Quantum memories and Schrödinger's Cat

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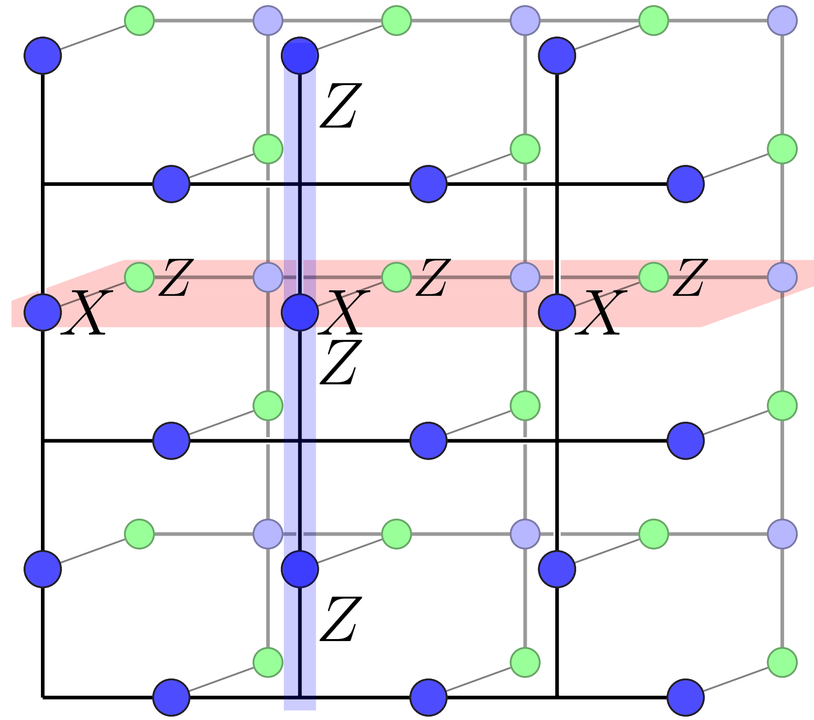
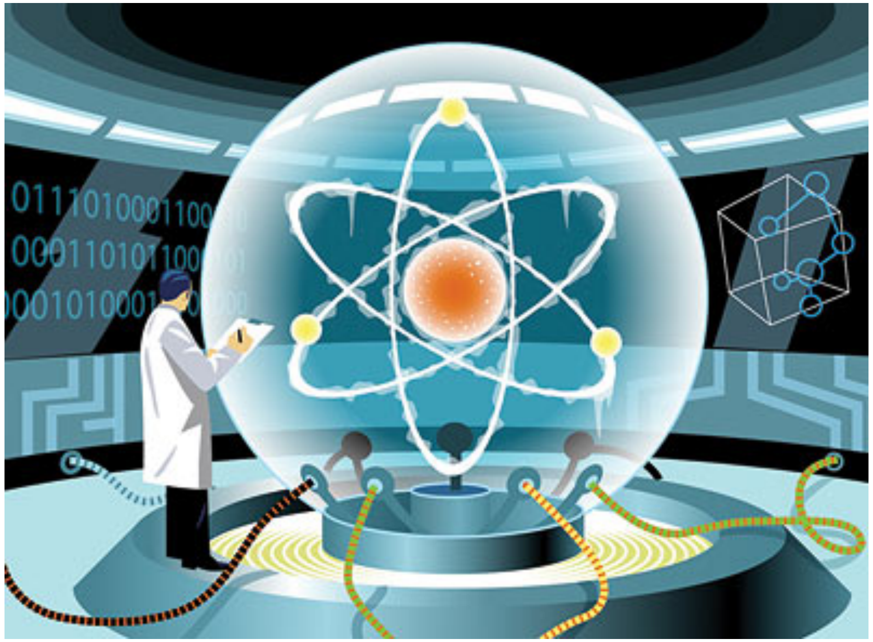
THE UNIVERSITY OF SYDNEY

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

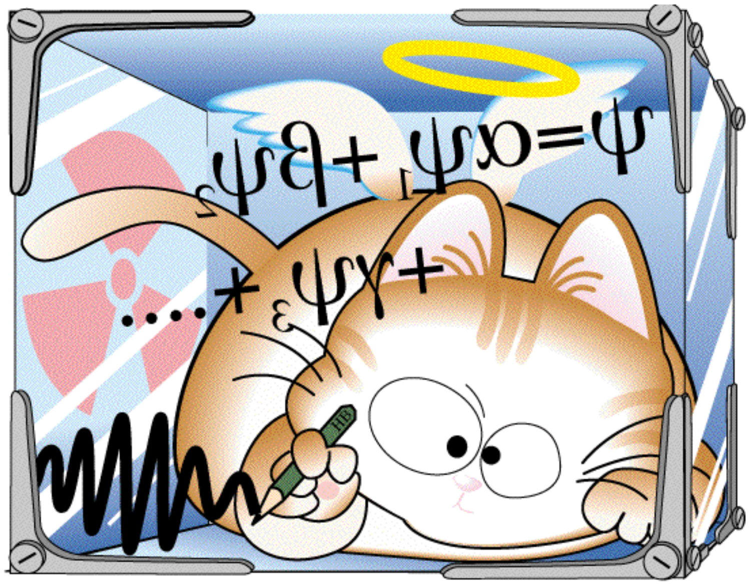


The big question

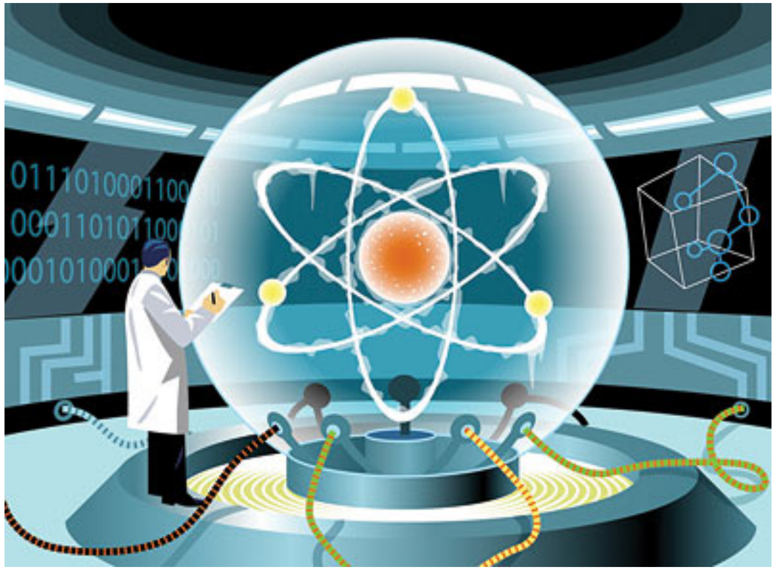


How do we maintain the coherence of a macroscopic system for a long time in the presence of noise?

The big question



How do we maintain the coherence of a macroscopic system for a long time in the presence of noise?



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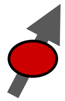
Quantum vs classical memories

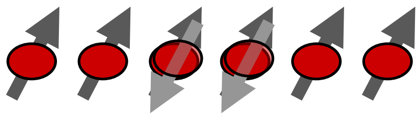
What makes a good *classical* memory?

Ising spin magnets as classical memories

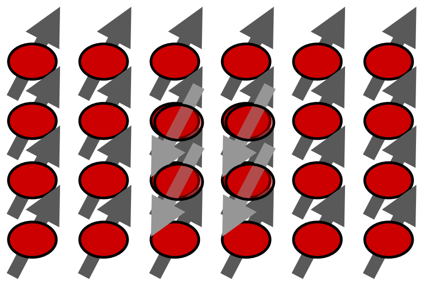
Each spin prefers to be aligned with its neighbour(s)

One spin:  **BAD**

Low energy errors
No error correction

1-D chain:  **OK**

Low energy errors
Error correction!
Uncorrectable errors have low energy too

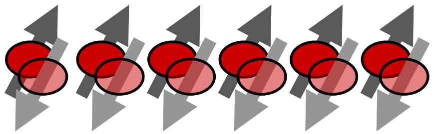
2-D lattice:  **GREAT**

Low energy errors
Self-correcting!
Larger errors cost more energy

… but doesn't preserve quantum info.

What makes a good quantum memory?

Quantum spin magnets

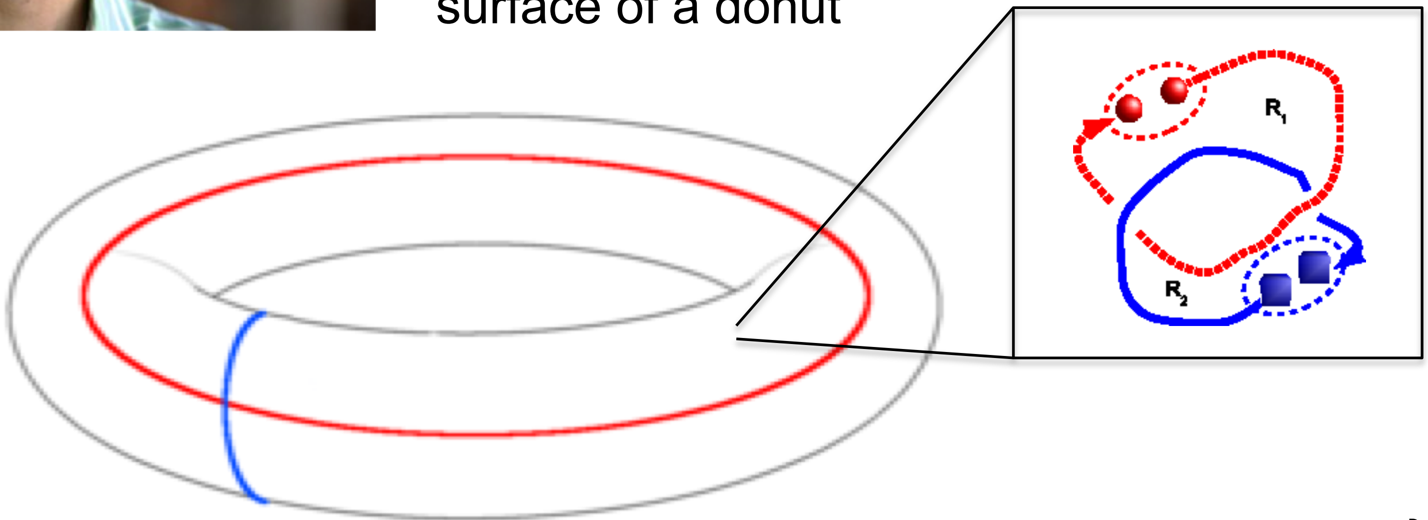
1-D chain:  **BAD**

2-D lattice: **???**

Quantum Memories

Alexei Kitaev – 1997

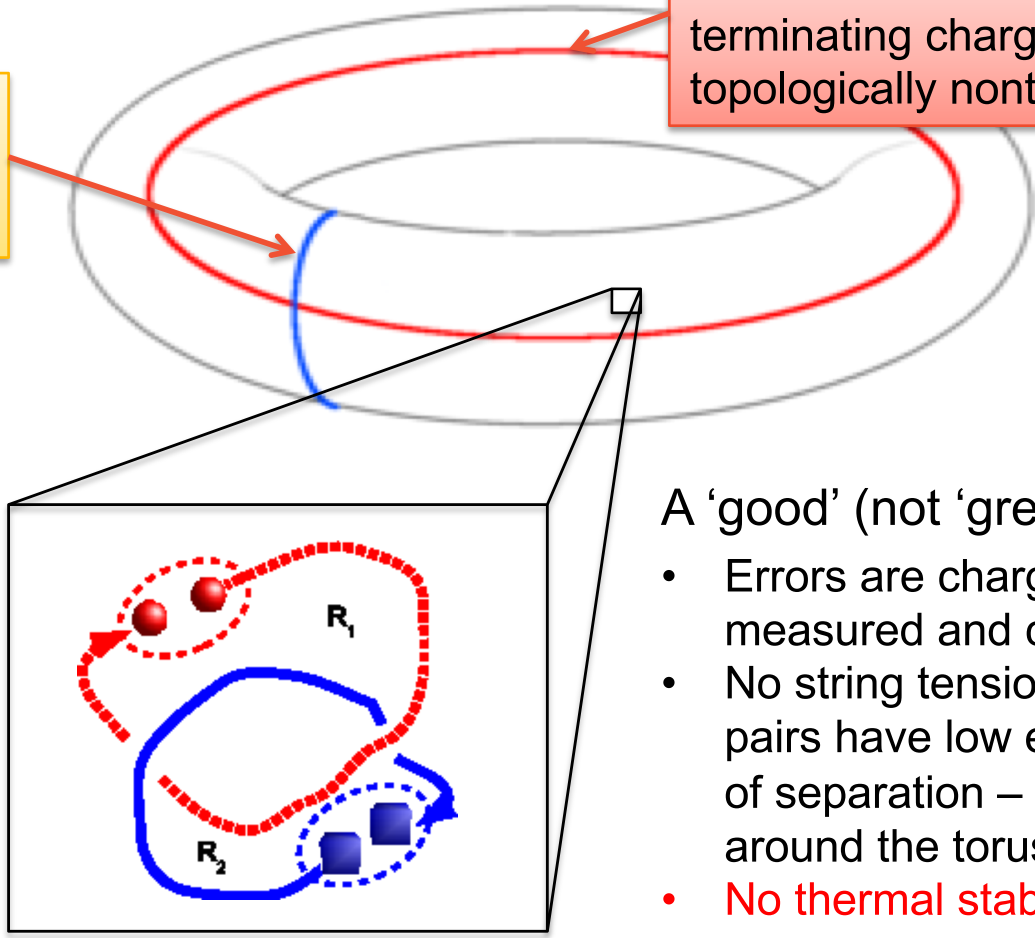
Good quantum memory:
need a spin lattice that emulates 2D quantum electromagnetism on the surface of a donut



The toric code

Magnetic flux with no terminating charge; topologically nontrivial

Electric flux with no terminating charge; topologically nontrivial



A simple exactly-solvable model:

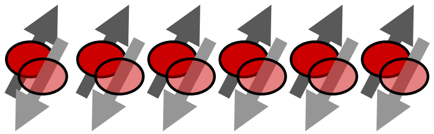
- 4-fold degenerate ground space
- ‘Topologically ordered’
- Excitations are anyons – electric and magnetic charges

A ‘good’ (not ‘great’) q. memory:

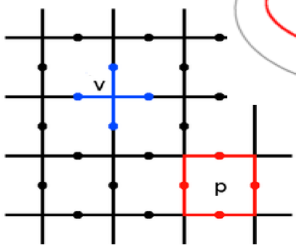
- Errors are charge pairs, can be measured and corrected
- No string tension/confinement – pairs have low energy regardless of separation – can wander around the torus
- No thermal stability

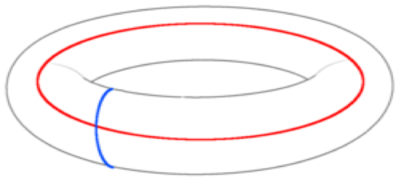
What makes a good memory?

Quantum spin magnets

1-D chain:  **BAD**

Low energy errors
Can correct flip errors, but not phase errors

2-D lattice: 

 **OK**

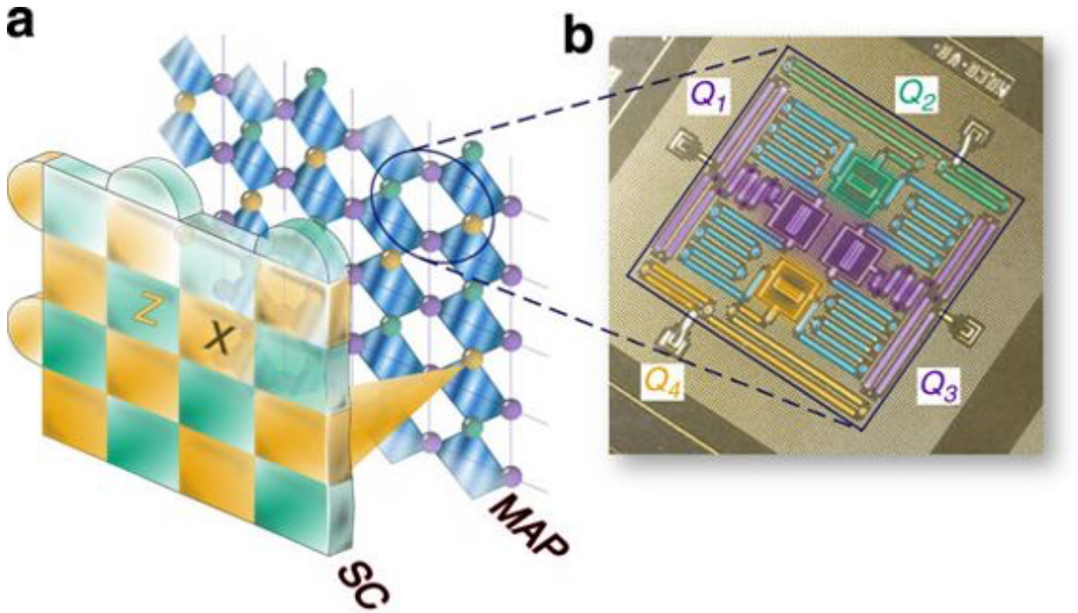
"Toric Code"

Low energy errors
Error correction for flip and phase errors!
Uncorrectable errors have low energy too

‘Surface code’ architecture for quantum computing

Most common quantum architecture:

- ‘Planar’ version
- Requires constant measurements of local electric/magnetic flux loops
- Can suppress <1% errors per clock cycle
- 1000’s of physical qubits per encoded qubit at realistic error rates – very large overheads

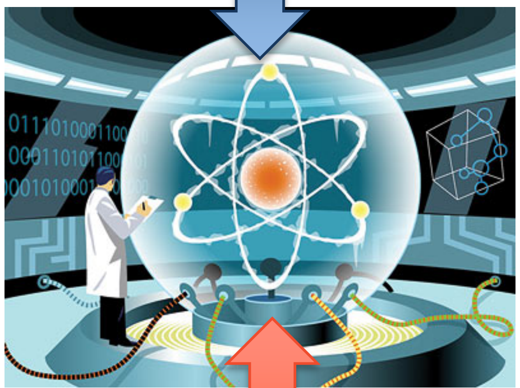


IBM proto-code device, 2016

You said ‘topological’ codes… is that topological q computing?

Synthesise new materials with topological phases and anyonic excitations

Develop control techniques to manipulate anyons and process information

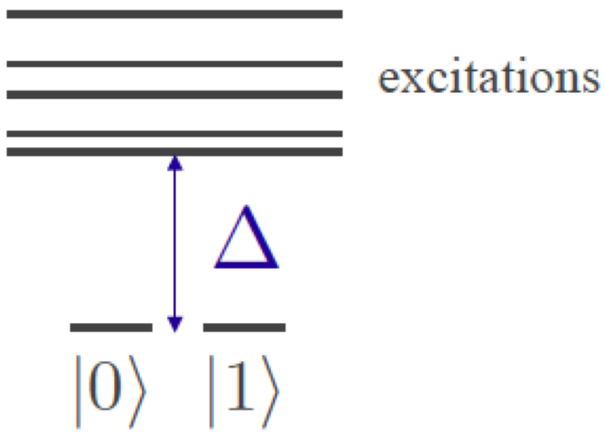


Construct topological codes out of these qubits and gates

Build high-fidelity qubits and quantum gates

TQFTs, Chern-Simons ⟷ Spin lattice models

The miracle of topological codes…



- Degenerate ground states allow for storage of quantum information
- No relaxation
- No dephasing (actually exponentially suppressed)
- Errors (excitations) to higher energy levels
  - suppressed by the gap
  - correctable if local
- High thresholds, nice q computing architectures

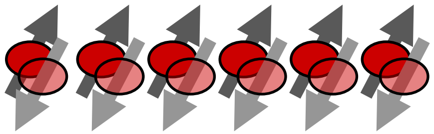
But: With (most) topological stabilizer codes, quantum information is **not stable** on its own

Need to constantly perform error correction

What makes a good memory?

Quantum spin magnets

1-D chain:



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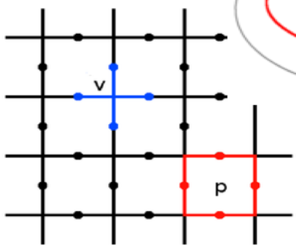
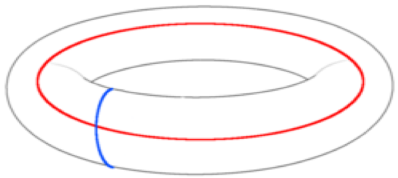
Low energy errors
Can correct flip errors, but not phase errors

2-D lattice:





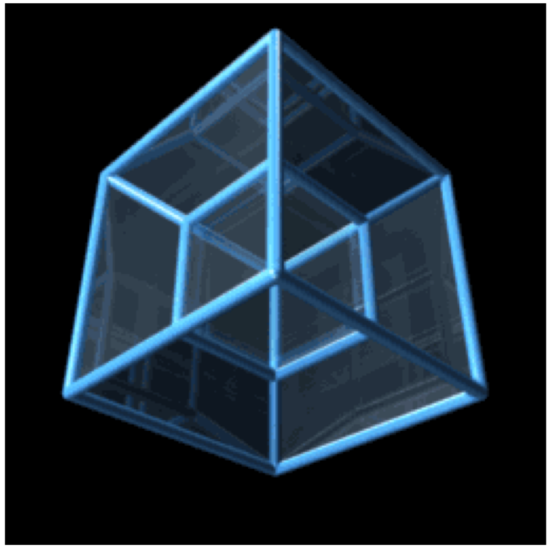
OK

“Toric Code”

Low energy errors
Error correction for flip and phase errors!
Uncorrectable errors have low energy too

????

Toric code in four dimensions



How good are you at picturing 4D?

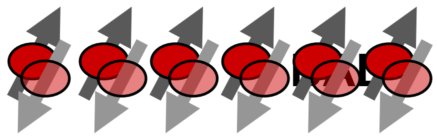
- 4D Z_2 lattice quantum electromagnetism
- Electric and magnetic 'charges' are not point-like, but loop-like, with *tension*
- Energetics is like the 2D Ising model, but for both electric and magnetic sectors
- Errors need a macroscopic energy to grow
- Finite-temperature phase transition

Dennis, Kitaev, Landahl, Preskill 2003

What makes a good quantum memory?

Quantum spin magnets

1-D chain:



Low energy errors
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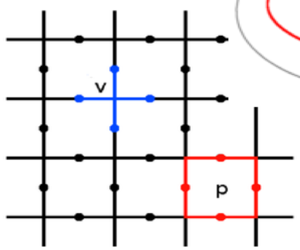

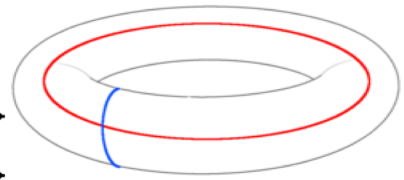

"Toric Code"

Low energy errors
Error correction for flip and phase errors!
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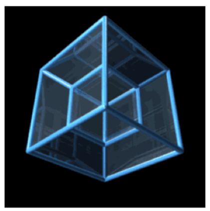
4-D lattice:

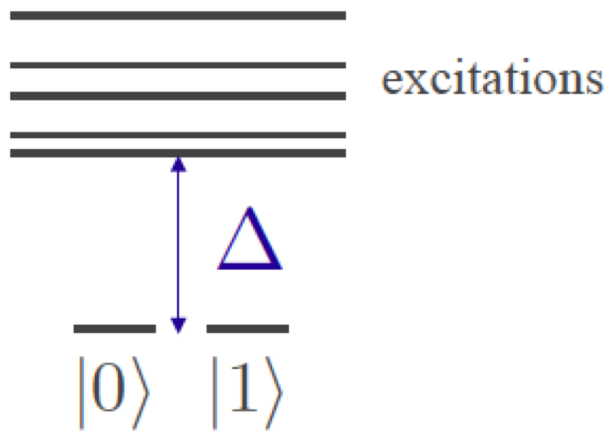


4D Toric Code

Low energy errors
Self-correcting
Larger errors cost more energy

Quantum memories in 3-D

Can we design a self-correcting quantum memory ?



The Caltech rules

1. a spin lattice
2. local interactions
3. degenerate ground space
4. stable under small perturbations
5. coupled to a thermal bath at non-zero temperature, lifetime of the encoded qubit scales exponentially in the size of the lattice

No-go theorems for 2 and 3 dimensions

- Lifetime typically given by Arrhenuis law: $\tau \sim \exp(\beta \Delta_B)$

  energy barrier of logical operator

- Models in 2D have a constant energy barrier:
  - Bravyi and Terhal (2008) – 2D stabilizer models
  - Landon-Cardinal and Poulin (2012) – Most 2D topological models (locally commuting projector codes)
  - **Deconfined anyons are a hallmark of topological order in 2D**
- Most models in 3D have a constant energy barrier:
  - 3D topological stabilizer codes generically have the same problems
  - Yoshida (2011), Pastawski and Yoshida (2014)

Symmetry-protected self-correcting quantum memories

Sam Roberts and Stephen Bartlett

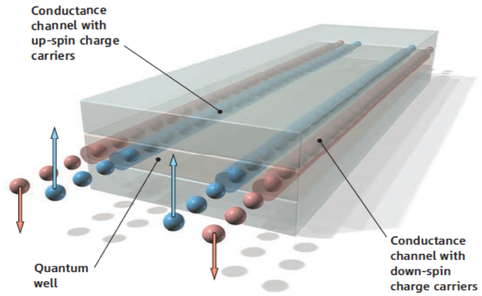
arXiv:1805.01474

What role can symmetry play?

From topological order to symmetry-protected topological order

Symmetry-protected topological order

- Restricted form of topological order
- Robust to local perturbations that respect a symmetry



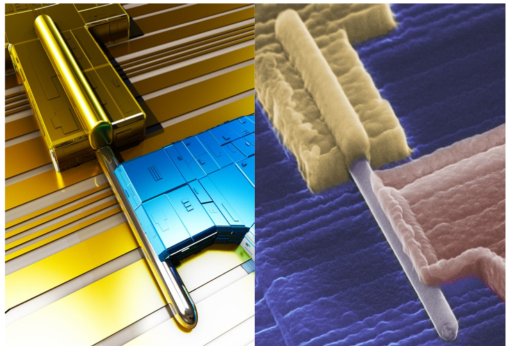
Quantum Spin Hall Insulator State in HgTe Quantum Wells

Markus König,[1] Steffen Wiedmann,[1] Christoph Brüne,[1] Andreas Roth,[1] Hartmut Buhmann,[1] Laurens W. Molenkamp,[1*] Xiao-Liang Qi,[2] Shou-Cheng Zhang[2]

2 NOVEMBER 2007 VOL 318 SCIENCE www.sciencemag.org

Topological insulators

Majorana fermions in nanowires



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]†

www.sciencemag.org SCIENCE VOL 336 25 MAY 2012

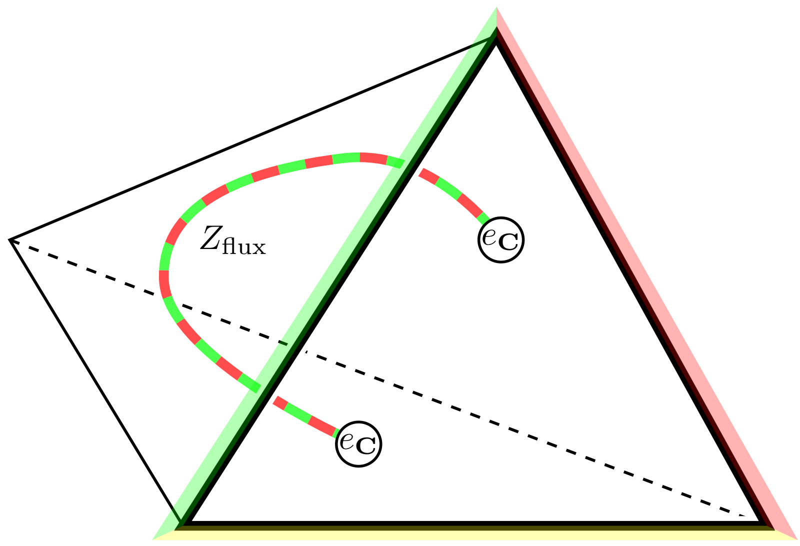
SPT order offers new phenomena

In 3D, topological order and SPT order can coexist and interact

The physics of energy barriers in 3D

- 3D topological models encode quantum information on the boundaries
- Bulk excitations can be confined (string-like) but boundary excitations are deconfined
- If we can couple the boundary and bulk theories, we can have confinement of all excitations
- An exotic type of symmetry is needed:

  1-form symmetry

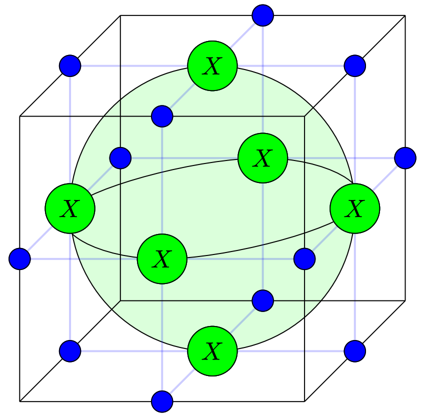


A little nugget from string theory!

- A new type of symmetry: **1-form symmetry**
- Imposes a Gauss-type law on topological charge

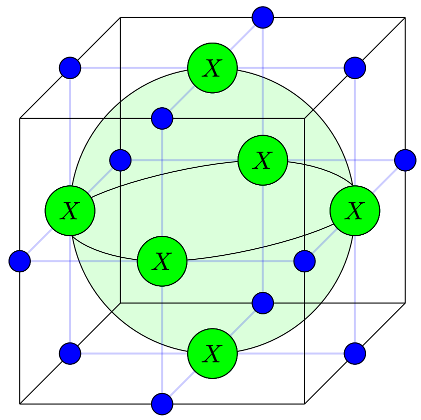
- Natural generalization of on-site (0-form) symmetry
- Global q-form symmetry acts as $U_g(\mathcal{M})$ on a closed q-codimension manifold $\mathcal{M}$
- Charged excitations have dimension q
- Symmetries impose conservation laws on higher-dimensional charged objects

- *Think of it a bit like a local gauge symmetry*

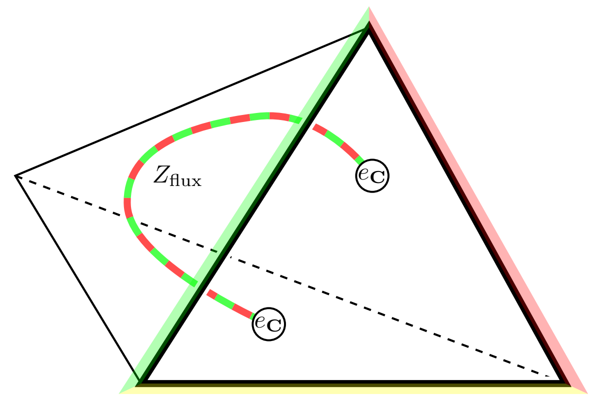


Baez and Huerta (2010)
Kapustin and Thorngren (2013)
Kapustin and Seiberg (2014)
Giaotto, Kapustin, Seiberg, and Willett (2015)
Yoshida (2015)

Symmetry-protected self-correcting memory in 3D

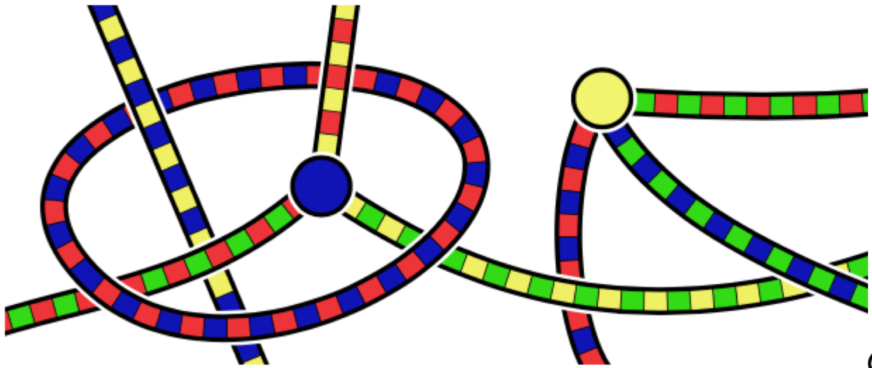


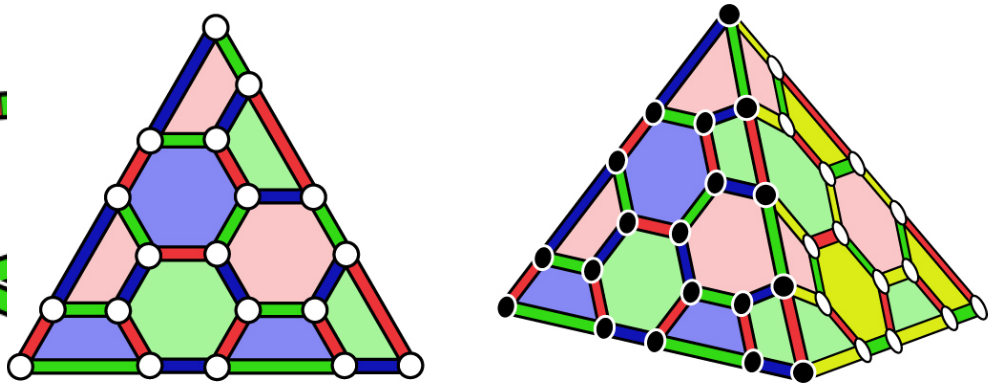
- Simplest model: Z2 x Z2 1-form symmetry
- Bulk model is SPT ordered
  - Bulk excitations are closed loops with tension
  - Two types, on primal and dual lattices
- Boundary is SET ordered
  - Electric and magnetic anyons, like the toric code
  - Symmetry couples these anyons to bulk loops, and confines them
  - Boundary theory should not exist! *Anomalous*
  - SET model only exists on boundary of SPT bulk
- SPT ordered model is thermally stable!



Self-correction, symmetries, and emergence

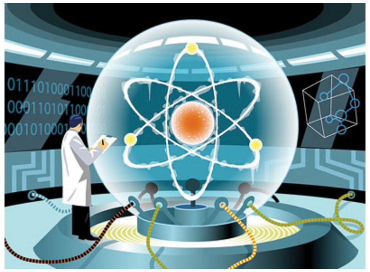
- 1-form symmetric SPT phases in 3D can be self-correcting quantum memories
- Higher-form symmetries appear necessary for thermal stability, but are very strong symmetry constraints
- 1-form symmetries can be enforced through error correction
- 1-form symmetries can be emergent
  - Can they emerge in a model where all excitations are confined?





Gauge color code (Bombin, 2015, 2016)

Quantum Memories – summary



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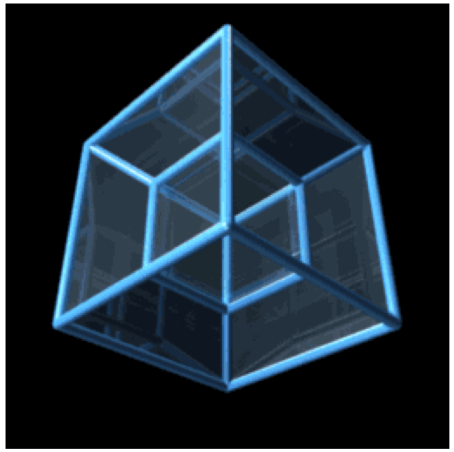
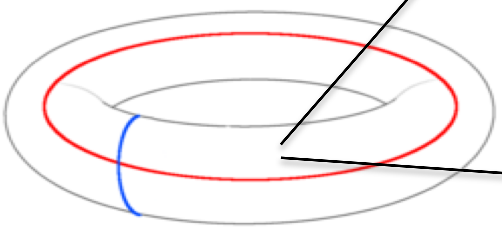
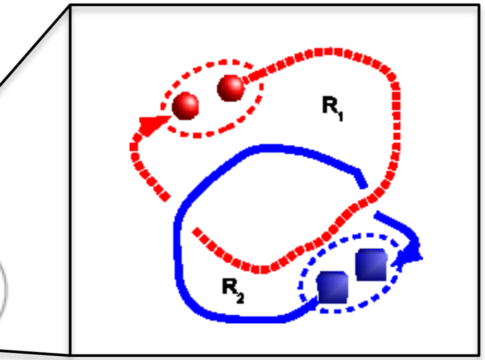
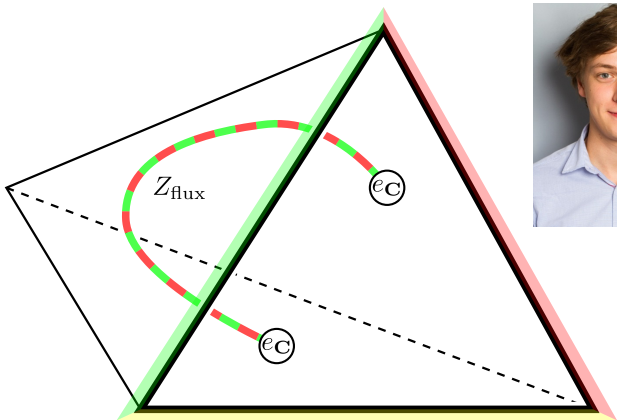








Quantum Science @ Sydney

Quantum Nanoscience

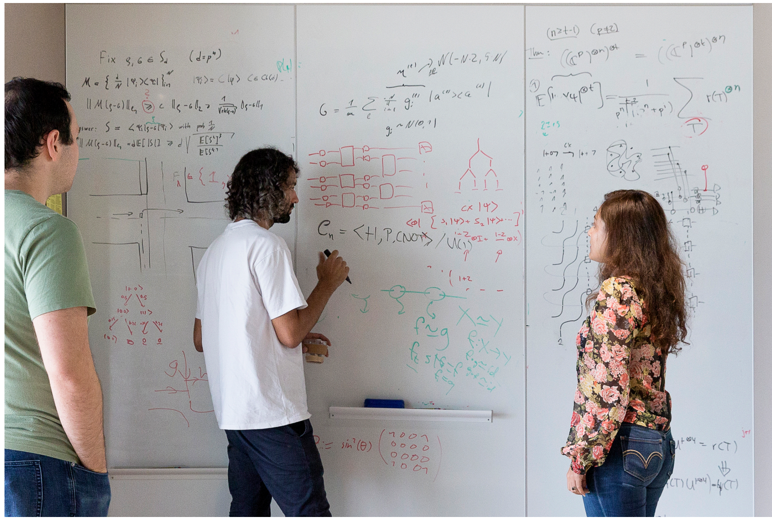
David Reilly

Microsoft

Quantum Control

Michael Biercuk

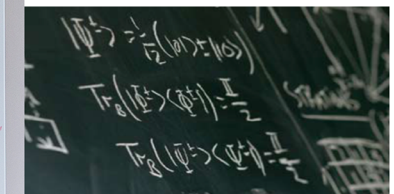
Q-CTRL



Quantum Theory

Stephen Bartlett

Steven Flammia

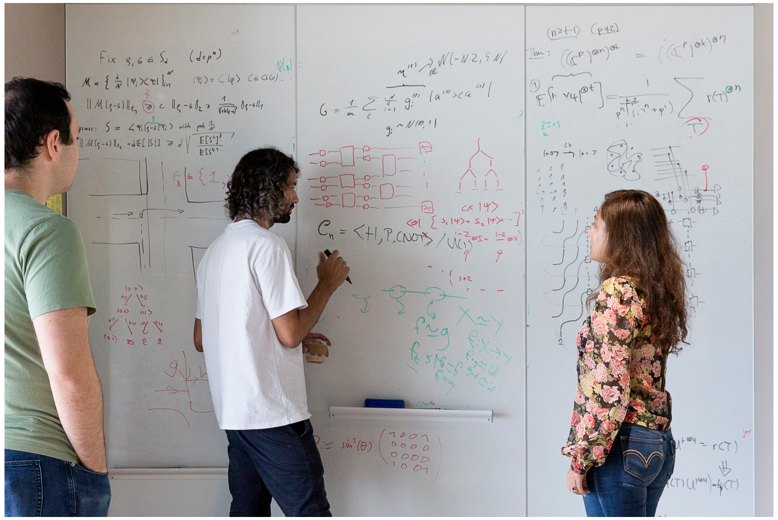


Quantum Science @ Sydney – come join us!

Quantum information theory group leaders:

Stephen Bartlett, Steve Flammia, Arne Grimsmo, Isaac Kim

Postdoc positions now accepting applications:



'Women of EQUS' Deborah Jin Fellowship

http://equs.org

Sydney Quantum Academy offering PhD and postdoc positions starting 2020