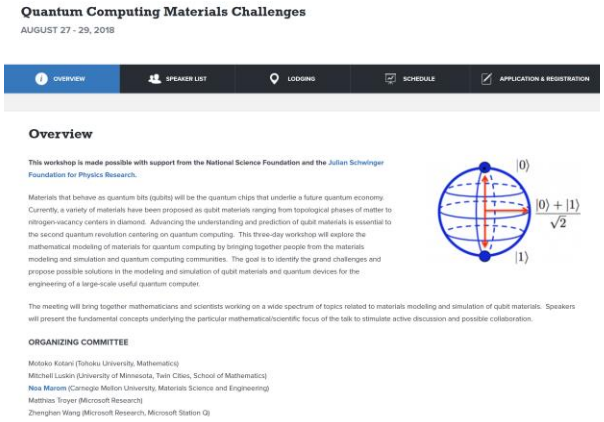
Qubit Materialization Challenges: Rise above the Noise



Quantum Computing Materials Challenges

AUGUST 27 - 29, 2018

Overview

This workshop is made possible with support from the National Science Foundation and the Julian Schwinger Foundation for Physics Research.

Materials that behave as quantum bits (qubits) will be the quantum chips that underlie a future quantum economy. Currently, a variety of materials have been proposed as qubit materials ranging from topological phases of matter to nitrogen-vacancy centers in diamond. Advancing the understanding and prediction of qubit materials is essential to the second quantum revolution centering on quantum computing. This three-day workshop will explore the mathematical modeling of materials for quantum computing by bringing together people from the materials modeling and simulation and quantum computing communities. The goal is to identify the grand challenges and propose possible solutions in the modeling and simulation of qubit materials and quantum devices for the engineering of a large-scale useful quantum computer.

The meeting will bring together mathematicians and scientists working on a wide spectrum of topics related to materials modeling and simulation of qubit materials. Speakers will present the fundamental concepts underlying the particular mathematical/scientific focus of the talk to stimulate active discussion and possible collaboration.

ORGANIZING COMMITTEE

Motoko Kotani (Tohoku University, Mathematics)
Mitchell Luskin (University of Minnesota, Twin Cities, School of Mathematics)
Noa Marom (Carnegie Mellon University, Materials Science and Engineering)
Matthias Troyer (Microsoft Research)
Zhenghan Wang (Microsoft Research, Microsoft Station Q)

Assignment:

a summary talk,
with some thought-provoking ideas
and suggestions for what is next.

Zhenghan Wang
Microsoft Station Q & UC Sana Barbara

IPAM, August. 29, 2018

Thank S. Das Sarma and S. Girvin

Sankar Das Sarma (Maryland, physicist):

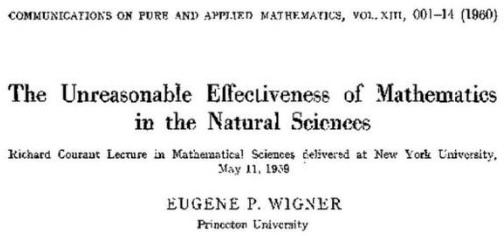
- **Can quantum error corrections be performed in the laboratory for many coupled qubits (are there materials which will make the physical errors small enough to make this feasible)-- what are the mathematical constraints on the materials properties necessary for this?**
- How do errors scale with increasing number of qubits?
- What is the real error correction thresholds in real materials where the errors are not uncorrelated?
- **Can materials science be perfected to create an "easy" Fibonacci topological quantum computer where dense topological quantum computing would become possible? What are the minimal mathematical requirements?**
- How best to combine ordinary and anyon-based topological quantum computing so that the advantage of robust quantum memory can be seamlessly combined with the advantage of simple gate operations?
- What are the best ways of carrying out topological gate operations in real materials using Majorana zero modes? (There are many competing proposals right now, none seems to work at this point as you know well.)
- What is the trade off between the number of qubits versus the number of gate operations in quantum computers made of real materials to solve real problems? A TQC may have very little error, but it may require far too many operations to be useful. A circuit based QC may have limited number of gate operations, but may necessitate exponentially large number of qubits!
- **Topological qubit versus topological code using regular qubits-- is there a specific advantage in one versus the other in real materials or is it simply a trade off between number of qubits (in the topological code) versus the difficulties in making a qubit (in the topological qubit)-- can some precise mathematical statement be made here?**

Steve Girvin (Yale, physicist):

- **Can we using electronic structure calculation methods to discover new optical defect centers with better properties as qubits? This type of theoretical modeling is just getting underway.**

  Talks: Cances, Muller, Economou
- What defects are the source of dissipation and dephasing in the various solid-state qubits (superconducting, NV centers, etc.)
- There is growing interesting optomechanics and quantum acoustics for quantum information storage and processing. What types of defects limit the quality factors of mechanical resonances?
- What is the optimal encoding for transmission of bosonic information through an amplitude damping channel? If it is GKP, what is the optimal decoding transformation?
- What is the quantum channel capacity for the Gaussian thermal channel? What is the optimal code for this channel? What is the optimal decoder?

Can Mathematicians Help?



COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. XIII, 001–14 (1960)

The Unreasonable Effectiveness of Mathematics
in the Natural Sciences

Richard Courant Lecture in Mathematical Sciences delivered at New York University,
May 11, 1959

EUGENE P. WIGNER
Princeton University

For his contributions to the theory of the atomic nucleus
and the elementary particles, particularly through the discovery
and application of **fundamental symmetry principles**

Classical computation:

Babbage, Turing, Shannon, von Neumann,…

Quantum computation:

???

How?

- **Software and design**: easy
- **Hardware or materials**: hard

  ideal for mathematicians: solve equations with given initial conditions

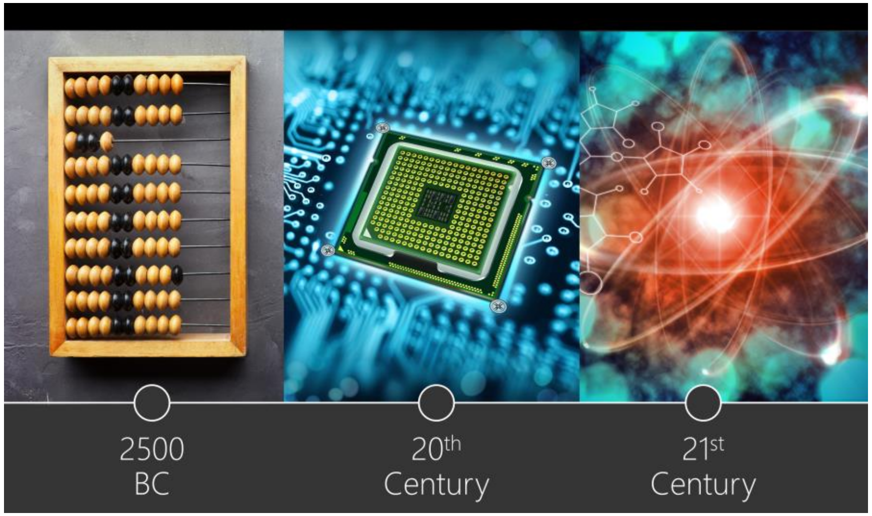
  more realistic: collaboration with physicists and engineers for simulation, growth, characterization, fabrication of qubit materials and qubit measurement.

  Fortunately, this is the perfect time to do so as there are not yet winners of any particular kinds of qubits---maybe mathematicians can help to decide.

- **More abstractly:**

  Study effective theory of quantum materials, e.g. topological quantum field theories or modular tensor categories for topological phases of matter, and classify them.

Why Quantum Computing?



More than 4000 years between Abacus and modern chip, but same principles and information unit---the **Bits**.

Quantum building blocks fundamentally different—the **Qubits**.

An instrument like telescope and microscope for the quantum world, and the potential to change classical logic---how to prove mathematical theorems, and convict criminals in a quantum justice system.

A quantum age: quantum control and engineering
Talk: Troyer

Quantum Computing

- 1959, Feynman: there is plenty of room at the bottom
- …
- 1994 Shor’s algorithm
- 1996 Shor, Steane error correction
- …
- **build a raw quantum device (no error correction)** with any kinds of physical qubits to do some useful quantum computing, e.g. quantum games for education. Talks: coherent Ising machine (Yamamoto), quantum annealing (Nishimori). **Need both software and hardware to find something useful to do.** Talks: quantum chemistry (Chan and Reiher)
- …
- Quantum supremacy
- …
- Scalable universal quantum computer

Where Are We? Analog vs Digital

- 1843 Ada on Babbage’s analytical engine
- 1847 Boolean logic
- 1890 Census by punch-card machines by H. Hollerith
- **1931 Vannevar Bush devise differential analyzer.**
- 1935 Tommy Flowers use vacuum tubes as switches
- 1937 Turing, Shannon, …
- …
- **1939 Turing arrives at Pletchley park**
- …
- **1944 von Neumann works on ENIAC**
- …

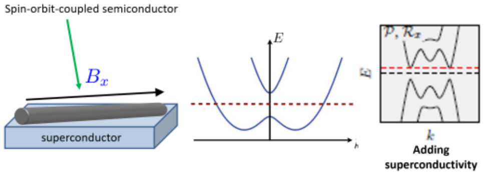
The innovators, W. Isaacson

What is Next?

- **Strongly correlated materials:**

  Explore the wide region of Hilbert spaces

- **Simulation, fabrication of semi-conductor and superconductor interface:**



$$H = \int d^2\mathbf{r}\psi^\dagger\left[-\frac{\nabla^2}{2m} - \mu - i\alpha(\sigma^x\partial_y - \sigma^y\partial_x) + V_z\sigma^z\right]\psi$$
$$+ \int d^2\mathbf{r}(\Delta\psi_\uparrow\psi_\downarrow + h.c.)$$

(Sau, Lutchyn, Tewari, & Das Sarma 2009)

- **Error correction especially adversary noise:**

  beyond uncorrelated unrealistic error models,

  materials and device specific error models, protection and correction

All About Errors: Nature Abhors Conformity

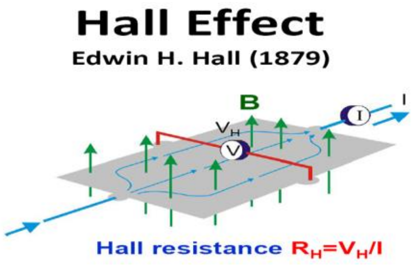
- **Nature idealized to quantum:**

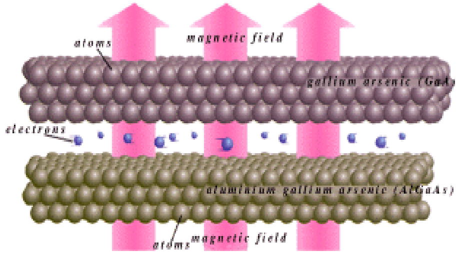
  Contradictory requirements---
  superposition needs isolation and
  entanglement needs coupling.
- **Errors:**

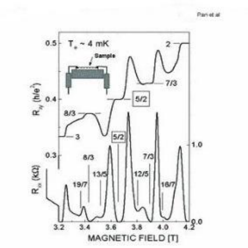
  noise for Hamiltonian (gates),
  quantum state decoherence---
  leakage of information to environment

Mitigate Errors

- **Error protection (**topological or chemical**)**
- **Error correction**
- **Many layers of error modeling:** error model of each specific qubit materialization---errors in effective theory, errors in materials and errors in experiments. Talks: Dot qubit (Coppersmith, Barnes, Muller)
- **Lessons from topological quantum computing (TQC):** why TQC with fractional quantum Hall liquids are not working yet---theory, thermal anyon, random potential. Talks: Lutchyn, Bauer, Kawahigashi

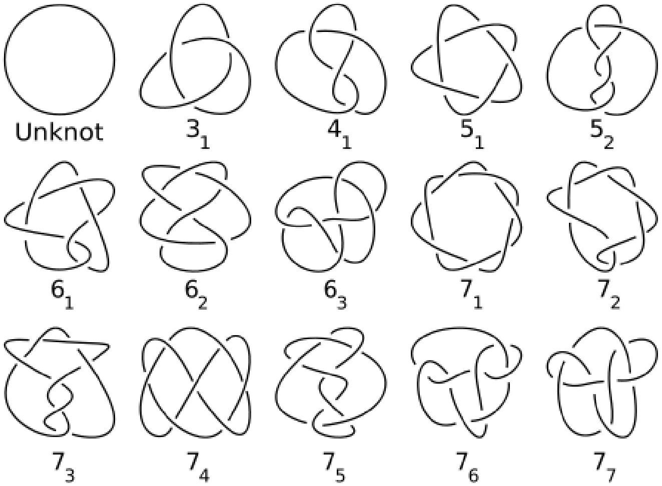






Topological Protection

- **Topology** is conceived of as the part of geometry which survives deformation.



- But, equally, **topology** is the part of quantum physics which is robust to deformation (error).

TQC (topological) vs tQC (traditional)

- Theoretically ground states of **topological phases of matter (where information stored)** form error correction codes
- **No** fully controlled **topological qubits** yet

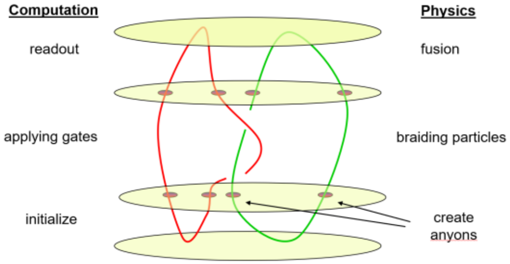
	TQC	tQC
$Physical$	NA	~ 72
$Logical$	$\epsilon < 1$	$\delta < 1$

Freedman

Kitaev

Topological Quantum Computation (TQC)

Freedman 97, Kitaev 97, Freedman-Larsen-W. 00



- Mathematics of topological quantum computing (with E. Rowell), Bull. AMS, vol. 55, 2018, arXiv:1705.06206
- Topological quantum computation, CBMS monograph, vol. 112, 2010, http://web.math.ucsb.edu/~zhenghwa/course.php

Microsoft’s unique approach

Revolutionary topological approach

Our quantum approach brings theory to reality, harnessing topological qubits that perform computations longer and more consistently, with fewer errors.

Bold investments and a global team

For more than a decade, we’ve made consistent investments and built the quantum dream team with collaboration across universities, industries, and more.

Scalable, end-to-end technology

Our full-stack quantum-computing solution is designed so you and your developers can approach quantum computing right away, with the ability to scale.