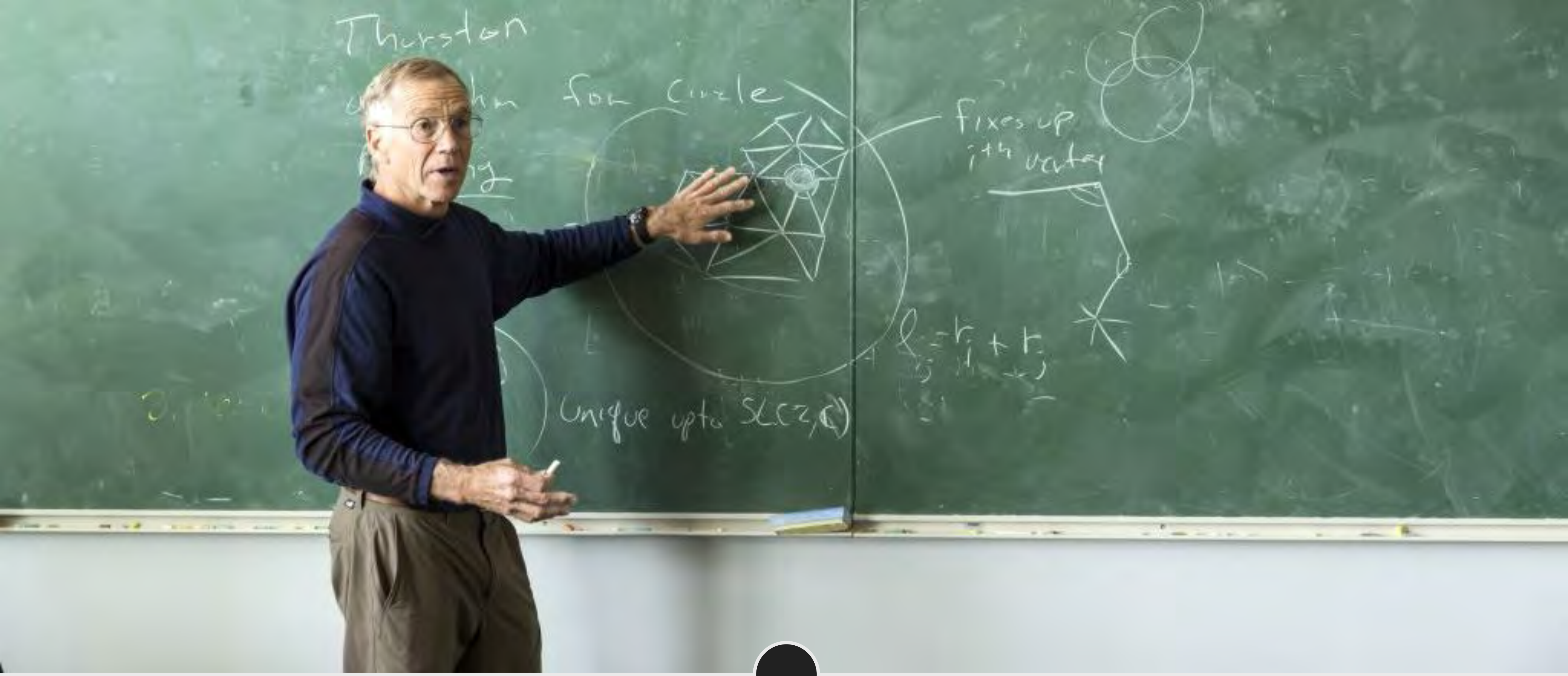
Quantum Computing at Microsoft

Dave Wecker

Microsoft


HOW'S YOUR QUANTUM COMPUTER PROTOTYPE COMING ALONG?
GREAT!
THE PROJECT EXISTS IN A SIMULTANEOUS STATE OF BEING BOTH TOTALLY SUCCESSFUL AND NOT EVEN STARTED.
CAN I OBSERVE IT?
THAT'S A TRICKY QUESTION.
Dilbert.com DilbertCartoonist@gmail.com
4-17-12 ©2012 Scott Adams, Inc./Dist. by Universal Uclick



2000

STATION Q

2006

"MAJORANA PARTICLE GLIMPSED IN LAB."

BBC NEWS

2012

Bits

Microsoft Spends Big to Build a Computer Straight Out of Science Fiction

By JOHN MARKOFF

SAN FRANCISCO — Microsoft is putting its considerable financial and engineering muscle into the experimental field of quantum computing as it works to build a machine that could tackle problems beyond the reach of today's digital computers.

There is a growing optimism in the tech world that quantum computers, superpowerful devices that were once the stuff of science fiction, are possible — and may even be practical. If these machines work, they will have an impact on work in areas such as drug design and artificial intelligence, as well as offer a better understanding of the foundations of modern physics.

Microsoft's decision to move from pure research to an expensive effort to build a working prototype underscores a global competition among technology companies, including Google and IBM, which are also making significant investments in search of breakthroughs.

In the exotic world of quantum physics, Microsoft has set itself apart from its competitors by hoosing a different path. The mpany's approach is based on raiding" particles known as ons — which physicists dee as existing in just two disions — to form the building s of a supercomputer that exploit the unusual physierties of subatomic parti-

edge that barriers still remain to building useful quantum machines, both at the level of basic physics and in developing new kinds of software to exploit certain qualities of devices known as qubits that hold out the possibility of computing in ways not possible for today's digital systems.

Unlike conventional transistors, which can be only on or off at any one time, representing a digital 1 or 0, qubits can exist in superposition, or simultaneously in both states. If qubits are placed in an "entangled" state — physically separated but acting as though they are deeply intertwined — with many other qubits, they can represent a vast number of values simultaneously. A quantum computer would most likely consist of hundred or thousands of qubits.

Planning a prototype of a superpowerful quantum computer.

Microsoft began funding research in the field in 2005 when it quietly set up a laboratory known as Station Q under the leadership of the mathematician Michael Freedman.

Microsoft now believes that it is close enough to designing the basic qubit building block that the compan

Todd Holmdahl, a veteran engineering manager who will direct the Microsoft effort. Over the years, he has led various Microsoft projects, including its Xbox video game machine and the yet-to-be-released HoloLens augmented reality system.

"Once we get the first qubit figured out, we have a road map that allows us to go to thousands of qubits in a rather straightforward way," Mr. Holmdahl said.

There is still a debate among physicists and computer scientists over whether quantum computers that perform useful calculations will ever be created.

A variety of alternative research programs are trying to create qubits using different materials and designs. The Microsoft approach, known as topological quantum computing, is based on a field that took on new energy when this year's Nobel Prize in Physics was awarded to three scientists who had done fundamental work in forms of matter that may exist in just two dimensions.

Mr. Holmdahl's project will also include the physicists Leo Kouwenhoven of Delft University, Charles M. Marcus of the University of Copenhagen, David Reilly of the University of Sydney and Matthias Troyer of E.T.H. Zurich.

They will all become Microsoft employees as part of the Artificial Intelligence and Research Group that Microsoft recently created under the leadership of one of its top technical

IAN C. BATES FOR THE NEW YORK TIMES

Todd Holmdahl, who has led Microsoft projects like the Xbox gaming console, will direct the quantum computing efforts.

cists say the decision to try to build a topological

confidence that the compan

and superconductors," Dr. Marcus said. The researchers recently made a "remarkable breakthrough" in their ability to control the materials used to form qubits, he said. Most of the competing approaches involve cooling quantum computers to near absolute zero temperatures.

So far, there are relatively few proven algorithms that could be used to solve problems more quickly than today's digital computers. One early effort, known as Shor's algorithm, would be used to factor numbers, giving hope that quantum computers might be used in the future for breaking codes.

That would potentially have world-shaking consequences because modern electronic commerce is built on cryptographic systems that are largely unbreakable using conventional digital computers. Other proposed approaches might allow faster searching of databases or perform machine learning algorithms, which are being used to make advances in computer vision and speech recognition.

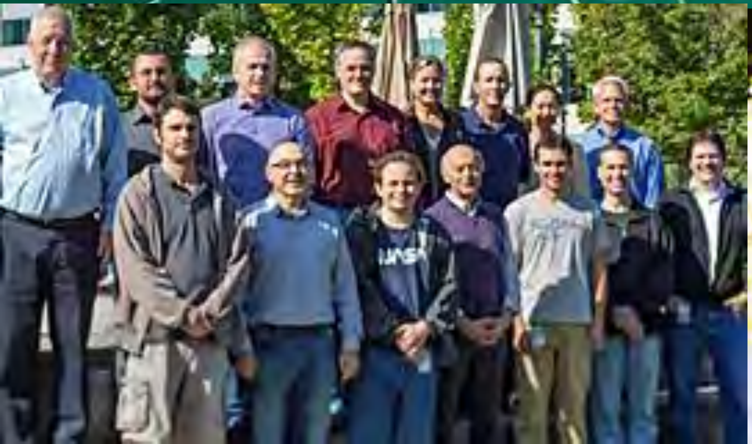
More immediately, however, these tools might advance the basic understanding of physics, a possibility the physicist Richard P. Feynman mentioned when he speculated about the idea of a quantum computer in 198

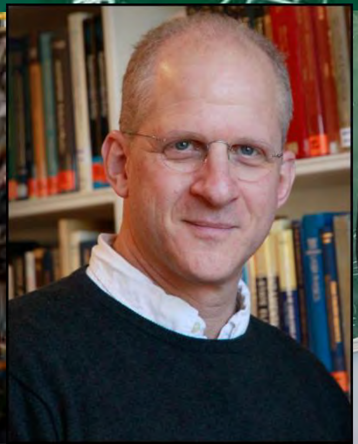
STATION

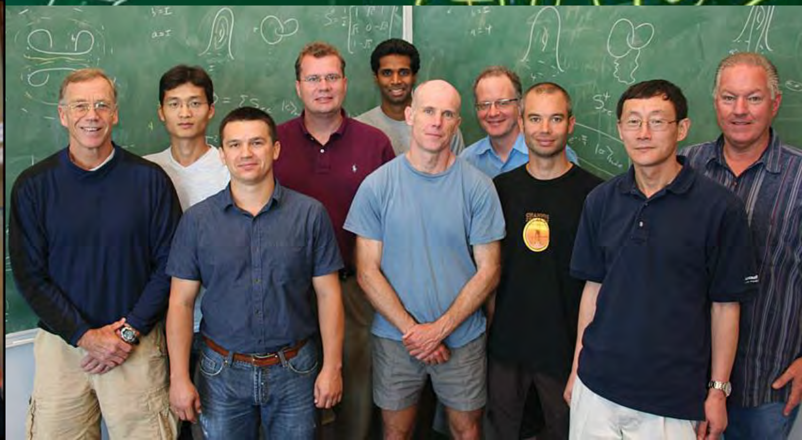
Q

www.microsoft.stationq.com

REDMOND SYDNEY, DELFT, COPENHAGEN SANTA BARBARA



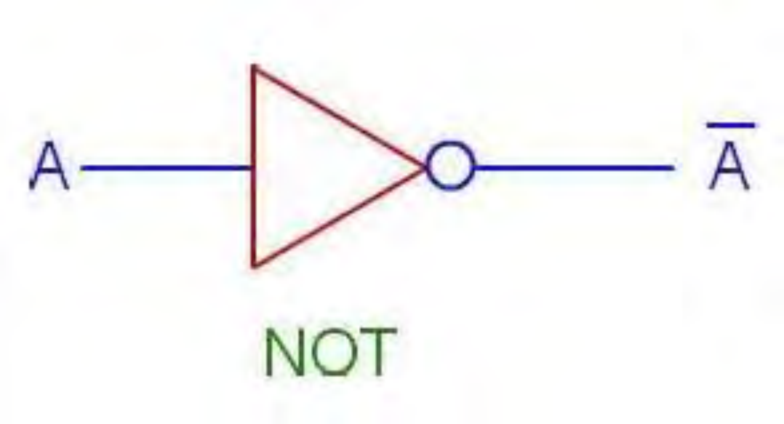




Classical vs. Quantum Computing

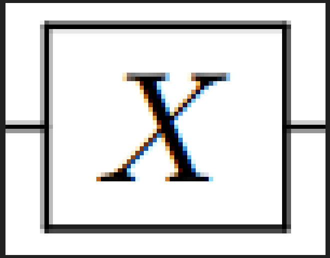
Basic unit: **bit** = 0 or 1

Computing: **logical** operation



Basic unit: **qubit** = unit vector $\alpha|0\rangle + \beta|1\rangle$

Computing: **unitary** operation



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

Classical vs. Quantum Computing

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

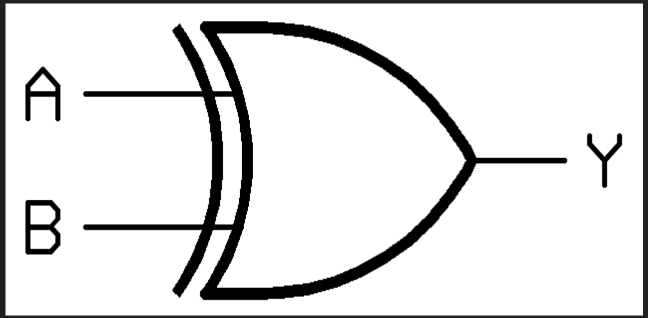
Computing: **logical** operation

Description: **truth table**

Basic unit: **qubit** = unit vector $\alpha|0\rangle + \beta|1\rangle$

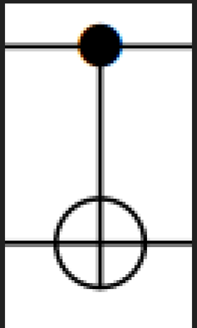
Computing: **unitary** operation

Description: **unitary matrix**



XOR gate

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



CNOT gate

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

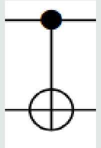
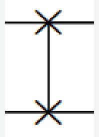
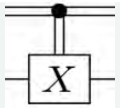
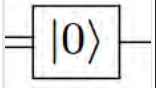
Classical vs. Quantum Computing

Basic unit: **bit** = 0 or 1	Basic unit: **qubit** = unit vector $\alpha\|0\rangle + \beta\|1\rangle$
Computing: **logical** operation	Computing: **unitary** operation
Description: **truth table**	Description: **unitary** matrix
Direction: Most gates only run forward	Direction: Most gates are reversible (matrices)
Copying: Independent copies are easy	Copying: Independent copies are impossible
Noise: Manageable with minimal ECC	Noise: Difficult to overcome. Sophisticated QECC
Storage: n bits hold 1 value from 0 to $2^n - 1$	Storage: n qubits can hold 2^n values
Input/Output: Linear	Input/Output: sub-Linear
Computation: An n-bit ALU performs 1 operation	Computation: An n-qubit ALU performs 2^n operations

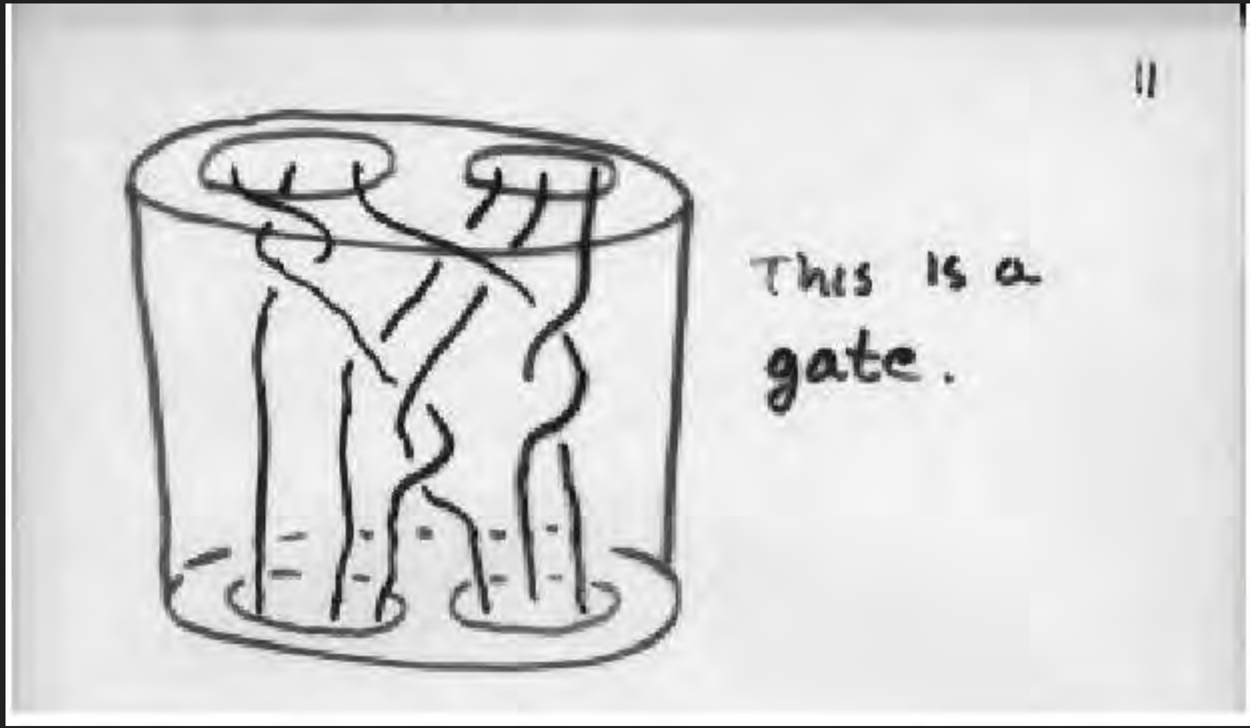
Quantum Gates

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

Type	Basis	U	Nam e	Sym
Pauli	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$	X	X
	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$	Y	Y
Z Rotation	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$	Z	Z
$e^{i\pi/2}$	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$	S	S
	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$	T	T
	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}0 & 1\\1 & e^{i\pi/8}\end{bmatrix}$	R4	$R4$
Identity	$\{\|0\rangle, \|1\rangle\}$	$\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$	I	I
Hadamar d	$\{\|0\rangle, \|1\rangle\}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$	H	H

Type	Basis	U	Nam e	Sym
Controlled Not	$\left\{\begin{matrix}\|00\rangle, \|01\rangle,\\ \|10\rangle, \|11\rangle\end{matrix}\right\}$	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$	CNOT (CX)	
	$\left\{\begin{matrix}\|00\rangle, \|01\rangle,\\ \|10\rangle, \|11\rangle\end{matrix}\right\}$	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 0 & 1 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\end{bmatrix}$	SWAP	
Measure	$\{\|0\rangle, \|1\rangle\}$	Qubit to Bit	M	
Binary Control	$\{\|0\rangle, \|1\rangle\}$	Conditional Application	BC	
Restore	$\{\|0\rangle, \|1\rangle\}$	Bit to Qubit	Reset	

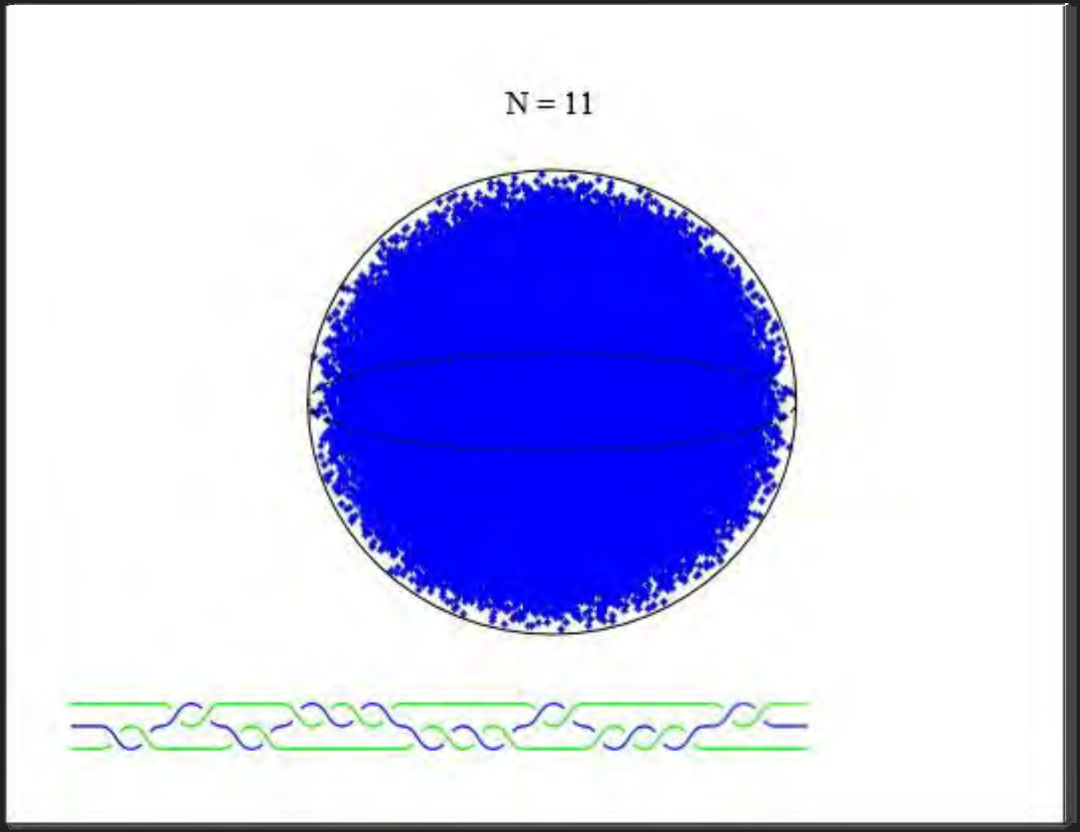
Inspiration



From "A topological modular functor which is universal for quantum computation"

Talk given by Michael Freedman at "Mathematics of Quantum Computation", MSRI, Feb. 2000 (available online).

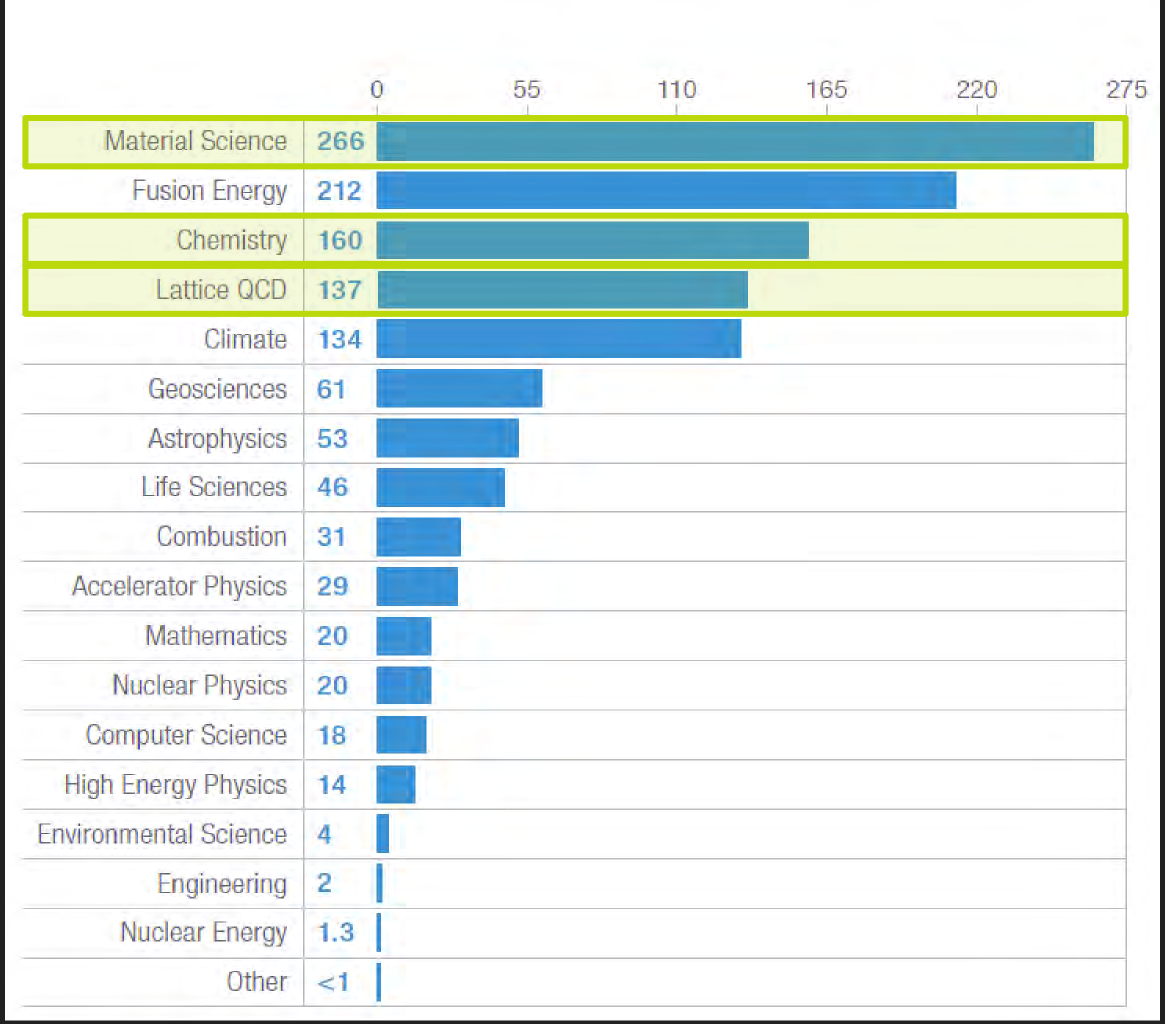
Braiding



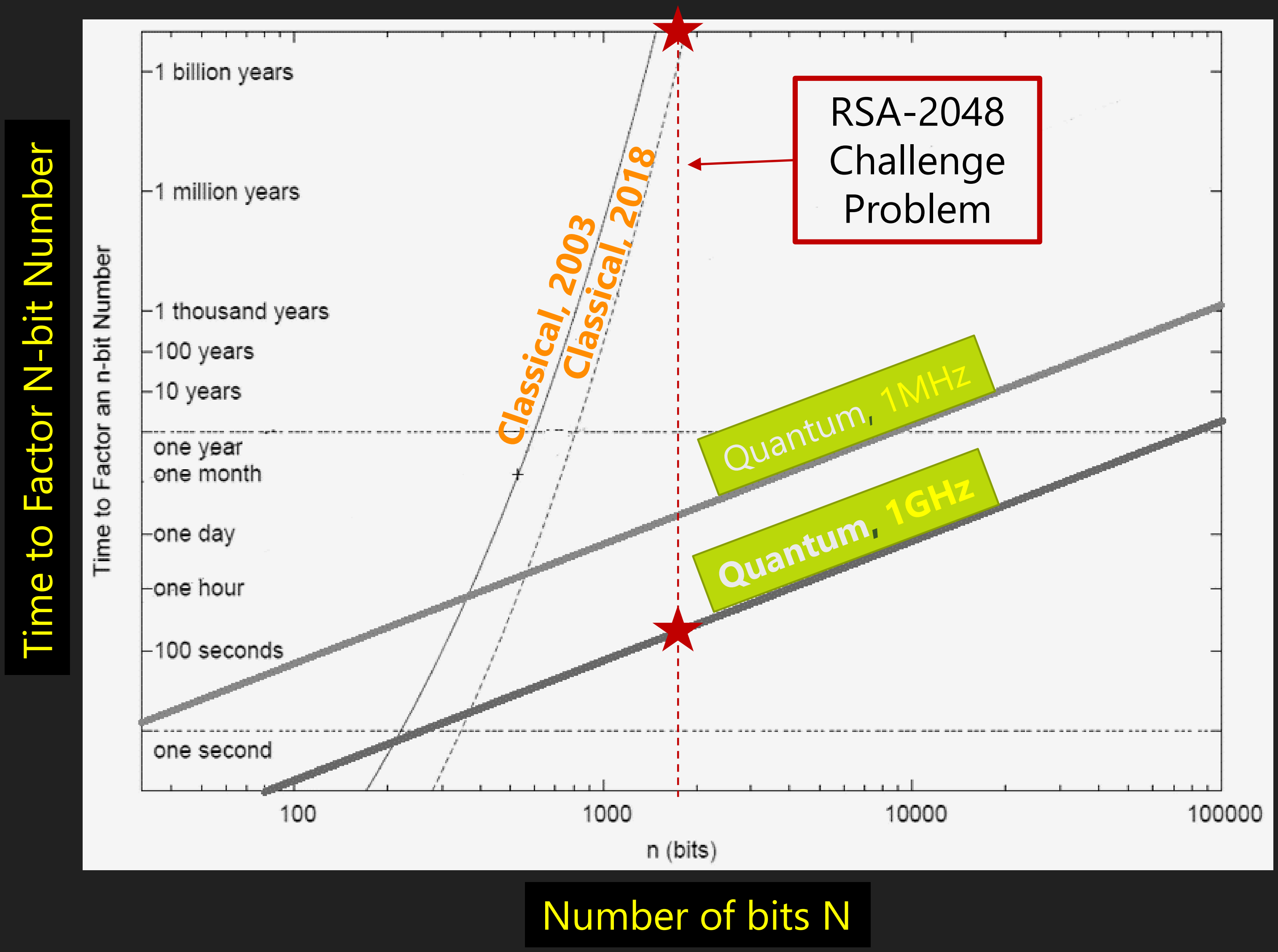
From: Nick Bonesteel talk at KITP UCSB

Simulating physical systems

Hours (on Cray XE6)



Breaking RSA



Initial applications

Nitrogen fixation

100-200 qubits

Carbon capture

100-200 qubits

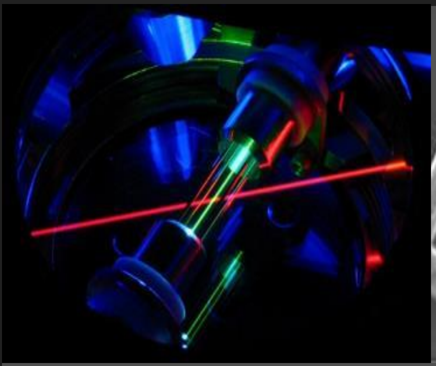
Materials science

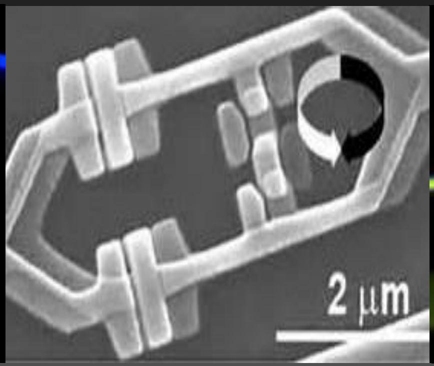
100s-1000s qubits

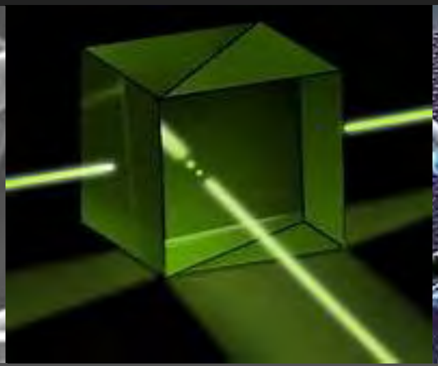
Machine learning

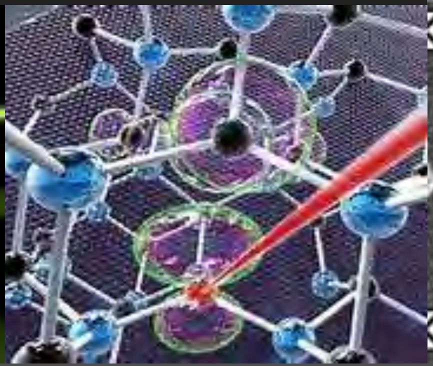
100s-1000s qubits

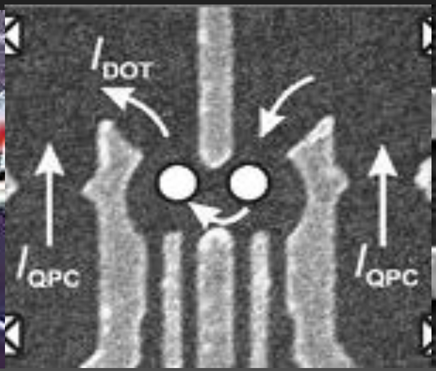
Quantum hardware technologies

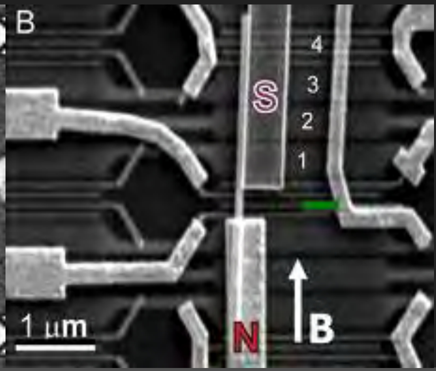












Ion traps

Super-conductors

Linear optics

NV centers

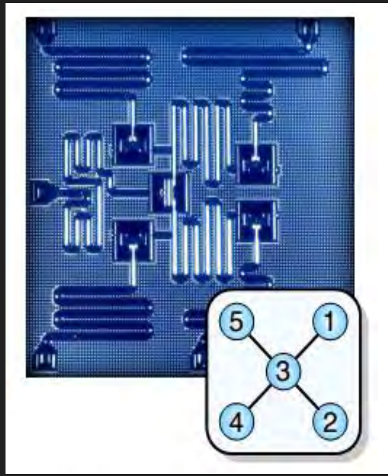
Quantum dots

Topological

Comparing quantum architectures

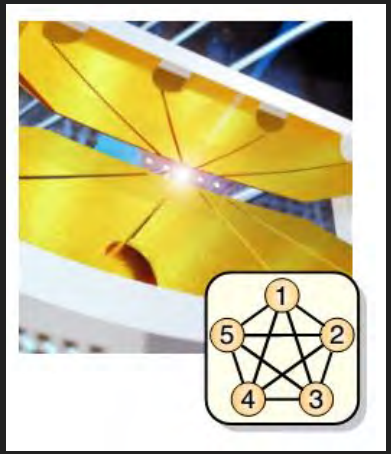
IBM sc system

- five transmon qubits: JJ charge states, shunt capacitors, low sensitivity to charge noise
- Qubits are connected by microwave resonators
- Automatic calibration, twice a day
- Qubits drift between calibrations
- Addressing: qubit freqs around 5-5.4 GHz (all different)
- Fidelities:
  - Single qubit readout ~96%
  - Single qubit gate ~99.7%
  - Two-qubit gate ~96.5%
- Gate times:
  - Single qubit: ~130 ns
  - Two qubit ~250-450 ns
- Decoherence times:
  - $T_1 \sim 60\ \mu s$
  - T_2^* about equal to T_1
- Native gate set:
  - CNOTs (ECR ZX-90), constrained to star shape
  - Single qubit: Pauli, H, S, T



UMD ion trap system

- five $^{171}Yb^+$ ions: hyperfine states, low sensitivity to B field, linear Paul trap, laser cooled to motional ground state
- Qubits are connected through pairs of Raman beams
- Manual calibration, 2 post-docs, 3 grad students
- Almost no drift between calibrations
- Addressing: qubit freqs = 12.642821 GHz (all the same)
- Fidelities:
  - Single qubit readout ~99.4%
  - Single qubit gate ~99.1%
  - Two-qubit gate ~97.0%
- Gate times:
  - Single qubit: ~20 μs
  - Two qubit ~250 μs
- Decoherence times:
  - $T_1 \sim$ several hours
  - $T_2^* \sim 0.5$ s
- Native gate set:
  - XX(χ) gate (Molmer-Sorensen) on any pair
  - Single qubit: any rotation



[Monroe et al., 2017 arXiv:1702.01852]

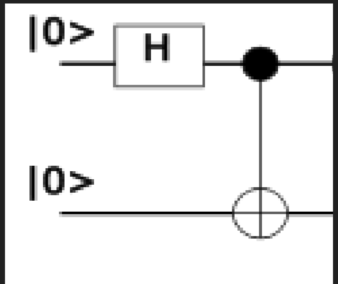
Qubit Technologies

Realizations	Lifetimes	Gate Speed	ECC cost
Topological (Majorana)	1 minute	Nanoseconds	$\mathbf{10^1}$
Flux Qubit	$/\ 10^{10}$	same	$10^3 - 10^4$
Charge Qubit	$/\ 10^{10}$	same	$10^3 - 10^4$
Transmon	$/\ 10^7$	same	$10^3 - 10^4$
Ion Trap	$/\ 10^2$	10^3 slower	$10^3 - 10^4$

- ECC is extremely painful (no “quantum refresh” like DRAM)
- Many can be fabricated with variations on standard semiconductor techniques

Teleport: Quantum "Hello World"

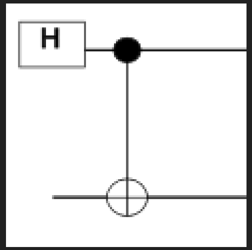
- Alice entangles two qubits
- Bob takes one of them far away
- Alice is given a new qubit with a message
- Alice entangles it with her local part of the Bell pair
- Alice measure the local qubits, yielding 2 classical bits
- Alice transmits the two bits via classical channels
- Remotely, Bob applies gates as determined by the 2 bits
- Bob recovers the sent message



Teleport: User Code

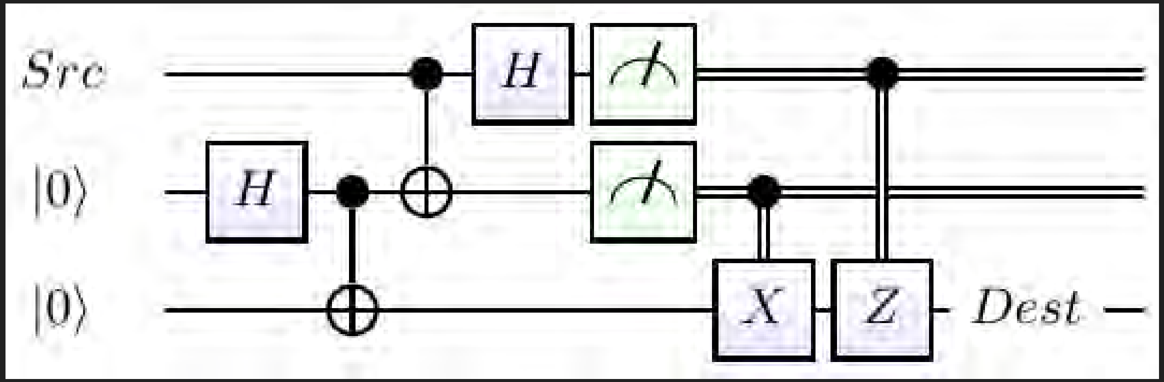
- Define a function to perform entanglement:

```
let EPR (qs:Qubits) = H qs; CNOT qs
```

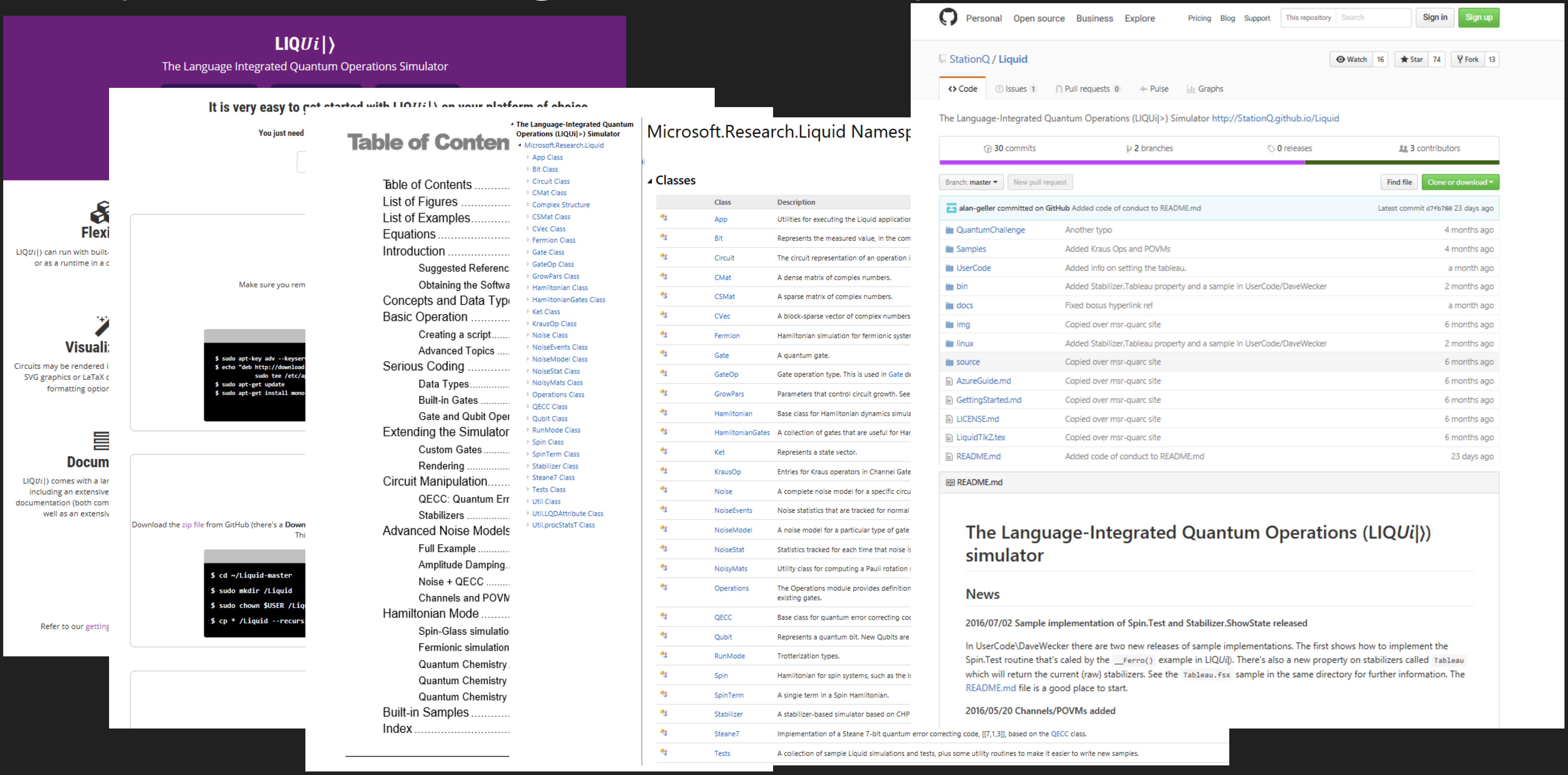


- The rest of the algorithm:

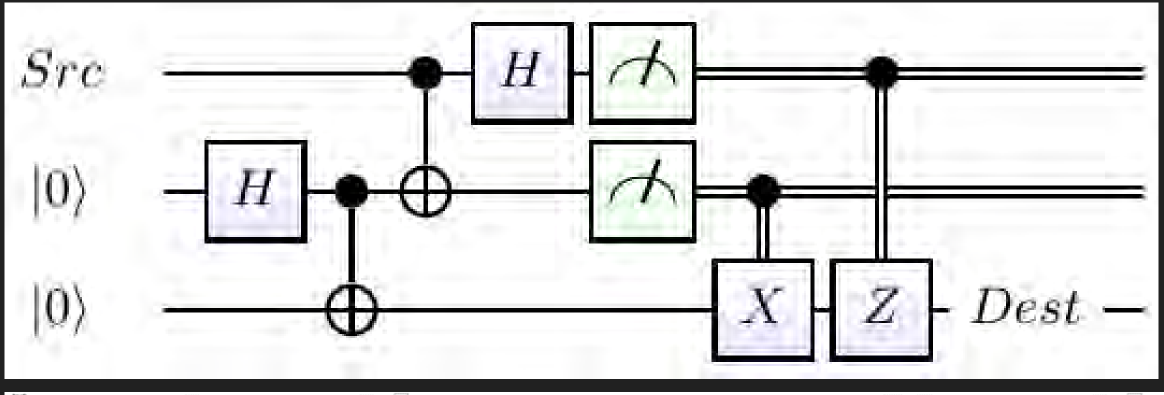
```
let teleport (qs:Qubits) =
    let qs'      = qs.Tail
    EPR qs'; CNOT qs; H qs
    M qs'; BC X qs'
    M qs ; BC Z !!(qs,0,2)
```



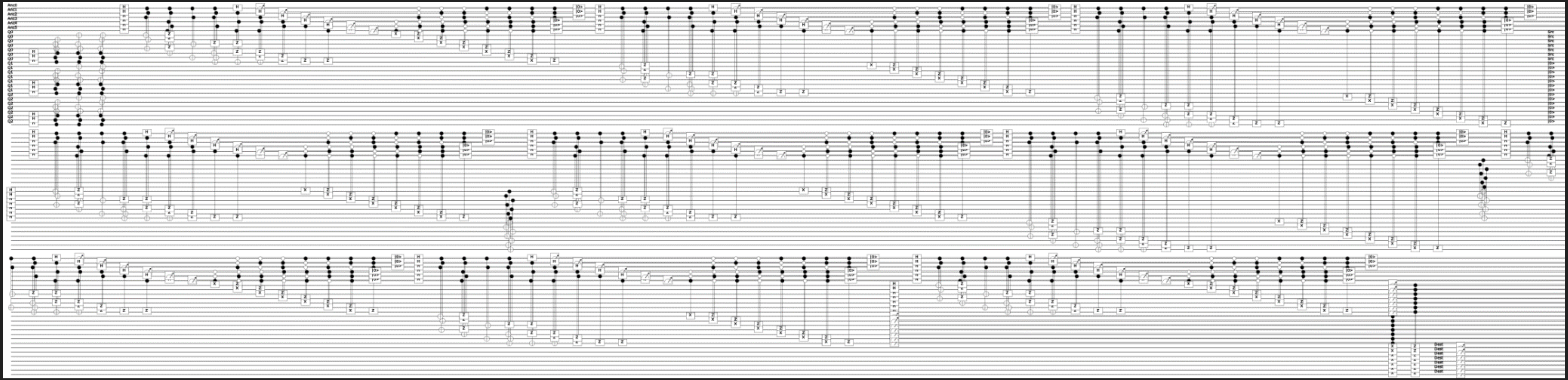
http://StationQ.github.io/Liquid/



Full Teleport Circuit in a Steane7 Code



3 qubits go to 27

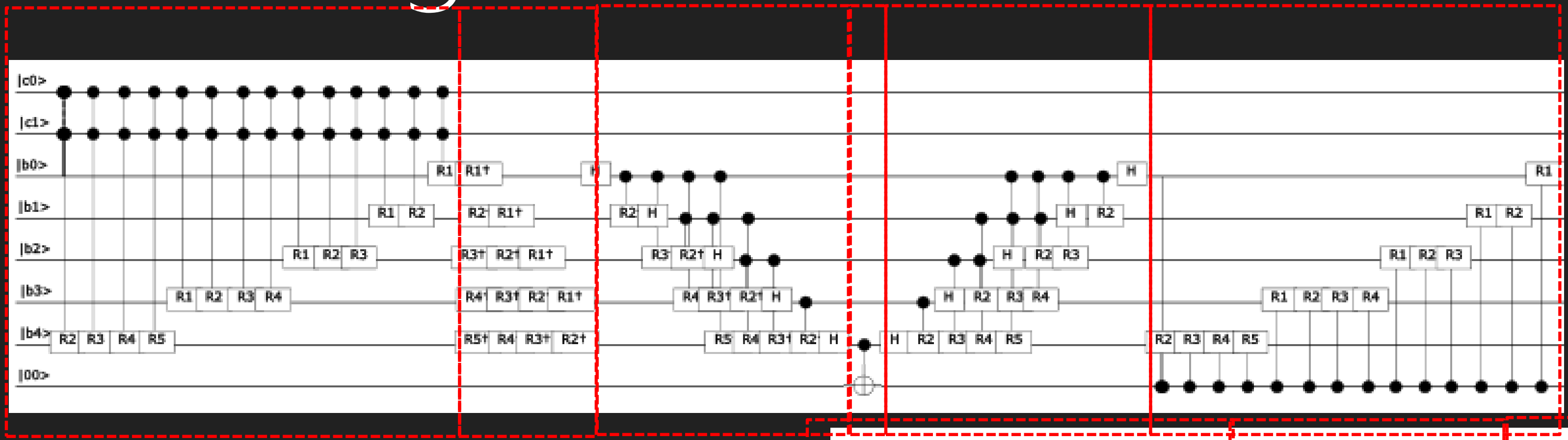


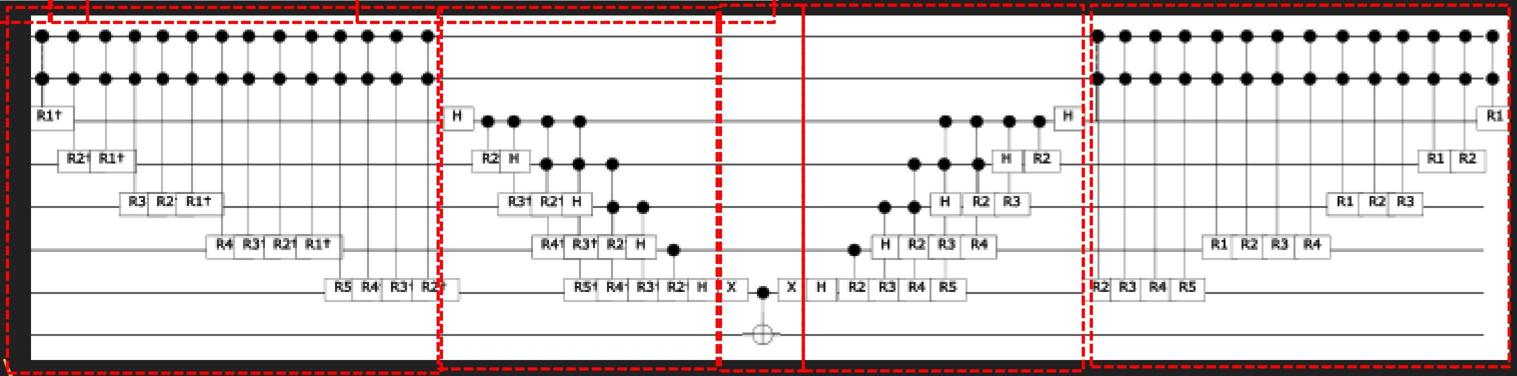
Shor's algorithm: (4 bits ≅ 8200 gates)

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

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

Shor's algorithm: Modular Adder



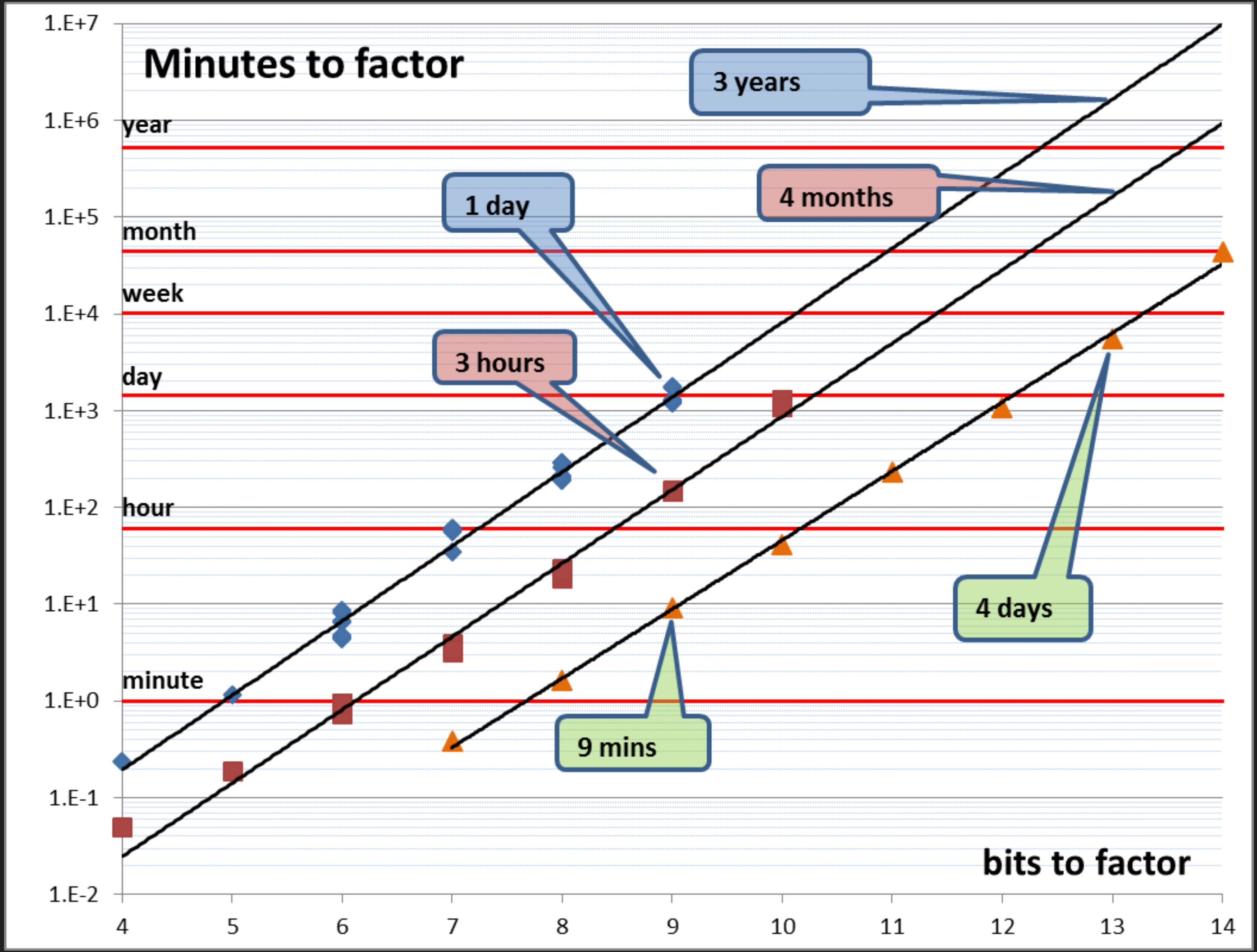


As defined in:
Circuit for Shor's algorithm using 2n+3 qubits
– Stéphane Beauregard

let op (qs:Qubits) =

CCAdd a cbs	// Add a to $\Phi\|b\rangle$
AddA' N bs	// Sub N from $\Phi\|a+b\rangle$
QFT' bs	// Inverse QFT of $\Phi\|a+b-N\rangle$
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 $\Phi\|a+b \: mod \: N\rangle$
QFT' bs	// Inverse QFT
X [bMx]	// Flip top bit
CNOT [bMx;anc]	// Reset Ancilla to $\|0\rangle$
X [bMx]	// Flip top bit back
QFT bs	// QFT back
CCAdd a cbs	// Finally get $\Phi\|a+b \: mod \: N\rangle$

Shor's algorithm results



Simulating quantum computers

- Need 2^N complex numbers to store the wave function of N qubits
- $O(2^N)$ classical operations to perform a quantum gate on N qubits

Qubits	Memory	Time for one gate
10	16 kByte	microseconds on a watch
20	16 MByte	milliseconds on smartphone
30	16 GByte	seconds on laptop
40	16 TByte	seconds on supercomputer
50	16 PByte	seconds on top supercomputer
60	16 EByte	minutes on future supercomputer
70	16 ZByte	hours on potential supercomputer?
…	…	…
250	size of visible universe	age of the universe

Quantum Chemistry

$$H = \sum_{pq} h_{pq} a_p^\dagger a_q + \frac{1}{2} \sum_{pqrs} h_{pqrs} \, a_p^\dagger a_q^\dagger a_r a_s$$

Can quantum chemistry be performed on a small quantum computer: Da
Hastings, Mat

As quantum c
computers wi
appear feasib
applications c
frequently me
simulating qu
of molecules
computationa
perform quan
the quantum
molecule twic
exactly. We fi
increase in th
required incre
executed is m
quantum com
problems, dra
http://arxiv.org/ab

Imp
H

tion
an
und
ls,
ed
e

Ferredoxin (Fe_2S_2) used in many metabolic reactions including energy transport in photosynthesis

- *Intractable on a classical computer*
- *Assumed quantum scaling: ~24 billion years (N^{11} scaling)*
- *First paper: ~850 thousand years to solve (N^9 scaling)*
- *Second paper: ~30 years to solve (N^7 scaling)*
- *Third paper: ~5 days to solve ($N^{5.5}$ scaling)*
- *Fourth paper: ~1 hour to solve ($N^3, Z^{2.5}$ scaling)*

Molecules simulated in LIQ$Ui|\rangle$

H_2

HF

H_2O

NH_3

CH_4

HCl

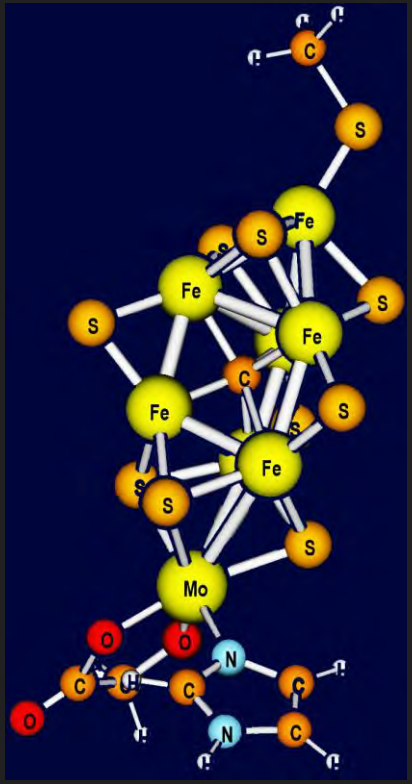
F_2

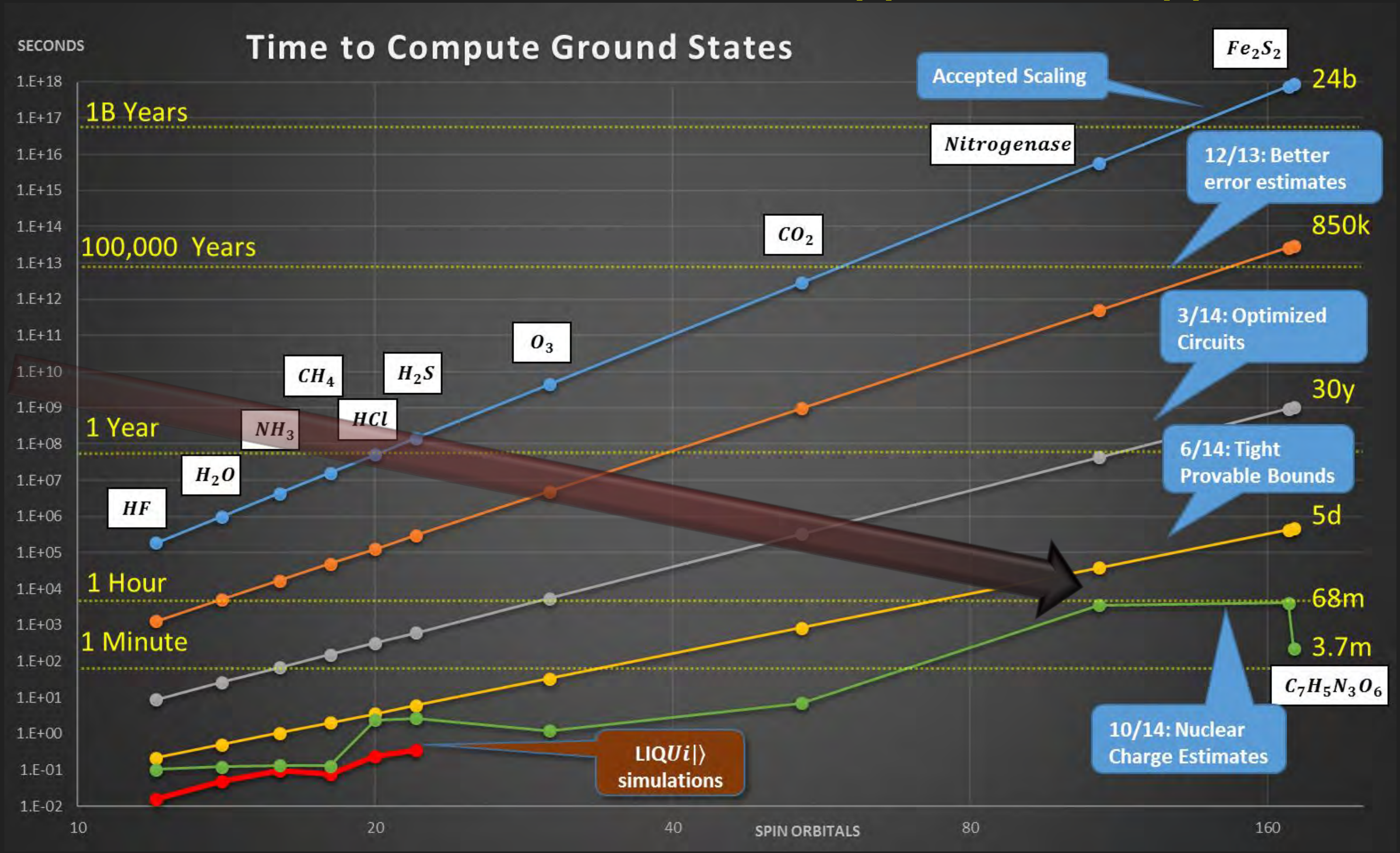
H_2S

Geometries and molecular models from http://www.colby.edu/chemistry/webmo/

Simulation Evidence

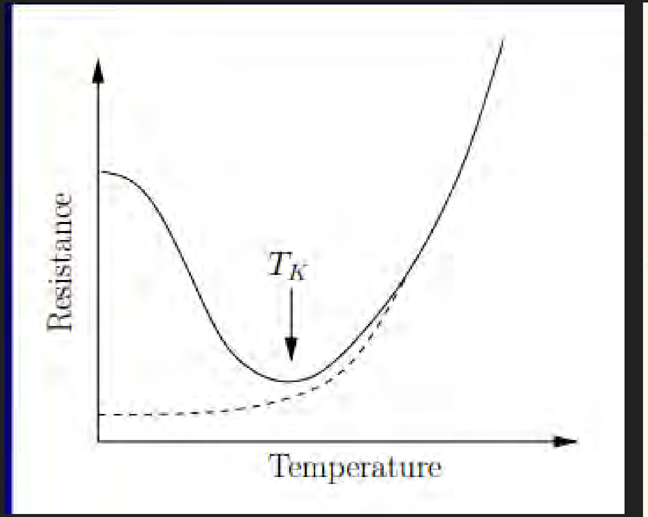
$$H = \sum_{pq} h_{pq} a_p^\dagger a_q + \frac{1}{2} \sum_{pqrs} h_{pqrs}\, a_p^\dagger a_q^\dagger a_r a_s$$

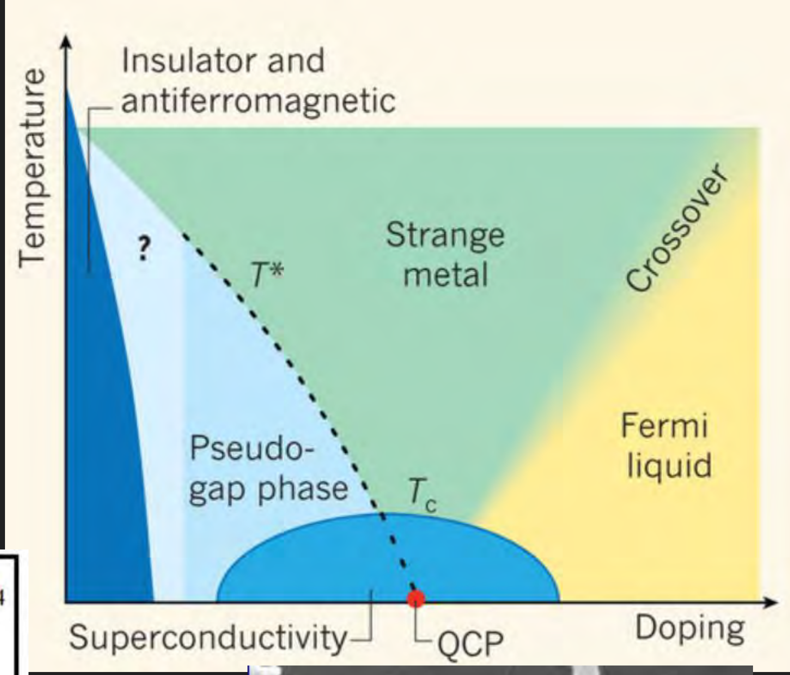


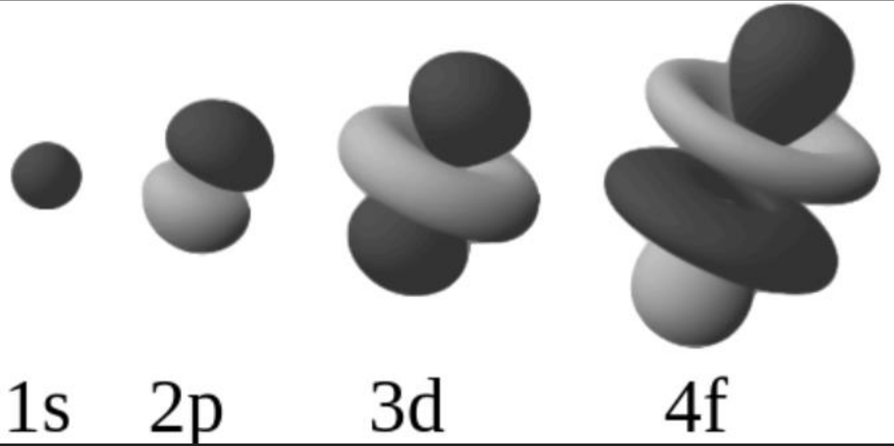


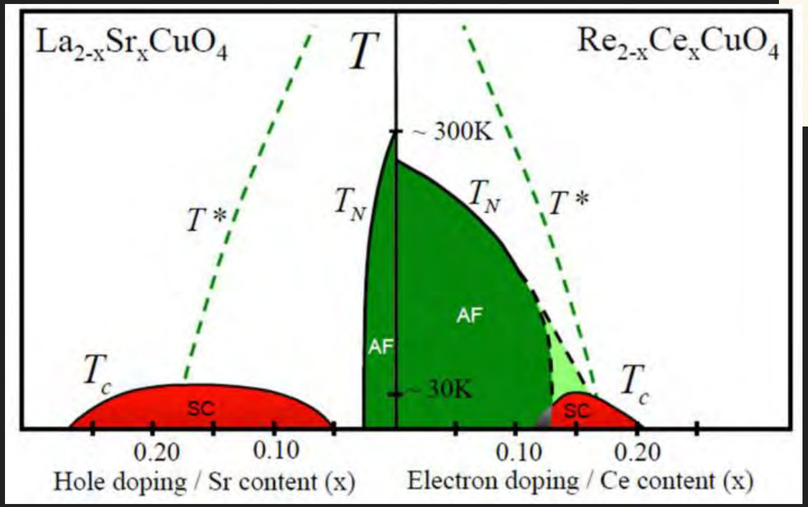
Quantum Algorithms for Quantum Impurity Problems

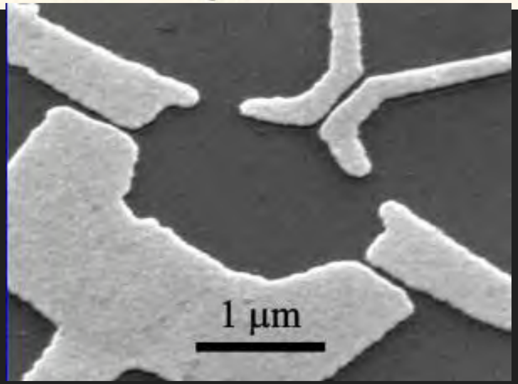
- Mott Insulators
- Transition Metal Compounds
  - Cuprates (e.g., High Tc SC)
- Lanthanides and Actinides
- Kondo Physics (Low temperature Resistance) from Magnetic Impurities
  - Quantum Dots









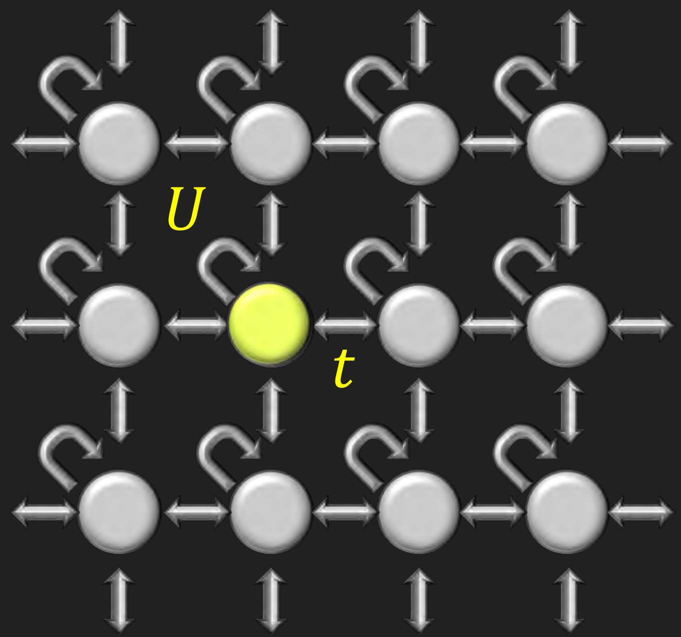


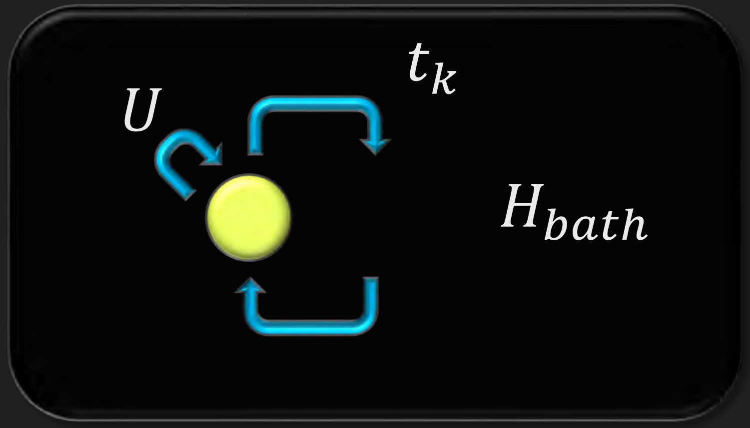
Materials Modeling

$$H_{hub} = U\Sigma_i n_{i\uparrow} n_{i\downarrow} - t\Sigma_{<i,j>,\sigma} c_{i\sigma}^{\dagger} c_{j\sigma}$$

$$H_{imp} = U n_{\uparrow} n_{\downarrow} - \Sigma_{k,\sigma}\left(t_k c_{\sigma}^{\dagger} a_{k,\sigma}^{bath} + h.c.\right) + H_{bath}$$

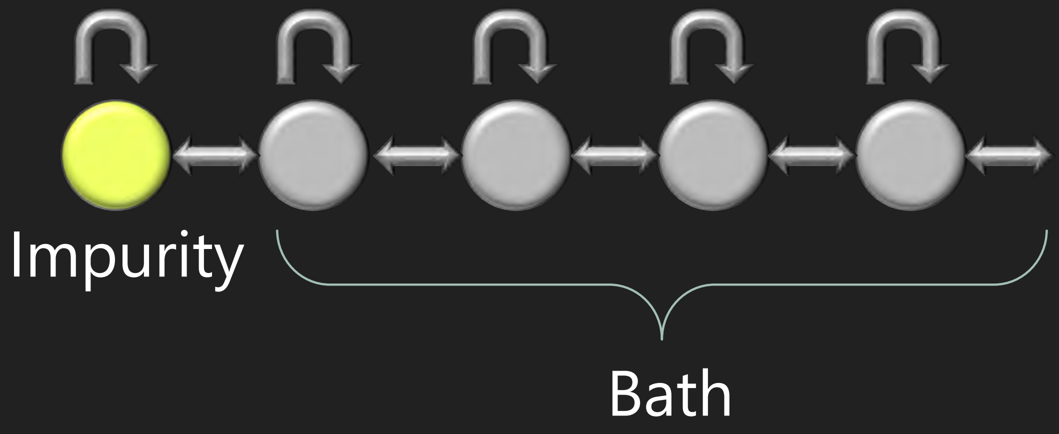
- Solids have regular structure that can be modeled as lattices
- The Hubbard model only implements H_{pp} and H_{pqqp} terms
- This doesn't cover many of the materials we're interested in
- One can choose a single site in the lattice to model
- The effect of the rest of the lattice can be modeled in terms of its effect on this site





Anderson Impurity Model

- Choose a single place in the lattice to model (the impurity). This may contain a collection of local sites
- The impurity is typically a full two-body model
- The effect of the rest of the lattice can be modeled in terms of its effect on the impurity (the bath) via a Dynamic Green's function $G(\omega)$
- The bath may have many sites and interconnections

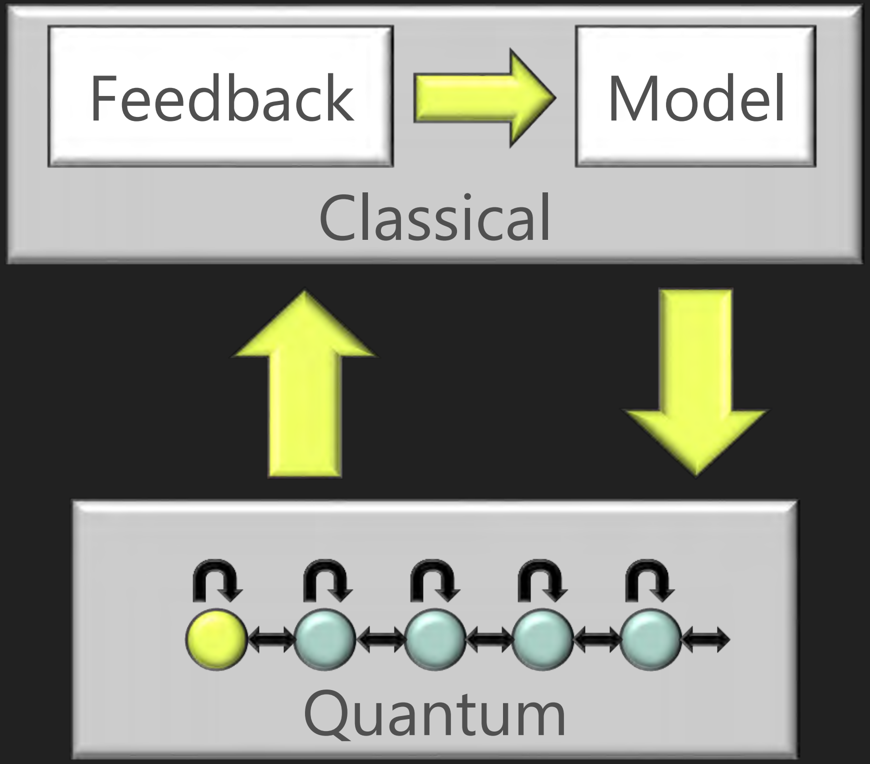


$$H = \sum_{ij} t_{ij} a_i^\dagger a_j + \frac{1}{2} \sum_{ijkl} w_{ijkl} a_i^\dagger a_j^\dagger a_k a_l + \sum_{ip} V_{ip} (a_i^\dagger a_p + a_p^\dagger a_i) + \sum_{pq} \epsilon_p a_p^\dagger a_q$$

Dynamical Mean Field Theory (DMFT)

$$G_{solver}(\omega) \rightarrow \sum(\omega) \rightarrow G(k,\omega) \rightarrow G_n(\omega) \rightarrow \Delta_n(\omega)$$

- We can posit an initial model for a material
- Measure quantum simulations at many sites and frequencies deriving a dynamical Green's function
- Use feedback to update model
- Repeat until converged
- The resulting model is defined classically and may be used to efficiently investigate many questions about the material



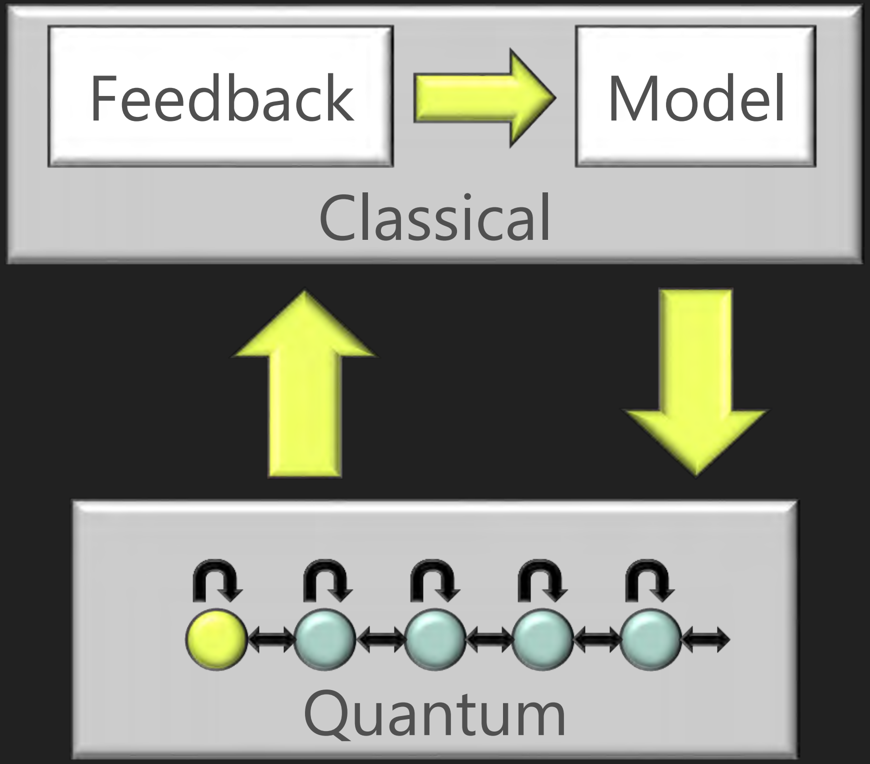
$$G_{solver}(\omega) = \langle\, c_i^\dagger(\omega)\; c_j(-\omega)\rangle$$

http://arxiv.org/abs/1012.3609

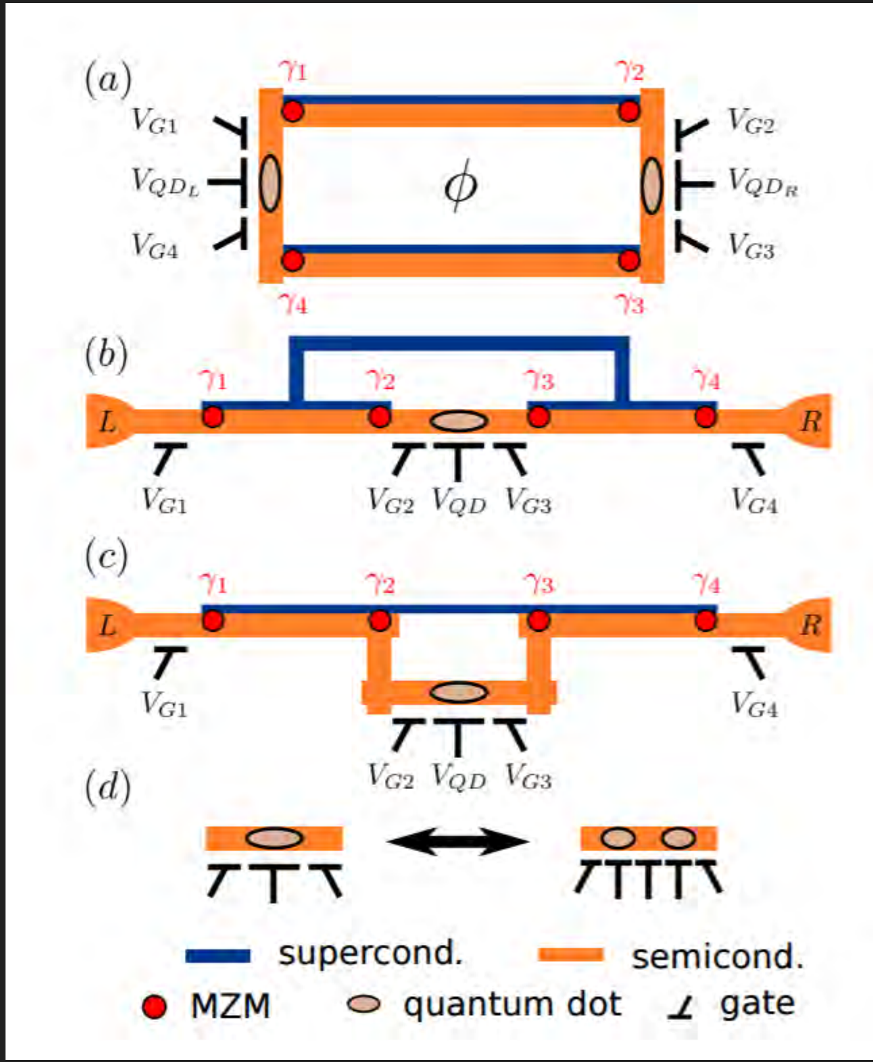
Variational Eigensolver

$$E_{gs} = \sum_k \left(H_{FF} + \sum_i \sum_j \theta_{ij} H_j + M(H_k) \right)$$

- Good: Only need to stay coherent for prep, evolution and measurement
- Bad: Parameters discovered by sampling (quadratically worse than PE)
- Useful for small machines with physical qubits that have relatively short coherence times.
- Only needs few thousand gate executions before losing coherence

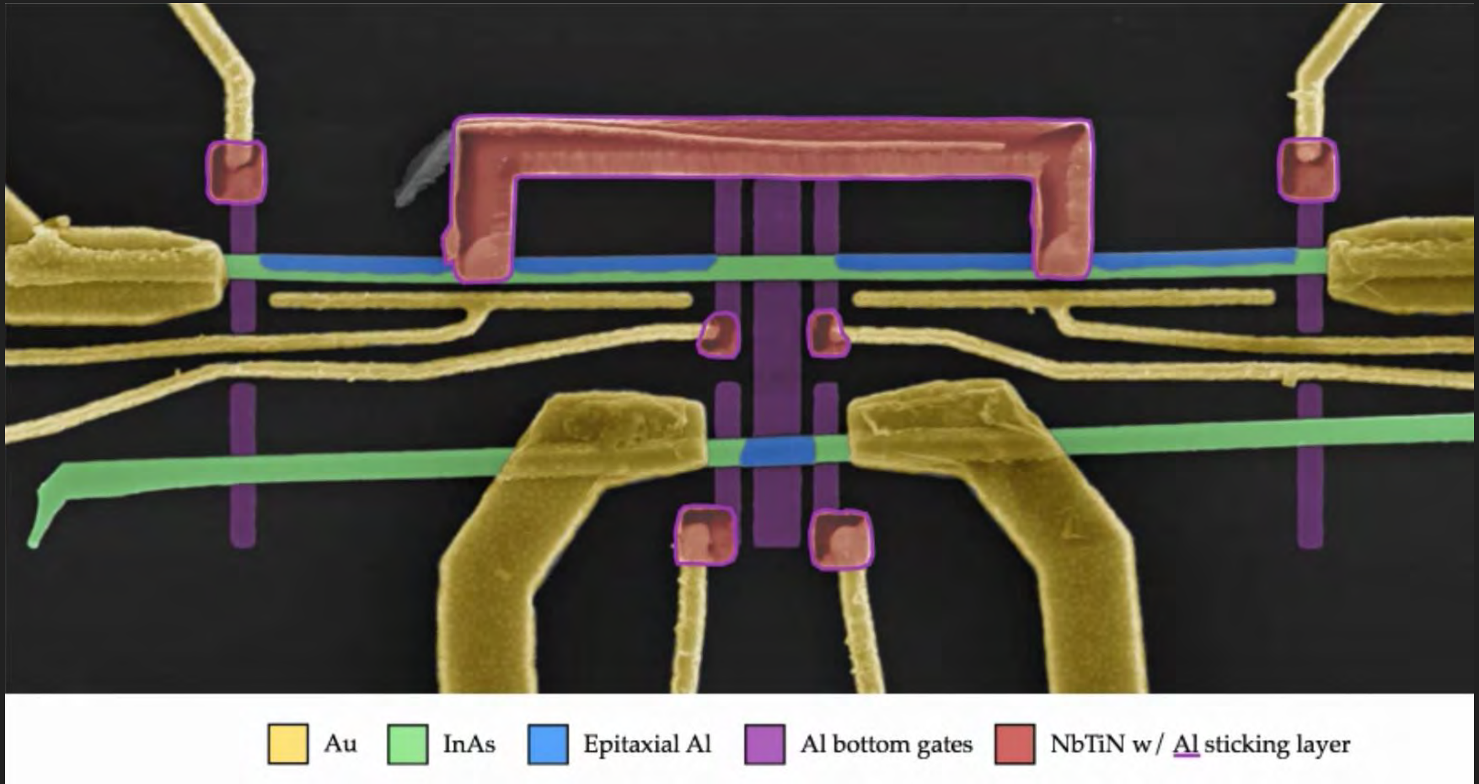


http://arxiv.org/abs/1012.3609



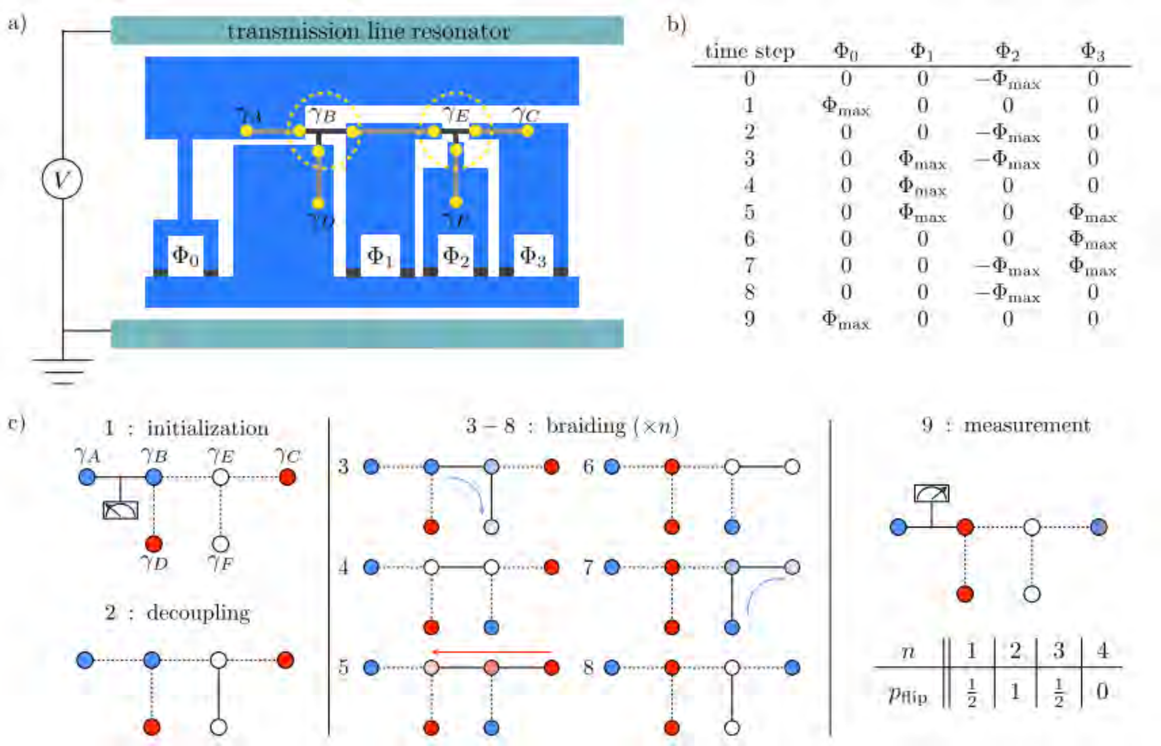
Scalable Designs for Quasiparticle-Poisoning-Protected Topological Quantum Computation with Majorana Zero Modes

Torsten Karzig,[1] Christina Knapp,[2] Roman M. Lutchyn,[1] Parsa Bonderson,[1] Matthew Hastings,[1] Chetan Nayak,[1,2] Jason Alicea,[3,4] Karsten Flensberg,[5] Stephan Plugge,[5,6] Yuval Oreg,[7] Charles Marcus,[5] and Michael H. Freedman[1,8]



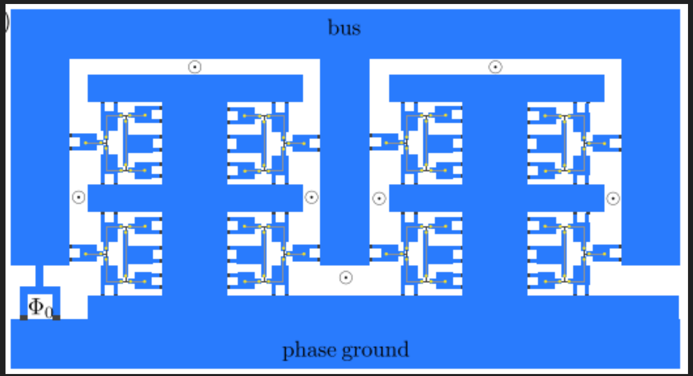
Photos courtesy of: Professor Charlie Marcus

Previously Proposed Architecture



time step	Φ_0	Φ_1	Φ_2	Φ_3
0	0	0	$-\Phi_{max}$	0
1	Φ_{max}	0	0	0
2	0	0	$-\Phi_{max}$	0
3	0	Φ_{max}	$-\Phi_{max}$	0
4	0	Φ_{max}	0	0
5	0	Φ_{max}	0	Φ_{max}
6	0	0	0	Φ_{max}
7	0	0	$-\Phi_{max}$	Φ_{max}
8	0	0	$-\Phi_{max}$	0
9	Φ_{max}	0	0	0

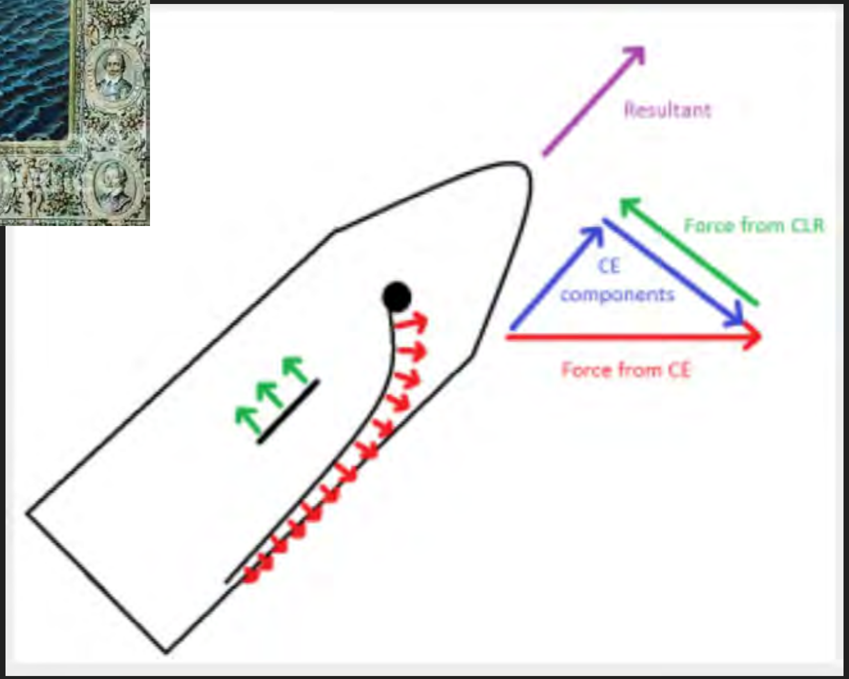
n	1	2	3	4
p_{flip}	$\frac{1}{2}$	1	$\frac{1}{2}$	0

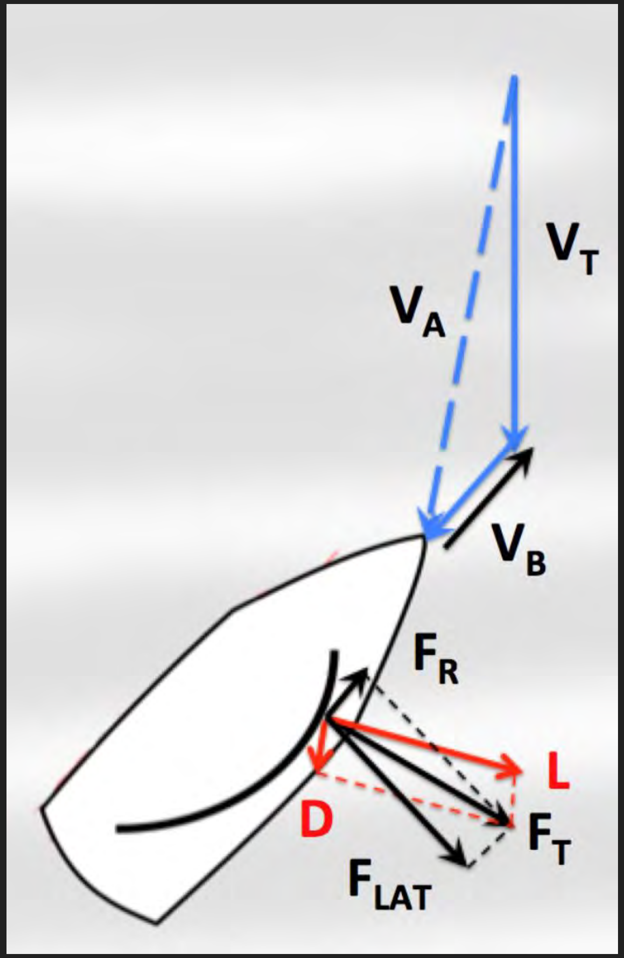


- Majoranas are the yellow dots
- Gray lines are nanowires
- Black lines are junctions
- Small black rectangles are Josephson Junctions
- Strong magnetic field must be **parallel** to all the nanowires and not affect the JJs… how?
- How do you keep coherence when changing directions in the junctions?

After Hyart et al 2013
http://arxiv.org/abs/1303.4379

Sailing into the Wind



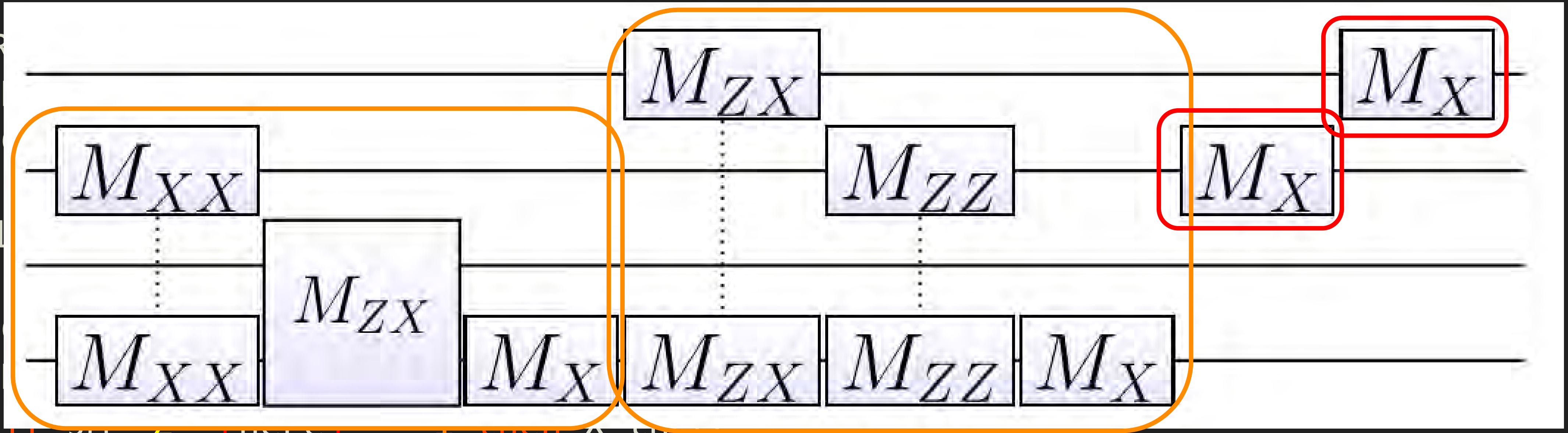


https://en.wikipedia.org/wiki/Forces_on_sails

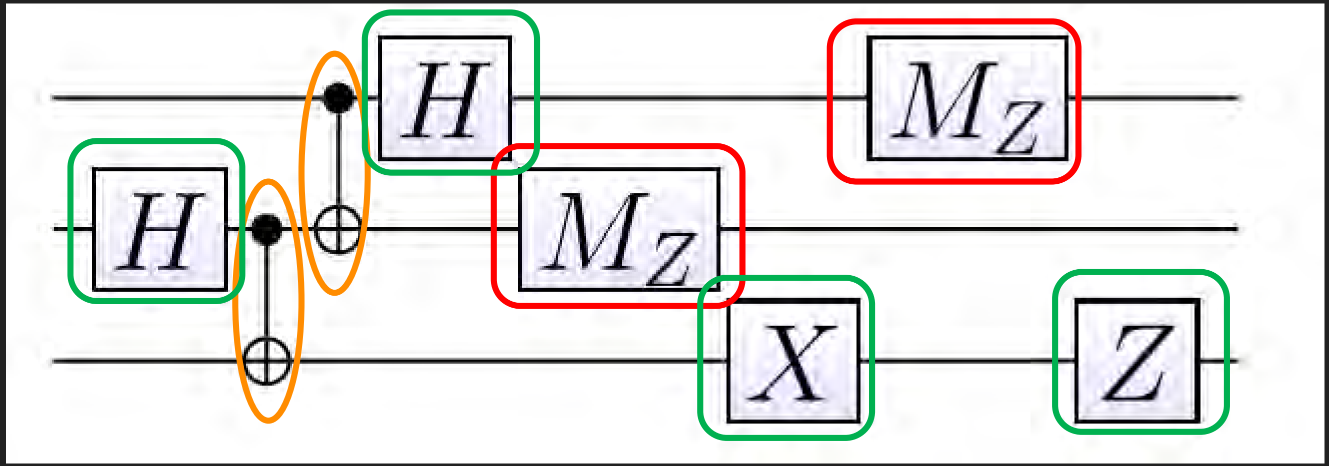
http://hayward.peirce.me/the-physics-of-sailing-ce-and-clr/

Teleport: SoLi|⟩ User Code

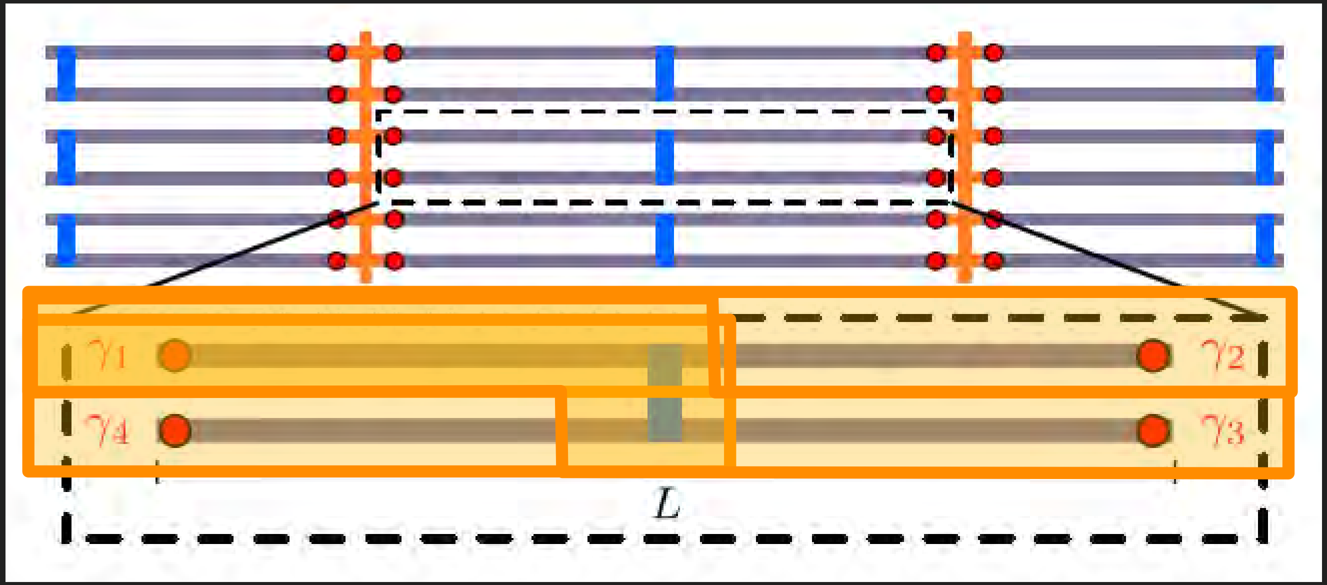
```
let EPR
let Tel
```



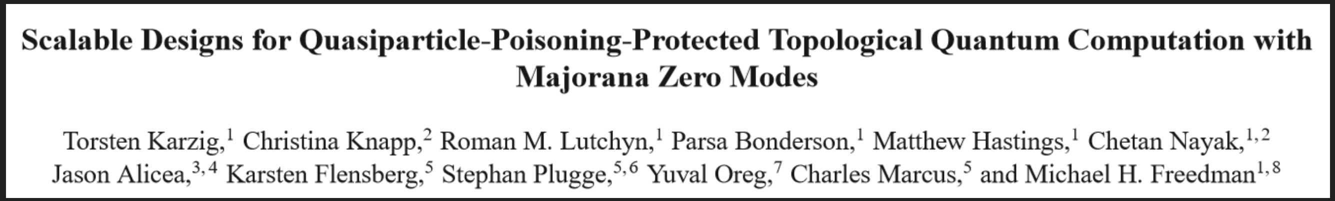

```
if JM "Z" [msg] = -1 then Z there
```



Box Qubits: 1 Qubit Measurements

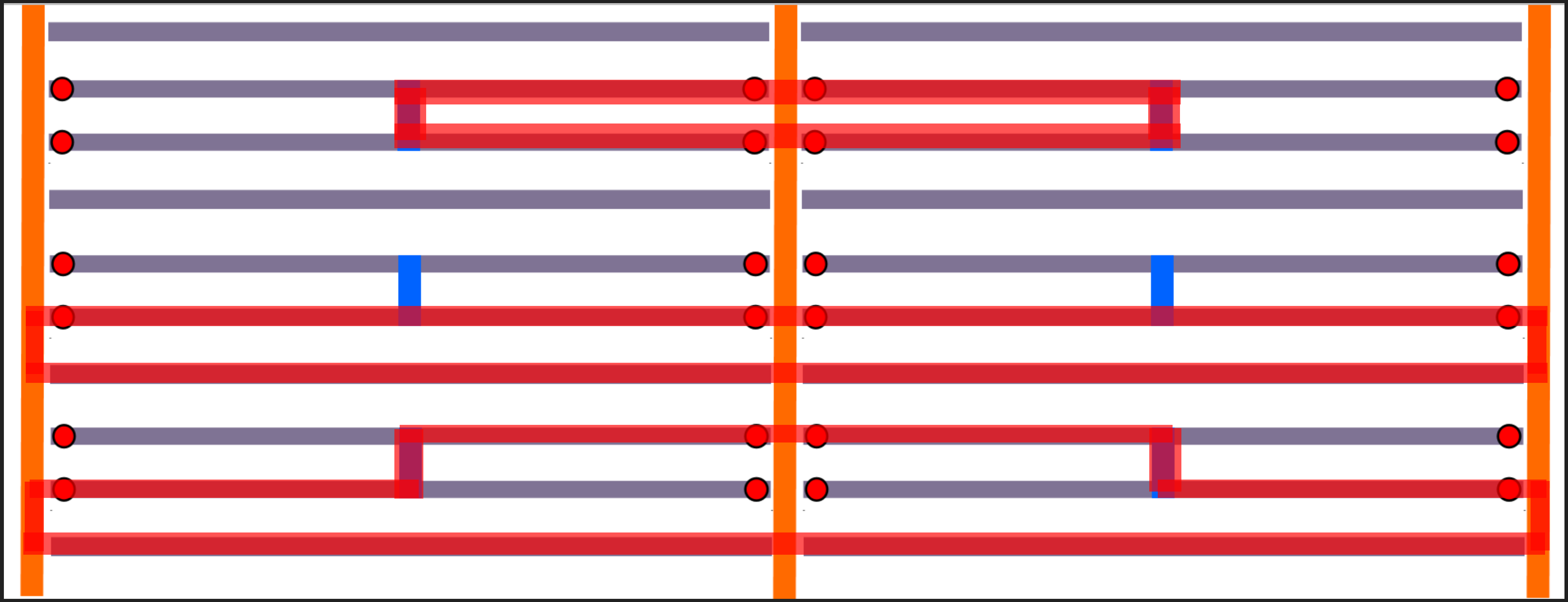


Measure two Horizontally = M_z
Measure two Vertically = M_x
Measure two Diagonally = M_y

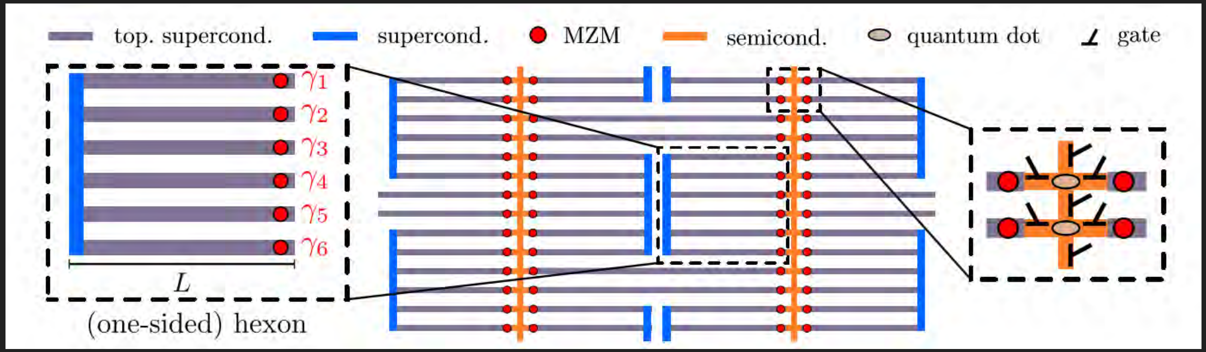

Scalable Designs for Quasiparticle-Poisoning-Protected Topological Quantum Computation with Majorana Zero Modes

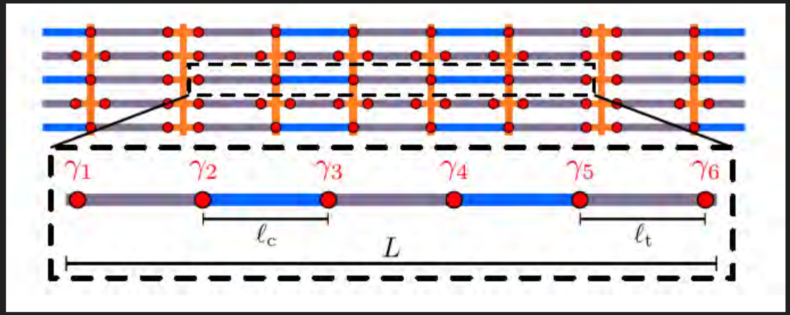
Torsten Karzig,[1] Christina Knapp,[2] Roman M. Lutchyn,[1] Parsa Bonderson,[1] Matthew Hastings,[1] Chetan Nayak,[1,2] Jason Alicea,[3,4] Karsten Flensberg,[5] Stephan Plugge,[5,6] Yuval Oreg,[7] Charles Marcus,[5] and Michael H. Freedman[1,8]

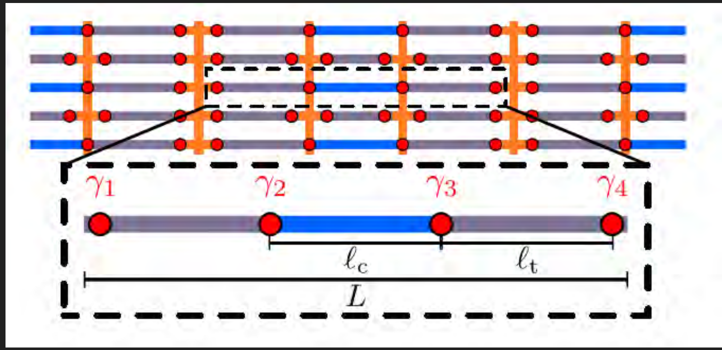
Box Qubits: Horizontal 2 Qubit Measurements

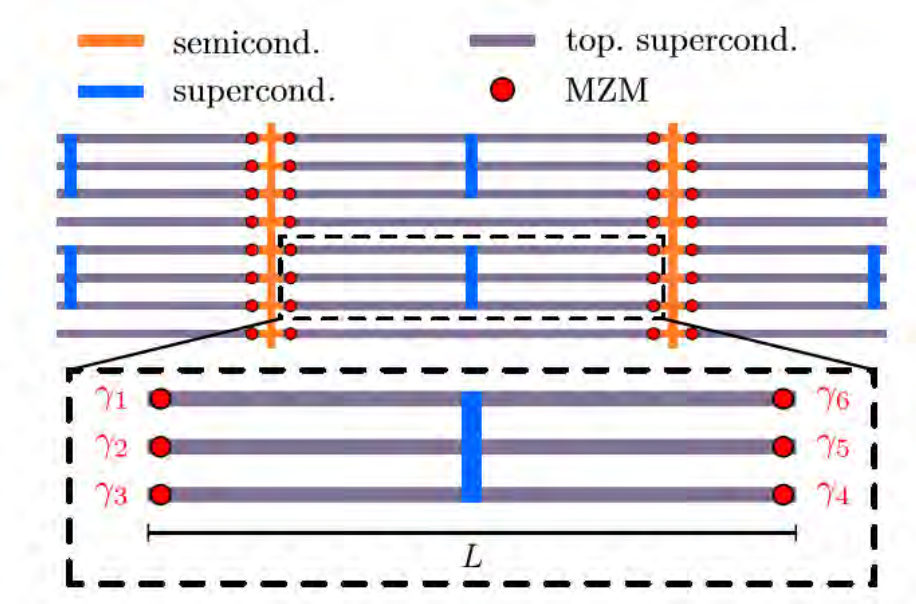


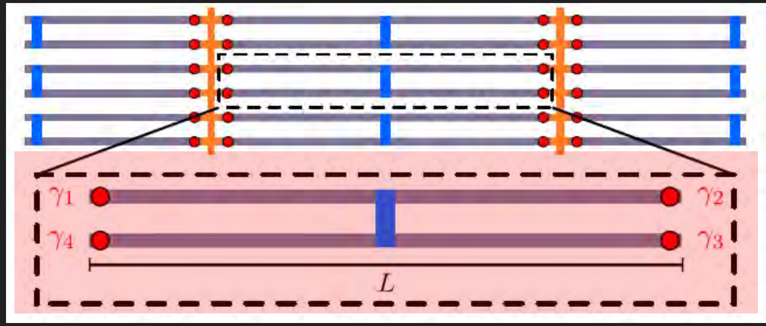
Some of the choices: Hexons and Tetrons







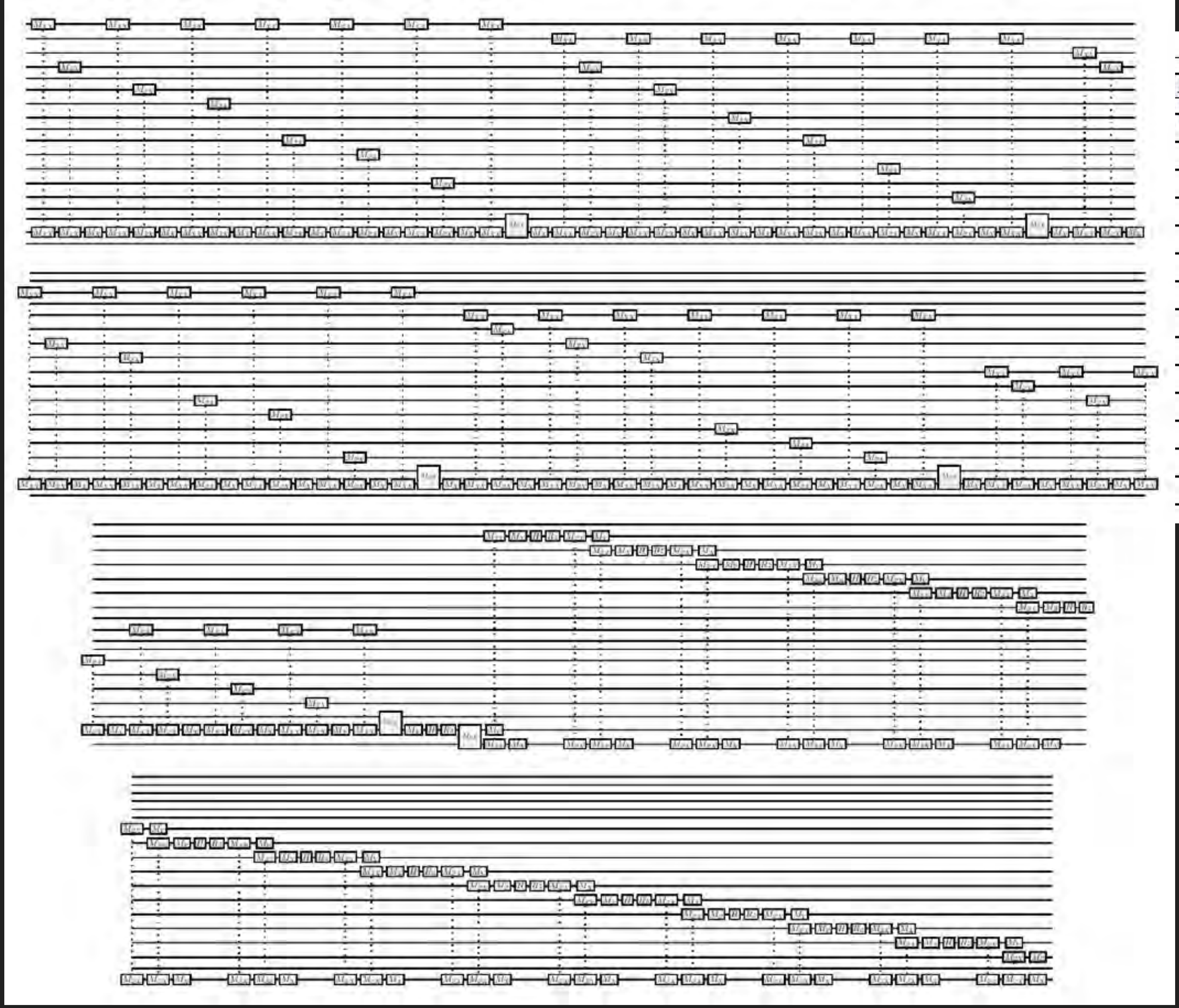


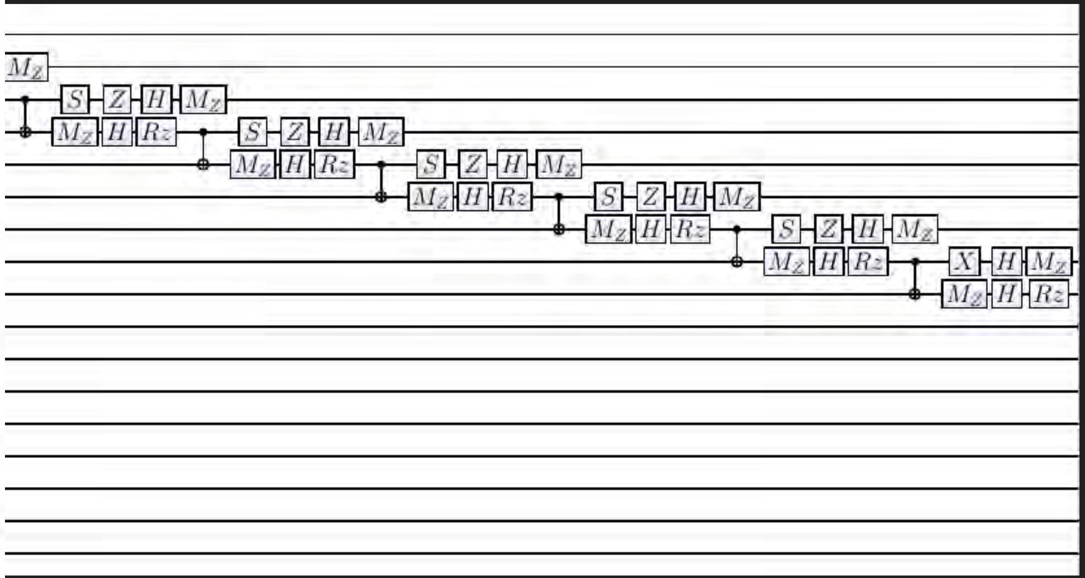


What about the single qubit Clifford operators?

- Create a frame (where do the axes point?): {x,y,z}
- Each slot (x,y,z) can contain any of: +X, +Y, +Z, -X, -Y, -Z
- Operators are now defined as:
  - X: Flip signs of y and z
  - Y: Flip signs of x and z
  - Z: Flip signs of x and y
  - H: Flip sign of y and interchange x and z
  - S: Interchange x with –y and y with x
- Measure in a basis (X,Y,Z) by looking at the entry for that basis (x,y,z):
  - E.g., with {Z,-Y,X} an M_x is M_z, M_y is $-M_y$ and M_z is M_x
  - Two qubit joint measurements are done according to each qubits’ frame

What about T gates?

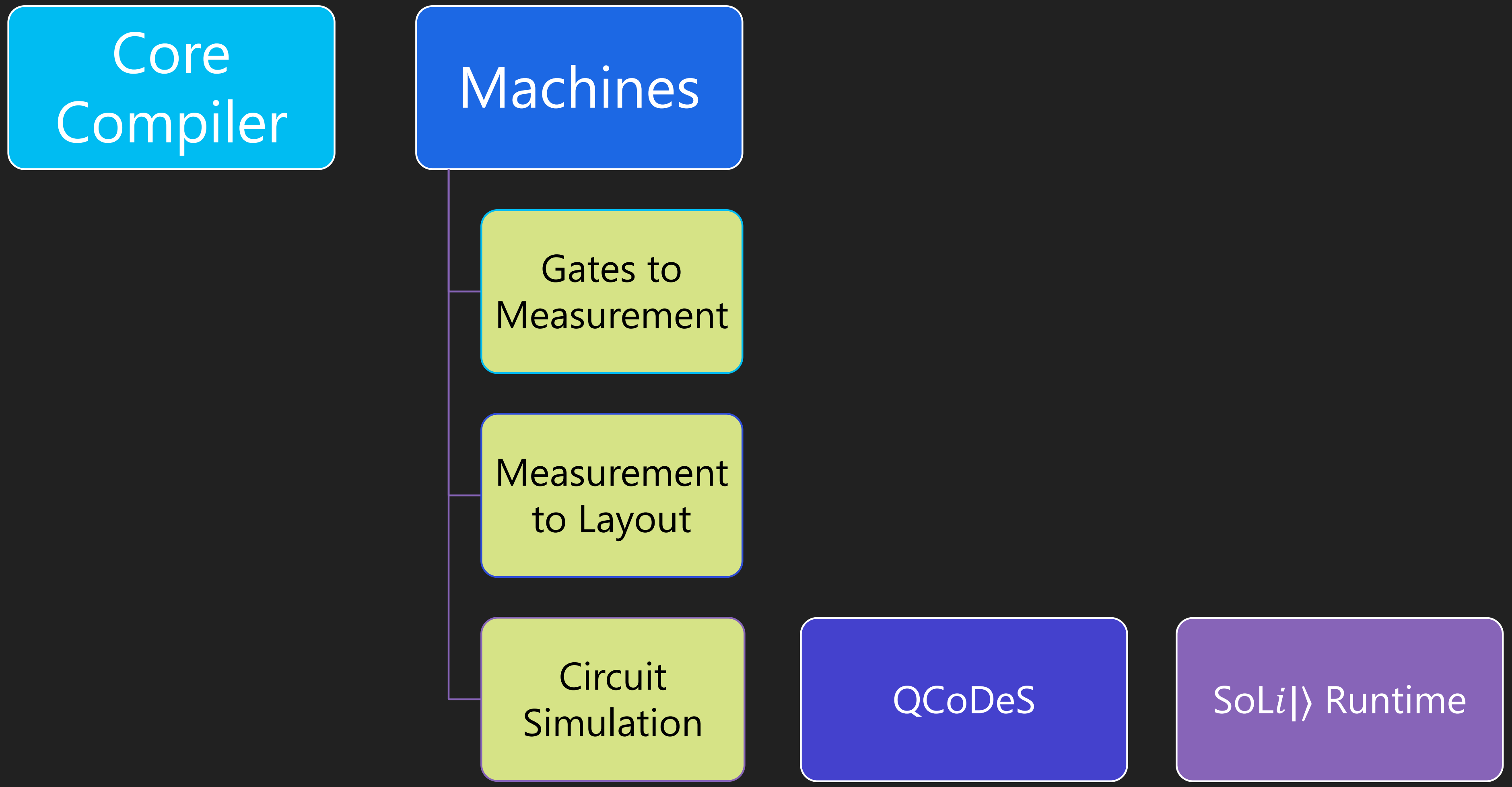




Surface codes: Towards practical large-scale quantum computation

Austin G. Fowler

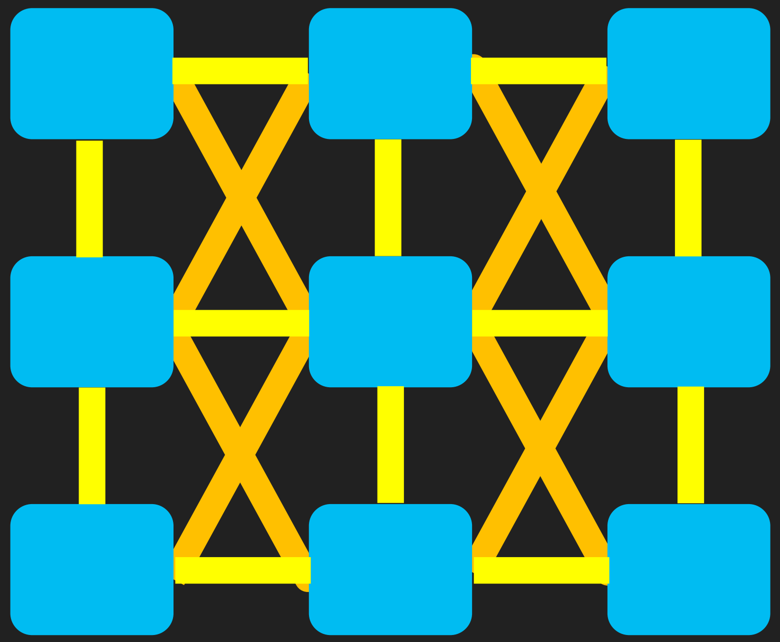
Compiling with SoL*i*|⟩



QCoDeS

- http://qcodes.github.io
- Python package for running experiments
  - Runs either command-line or within a Jupyter notebook
  - Targets quantum computing experiments but is general purpose
- Plug-in model for device drivers
  - Note that these are high-level interaction models, not kernel drivers
- Integrated support for real-time plotting and monitoring
- Integrated support for structured data storage

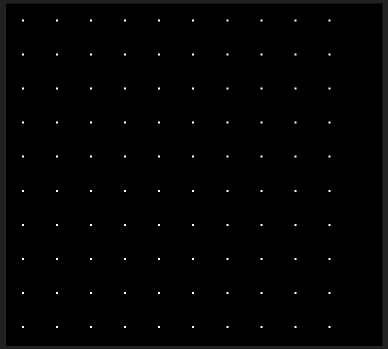
Layout options

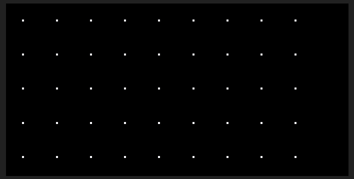


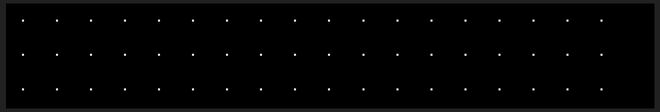
Layout of T factory (DistillT)

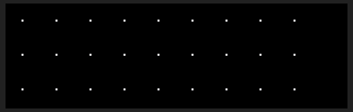
DistillT: 1Q=65 2Q=100 LogQ=81 Frames=277

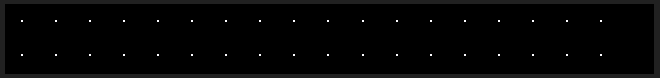
Connect	Dim	Data Rows	Phys Qubits	Data Teleport	Block Tele	Par Tele Depth
Rect	10x10	All	42	15/9	20/9	4*(9+9)=72
Rect	5x9	All	39	18/13	25/13	4*(13+13)=104
Rect	3x18	Half	39	40/31	40/31	4*(31+31)=248
Diag	3x9	Half	26	15/9	15/9	4*(9+9)=72
Diag	2x18	Half	34	39/24	36/24	4*(24+24)=192





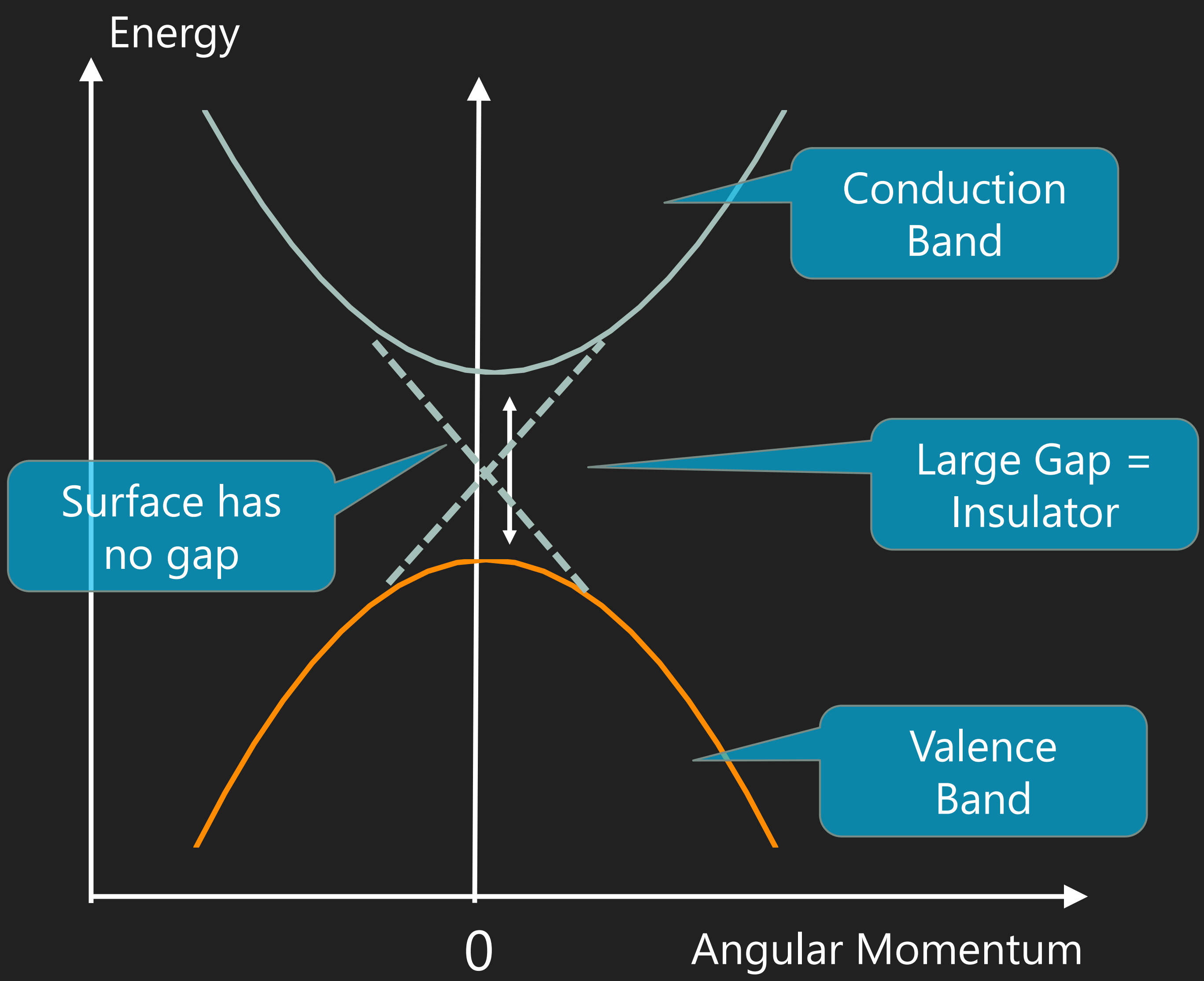






Photos courtesy of: Professor Charlie Marcus

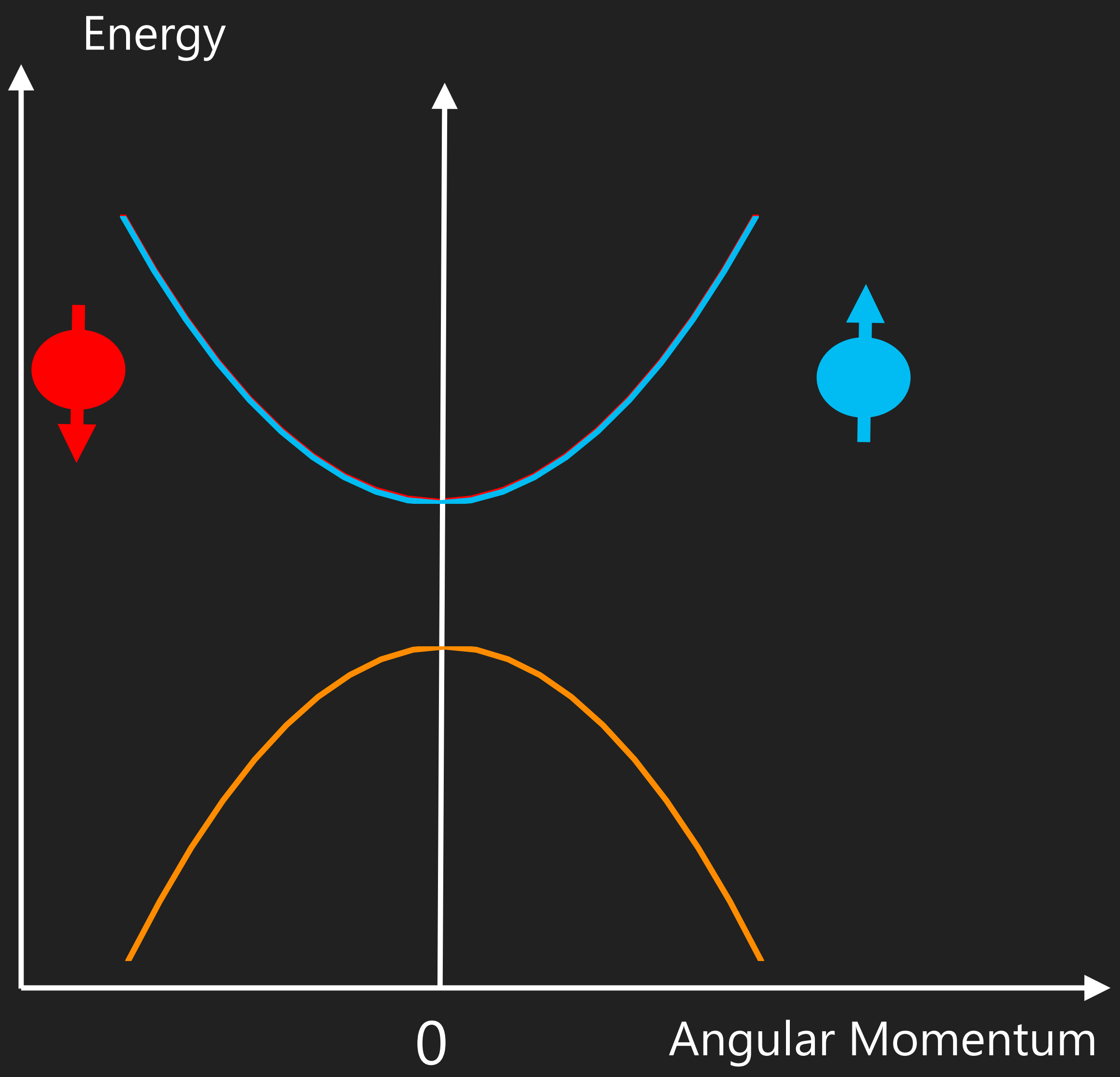
Topological Insulators



- Normal insulator (or un-doped semiconductor) has a large gap between the valence band and the conduction band
- A topological insulator has no gap at the boundary, acts as a conductor while the bulk is an insulator
- The surface of a 3D TI can be viewed as a 2D Electron Gas (2DEG)

After Hasan, Kane 2010
http://arxiv.org/abs/1002.3895

Spin-Orbit Coupling

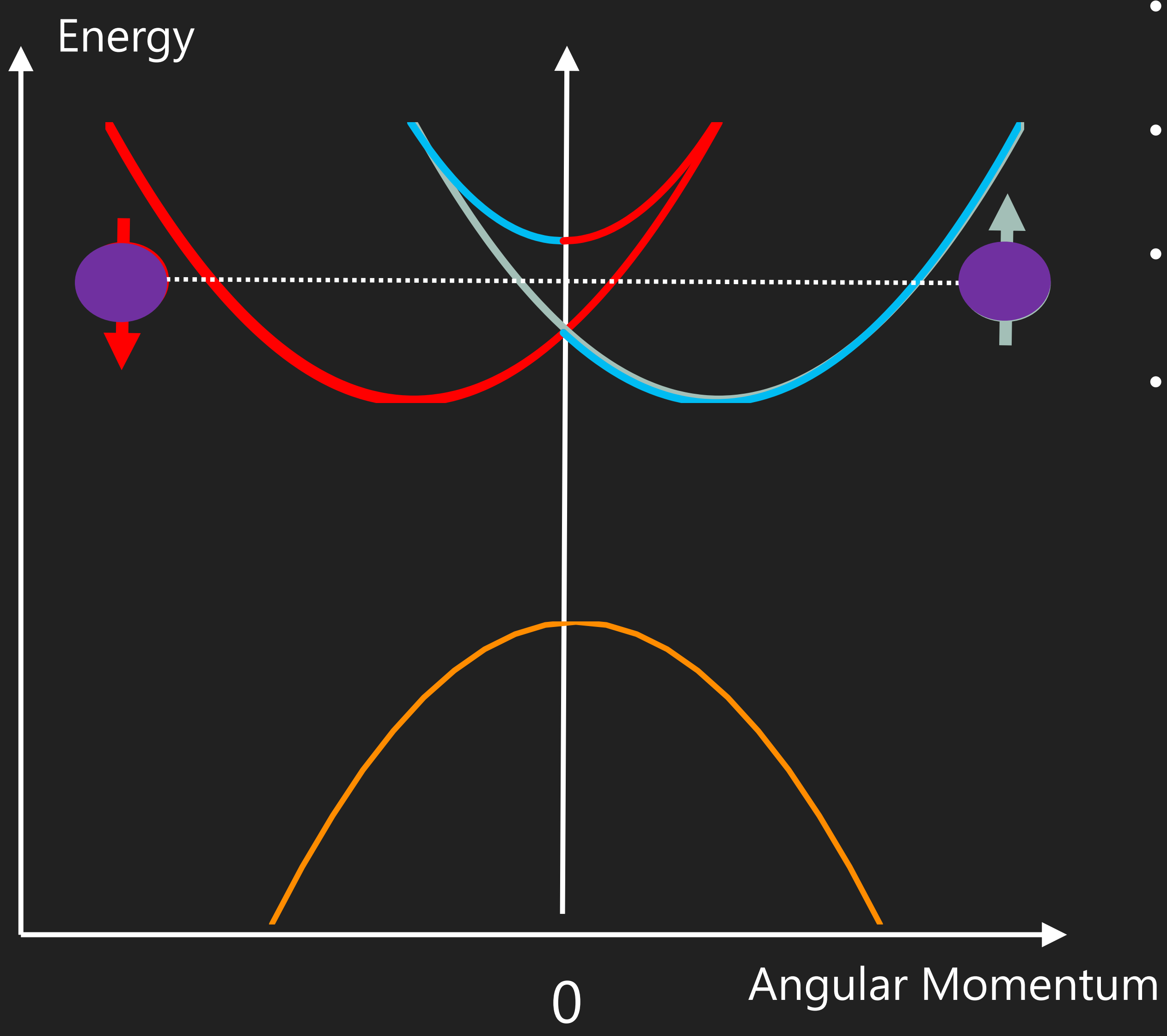


- If you make the TI out of large atoms, then the electrons are moving at relativistic velocity and there will have strong spin-orbit interaction (Rashba coupling).
- Electrons moving one way will be spin-up and the other way will be spin-down

$$H_{TI} = \int dx \psi^\dagger \left[-\frac{\partial_x^2}{2m} - \mu - i\hbar v \partial_x \sigma^y \right] \psi$$

After Jason Alicia, Winter 2010 Q Meeting

Making a P-Wave Superconductor



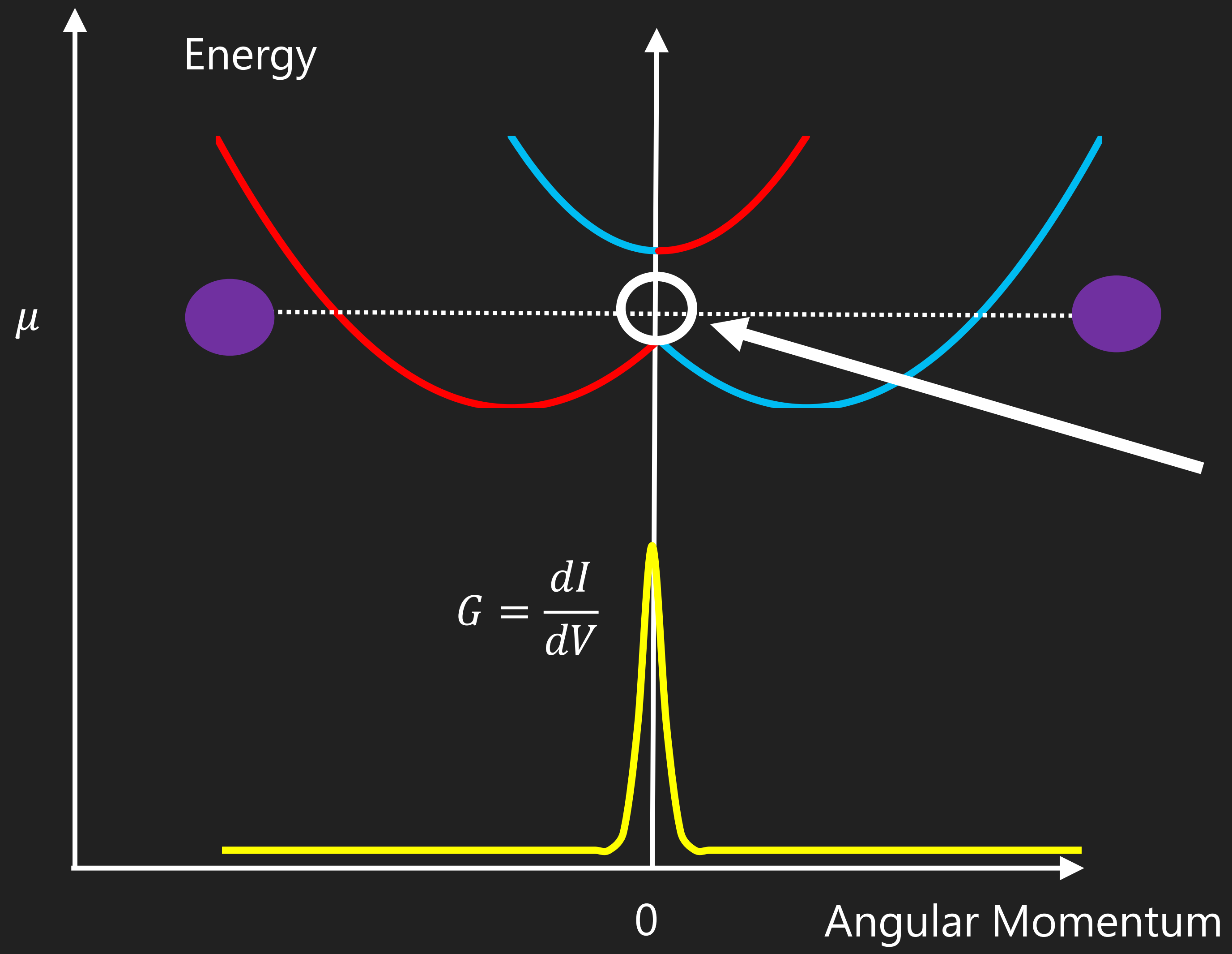
- Now apply a strong magnetic field (B) perpendicular to the plane opening a gap (Zeeman field)
- Bring an S-Wave superconductor into close proximity to induce pairing of the electrons.
- We've made a chiral P-Wave superconductor ($p_x + ip_y$)
- If we have superconductivity in the bulk, it still has a gap that does not allow quasi-particle excitations (topological superconductor)

$$H_{TIB} = \int dx \psi^\dagger \left[-\frac{\partial_x^2}{2m} - \mu - i\hbar v \partial_x \sigma^y - \frac{g\mu_B B}{2} \sigma^z \right] \psi$$

$$H_{p-wave} = H_{TIB} + (\Delta \psi_\uparrow \psi_\downarrow + h.c.)$$

After Jason Alicia, Winter 2010 Q Meeting

Majorana Quasiparticle



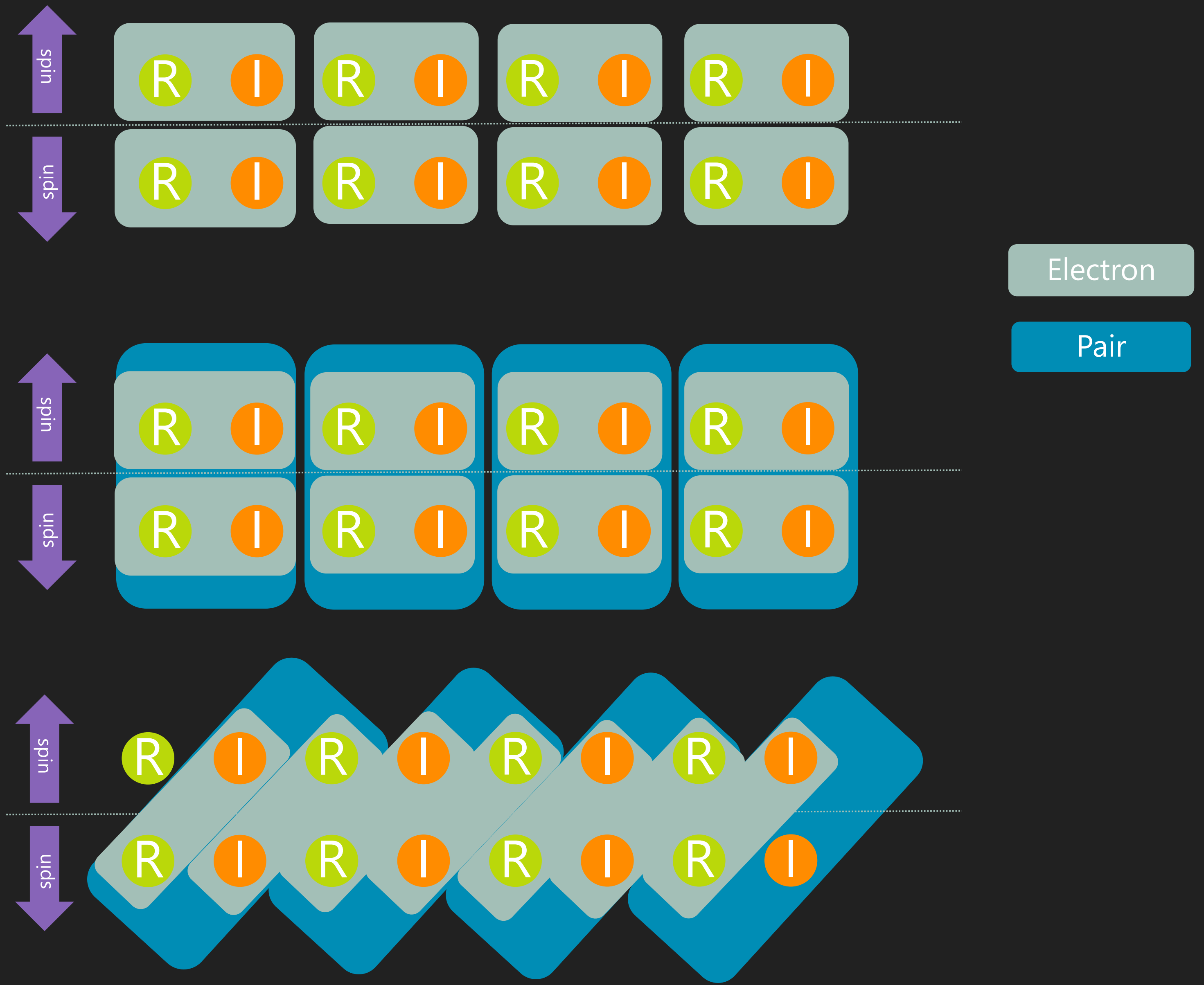
- Set the chemical potential (μ) in the gap
- Measure differential conductance (dI/dV)
- Zero mode peak has:
  - no spin
  - no mass
  - no charge
- Signature of a Majorana quasiparticle
- Only appears at defects or edges

After Leo Kouwenhoven, Summer 2012 Q Meeting

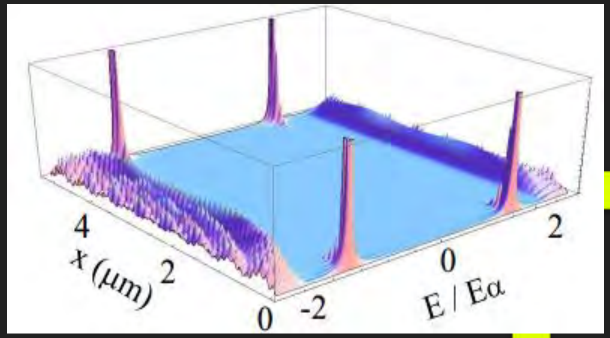
Insulator:

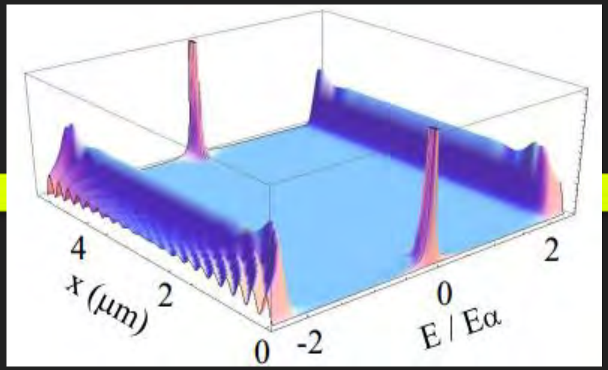
Normal S-Wave Superconductor:

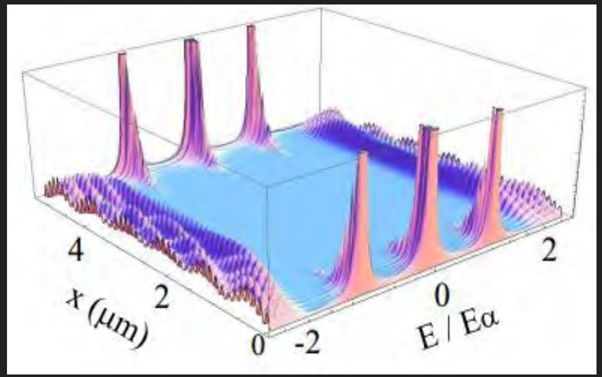
Topological Superconductor:

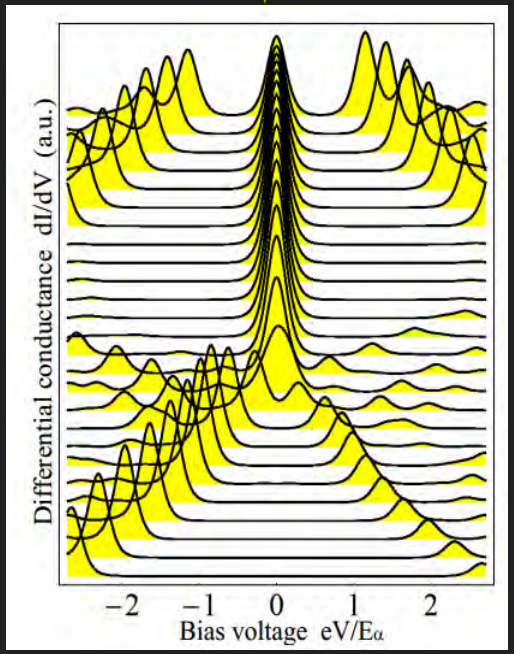


Signature of a MF in a magnetic field









- In a wire, we get the zero modes at the ends of the wire.
- If we vary the magnetic field, we can see the zero mode only appears when the field is strong enough to open a gap.
- If the field is stronger than the spin-orbit coupling, we get back into a non-topological phase

After Stanescu, Lutchyn, Das Sarma 2011
http://arxiv.org/abs/1106.3078

Periodic Table of Topological Insulators

AZ	Symmetry Θ	Ξ	Π	d = 1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	−1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	−1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	−1	−1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	−1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	−1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

Majorana chain ($InSb$)

$p_x + ip_y$ ($SrRuO_4$)

TI ($HgTe$)

Carbon nanotubes

TI ($BiSb$)

Integer Quantum Hall Effect (GaAs)

$Superfluid$ $^3He - B$

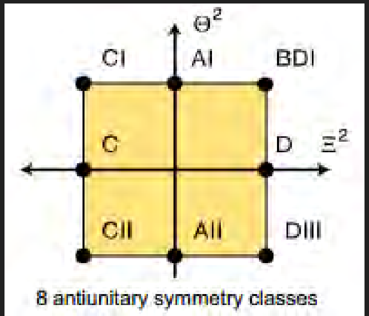
Bott Periodicity: $d \to d + 8$

Symmetries: ± 1 = Square of symmetry

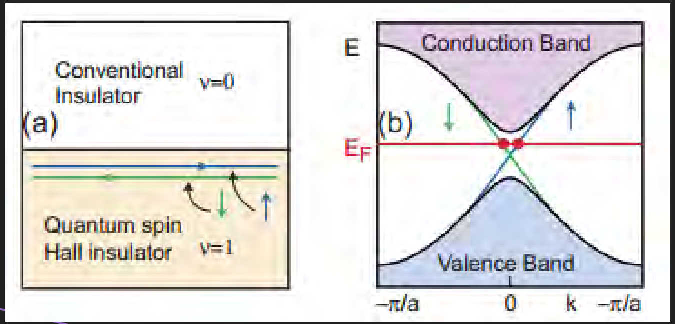
Θ = Time reversal: $\Theta H(\boldsymbol{k})\Theta^{-1} = +H(-\mathbf{k})$

Ξ = Particle-Hole: $\Xi H(\boldsymbol{k})\Xi^{-1} = -H(-\mathbf{k})$

Π = Chiral $\propto \Theta\Xi$: $\Pi H(\boldsymbol{k})\Pi^{-1} = -H(\boldsymbol{k})$



Altland-Zirnbauer Random Matrix Classes (http://arxiv.org/abs/cond-mat/9602137)



After Hasan, Kane 2010 http://arxiv.org/abs/1002.3895
and Kitaev 2009 http://arxiv.org/abs/0901.2686
and Freedman et. al. 2010 http://arxiv.org/abs/1005.058