QEC in 2017: Past, present, and future

topological quantum code

holographic quantum code
Maintaining coherence in quantum computers

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The effects of the inevitable coupling to external degrees of freedom of a quantum computer are examined. It is found that for quantum calculations (in which the maintenance of coherence over a large number of states is important), not only must the coupling be small, but the time taken in the quantum calculation must be less than the thermal time scale $\hbar/k_B T$. For longer times the condition on the strength of the coupling to the external world becomes much more stringent.

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“The thermal time scale thus sets a (weak) limit on the length of time that a quantum calculation can take.”
“...small errors will accumulate and cause the computation to go off track.”
Therefore we think it fair to say that, unless some unforeseen new physics is discovered, the implementation of error-correcting codes will become exceedingly difficult as soon as one has to deal with more than a few gates. In this sense the large-scale quantum machine, though it may be the computer scientist's dream, is the experimenter's nightmare.
Peter Shor

Quantum error-correcting codes (1995)
Fault-tolerant syndrome measurement (1996)
Using QEC to prove security of QKD (2000)
Alexei Kitaev

Topological quantum codes (1996)
Physically protected quantum computing (1997)
Computing with nonabelian anyons (1997)
Majorana modes in quantum wires (2000)
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And many others, of course: Steane, Knill and Laflamme, Aharonov and Ben-Or, Gottesman, ...
Modern heros: Bombin, Bravyi, Terhal, Poulin, Haah, ...
And a new generation!
Surprises

-- Industrial (and VC) investment in quantum technology ramped up faster than expected.

-- Many string theorists now appreciate the relevance of quantum error correction in quantum gravity research.

And ... what else? #QEC17
Questions to ponder

What to do about all the hype?

What role for academic researchers?
Surface Code Triumphant (for now)

There have been lots of interesting new ideas about fault-tolerant quantum computing over the past 10 years, but the 2D surface code (with holes or twists) is still our most promising idea for scalability in a universal quantum computer, at least in the relatively near term. (Geometric locality in 2D, and a high threshold, assuming fast classical processing ... though we would like faster decoding and a non-Clifford gate with lower overhead.)

This could change, e.g. if/when qubits have higher connectivity, or better gate error rates. Or if somebody has a better idea...
Added to Caltech QEC course since 2007

Color code and gauge color code (Bombin).

Codes and symmetry-protected topological phases.

Lattice surgery, code deformations for fault-tolerant (Clifford) gates.

Cleaning lemma and bounds on $[[n,k,d]]$ for local codes --- e.g., $kd^2 = O(n)$ in 2D (Bravyi-Poulin-Terhal). No self correction in 2D.

Bravyi-Koenig: Dth level of Clifford hierarchy in D-dim constant depth.

Ways to circumvent the Eastin-Knill theorem.

Majorana zero modes in quantum wires.

And ... what else has conceptual interest and enduring value? #QEC17

Added somewhat earlier (course has been taught since 1998)

Decoding the toric code using minimal weight perfect matching. Threshold estimate.

Equivalence of topological and circuit models of quantum computing.

Thresholds for Hamiltonian noise models: coherence and non-Markovian noise.

Magic state distillation protocols.

Subsystem codes (Bacon-Shor).
What’s hot? What’s not?

Underrepresented compared to past QEC meetings

Dynamical decoupling and noiseless subsystems
Coherent feedback and quantum control
Long distance quantum communication (repeaters)
Noisy channel coding, Shannon theory
Fault-tolerant adiabatic quantum computing
Quantum computing with nonabelian anyons and Majoranas
Skepticism of QEC and FTQC

This year’s breakdown (34 talks + overview talk)

(9) Topological codes (BS, toric, color): Yoder, Jones, Lithinski, Browne, Terhal, Kubica, Beverland, Brown, Krishna
(8) General fault tolerance: Flammia, Gottesman, Bravyi, Haah, Fowler, Campbell, Poulin, Chao
(8) Experiments/platforms (SC, ions, NV): Taminlau, Martinis, Paik, Schoelkopf, Linke, Marinelli, Gutierrez, Flühmann
(4) Gravitation, holography, and QEC: Harlow, Yoshida, Pastawski, Swingle
(2) General coding: Kastoryano, Nezami
(1) Continuous variables: Niu
(1) Sensing: Cappellaro
(1) AQC: Lidar
What to expect at QEC 2117?

We’ll have much, much, much better qubits. And big advances in systems engineering.

Won’t we? But how?

More reliable? Faster? Higher connectivity?

Ultimate speed limit: One gate per Planck time per Planck mass. ($10^{48}$ ops/sec for one gram --- processing speed of a black hole.)

Classical processors: Error correction was at first essential, then less important, now becoming quite important again.

*What do you think? #QEC17*
In the long run, which path to scalability is likely to succeed?

(1) Topological quantum computing with anyons.

(2) “Garden variety qubits” protected by QECC. (E.g. topological codes or concatenated codes).

In the long run, will both be crucial?

No matter how good our qubits are, we’ll always want better ones. There’s an incentive to build physical error protection into qubit design.

Even with very reliable qubits and gates, we can go further using codes atop the physical layer (Litinski’s talk).

Will the distinction between (1) and (2) blur over time? Or is there another idea we are still missing?
FTQC in small experiments
What might we learn by the time of #QEC2019?

How important are noise correlations?
How important are non-Markovian effects?
How important is coherence of noise?
How effective are noise tailoring methods?
How much do we gain by customizing decoders to noise in realistic devices?
What decoding methods work well and scale well? Machine learning?
Toward an eternal qubit!
Encouragement (or discouragement) concerning prospects for scalability.
From physical to logical benchmarking

Randomized benchmarking describes noise with a small number of parameters, separates gate and SPAM error.

The community has learned good data science practices for interpretation of physical benchmarking experiments.

Randomized benchmarking determines gate infidelity averaged uniformly over inputs. What that implies for e.g. the diamond norm or fault-tolerant thresholds is a complicated story (Flammia, Poulin talks).

Better worst case estimates when “unitarity” is low (Flammia’s talk).

Pauli noise is the “free-fermion model” of fault tolerance. It is not the real thing. Tensor network methods may be suited for more realistic noise modeling. (Poulin, Bravyi talks.)

Need to include ancillas for full fault tolerance. The era of logical benchmarking is beginning. (Initially, postselected, with error detection; later, with error correction).
Threshold, threshold, threshold, ...

(“everything and nothing” – Terhal)

Concatenated distance-3 codes, extended rectangles, malignant sets, ...

Postselected protocols, with higher thresholds.

Concatenated error-detecting code (“Fibonacci scheme”).

Hamiltonian non-Markovian noise. (Works for any bath, weakly coupled to system.)

Hamiltonian noise with long-range correlations.

Gaussian noise. (Works for an oscillator bath and low temperature.)

Codes and gadgets for higher threshold with biased noise.

Opportunities:

Threshold from experimentally observed data.

Improved threshold with noise tailoring to suppress coherence.
Some other cool stuff we heard about here
(incomplete list!)

$k$th level of Clifford hierarchy is transversal for $m \times m^k$ Bacon-Shor (Yoder’s talk).
(Bravyi-Koenig implies gates are not geometrically local.)

Transversal CCZ in 3D surface code (Browne’s talk).

Clifford group for the 2D toric code with twists (Brown’s talk).

Reducing qubit overhead using flags (Chao’s talk). Useful for near-term FT experiments?

Local approximate correctability (Kastoryano’s talk), and implications for holography
(Pastawski’s talk).

Protecting reference frame information and covariant QEC (Nezami’s talk). The power of continuous-variable codes. Perspective on Eastin-Knill.

Performance of bosonic mode codes (Niu, Schoelkopf, Flühmann talks, Albert poster)

Quantum error correction for metrology (Cappellaro’s talk). How practical?

Multiple partitions. Jochym-O’Connor and Laflamme (2013). One set of operations transversal with respect to one partition and another set with respect to another.

Code switching. Duclos-Cianci and Poulin (2014). For example, fix the gauge of a subsystem code in two distinct ways. Need to switch fault-tolerantly.

Code drift. Paetznick and Reichardt (2013). Need to return to the original code fault-tolerantly.


What unifying principle?
Majorana zero modes ~ Ising anyons  

(Litinski’s talk)

Two Majoranas (e.g. at ends of a wire segment): fermionic parity.

Qubit: Two states for four Majoranas with even parity.

Braiding: Single qubit Clifford group.

Entangling gate from four-mode (Z Z) measurement.

Non-topological T gate (perhaps protected by dynamical decoupling).

Braiding (in effect, a Berry phase) can be achieved by opening and closing “valves” --- two mode couplings that pulse on and off. This is topologically protected because coupling is exponentially small when valve is “off”.

Feasible in the near term:
Reading out fermionic parity of a pair (conversion to charge measurement).

Braiding in a tri-junction device (e.g., Aasen et al. 2016).
Self-correcting quantum memory
Stabilized at nonzero temperature by a time-independent local Hamiltonian

1) Finite-dimensional spins.

2) Bounded-strength local interactions.

3) Nontrivial codespace.

4) Perturbative stability.

5) Efficient decoding.

6) Memory time exponential in system size at nonzero temperature.

The 4D toric code obeys all the rules, but what about < 4 dimensions?
Some fundamental resource questions

Ratio (# physical qubits) / (# logical qubits) → constant asymptotically. (Gottesman 2013). Conjectured LDPC codes (many qubits per block) and Shor EC. Put your eggs in polylog number of baskets. No geometric locality constraint; fast, reliable classical computation assumed.

What if all processing is quantum and noisy? No geometrical locality.

**Conjecture:** Circuit size blows up by factor $O(\log^{2+\varepsilon} L)$ and circuit depth blows up by $O(\log \log L)$, where $L$ is the size of ideal circuit.

**Idea:** Use high-dimensional topological code, local rule for error correction, and rapid RG decoding of logical blocks (with nonlocal gates).

**Concatenated codes:** Size and depth blowup are polylog $L$.

**Classically:** Size blow up is $O(\log L)$ and depth blow up is a constant.

*Can the depth blow up be constant quantumly?*
How steep is the climb to scalability?

We tend to be too optimistic about the short run, too pessimistic about the long run.

Better qubits and gates! Faster gates, too?

Fast (and cold?) decoding.

Very daunting systems engineering issues.

A long way to go! New insights and developments could substantially alter the outlook.
Quantum error correction for sensing

Goal: estimate a Hamiltonian parameter using state preparation, Hamiltonian evolution, and measurement.

Heisenberg limit: ideal precision scales as 1/t where t is the probing time. But this becomes $1/\sqrt{t}$ scaling (standard quantum limit) for noisy probe.

Can QEC help? *How to distinguish the signal from the noise?*

Assume: Markovian noise for probe, noiseless ancilla, fast and accurate quantum gates and measurements.

Example: NV center. Electron spin is noisy probe. Nuclear spin is “noiseless” ancilla.


Spatial filtering: Distinguishing signal and noise if they have different spatial profiles (Cappallero’s talk). Cf., using dynamical decoupling when signal and noise differ temporally.

Highly idealized setting!
Quantum gravity

We want a quantum theory of gravity ...

1) To erect a complete theory of all the fundamental interactions in nature.

2) To resolve deep puzzles about the quantum physics of black holes.

3) To understand the very early history of the universe.

Experiments provided essential guidance for building the standard model of particle physics, excluding gravity. It’s hard (though perhaps not impossible) to do experiments which explore quantum gravity.

We are trying simultaneously to determine both what the theory predicts and what the theory is.

Are we smart enough to figure it out?

I don’t know ... But why not?
Weakly-coupled gravity in the bulk ↔ strongly-coupled conformal field theory on boundary.

Complex dictionary maps bulk operators to boundary operators.

Emergent radial dimension can be regarded as an RG scale.

Semiclassical (sub-AdS scale) bulk locality is highly nontrivial.

Geometry in the bulk theory is related to entanglement structure of the boundary theory.

Many boundary fields ("large N"), so AdS curvature large compared to Planck scale.

Strong coupling on boundary, so AdS curvature large compared to the string scale.

(Maldacena 1997)
Logical operator = “precursor”

A local operator in the bulk spacetime produces a disturbance which propagates causally in the bulk.

The effect of this bulk operator becomes locally detectable on the boundary at a later time.

The bulk operator corresponds to a nonlocal “precursor” operator on the boundary.

The precursor is more and more nonlocal for bulk operators deeper and deeper in the bulk.

We interpret the precursor as the logical operator acting on a quantum code, with better protection against error for bulk operators deeper inside the bulk.
The holographic dictionary is a quantum error-correcting code!

Low energy states on the boundary correspond to weakly perturbed AdS geometry in the bulk.

(Logical) local operators deep in the bulk are mapped to highly nonlocal boundary operators, protected against erasure of boundary regions.

This explains (Harlow’s talk):
How entropy on the boundary can correspond to area (an observable) in the bulk (holds only in the code space, and there are corrections due to bulk entanglement).

Why a bulk logical operator can be “reconstructed” on the boundary in multiple ways. (Different physical operators acting on the code space in the same way.)

Bulk local operators commute because they act on different logical subsystems.

Questions:
In what precise sense is a CFT an approximate QECC?

Boundary evolution (with local Hamiltonian) preserves code space. How to reconcile with Eastin-Knill? Note: approximate QEC, and continuous variable coding.

Is the black hole *interior* encoded at the AdS boundary? How to decode it?

How to understand emergent gauge symmetry in the bulk (operator algebra QEC).
Quantum error correction in 2017

-- Superconducting qubits and trapped ions are ready for demonstrations of QEC and fault tolerance.

-- Microwave resonators for continuous-variable codes and cat codes.

-- Topological protection is becoming a reality.

-- Other approaches to physical protection (e.g. superinductance).

-- Potential benefits from QEC in metrology.

-- QECC’s as RG fixed points of topological phases.

-- QEC in the AdS/CFT bulk-boundary dictionary.
Additional Slides
Can we build a quantum hard drive?

Error protection using only local processing (suboptimal threshold). Kubica’s talk

**Two ideas:**

Better stability in higher dimensions.

(Simulated) attraction between pointlike defects.

**Two sources of inspiration:**

Toom’s anisotropic local rule for 2D spin system.

Gacs’s robust 1D probabilistic cellular automata.

**Two paradigms:**

2D toric code, with anisotropic local rule for moving defects
(Harrington decoder, inspired by Gac).

4D toric code, with anisotropic local rule for shrinking string loops.
The 3D gauge color code as a topological phase

*Single-shot error correction*. Gauge generators define strings, syndrome defects are points where strings branch. Sufficient redundancy for resilience against measurement errors.

As a Hamiltonian system:

\[ H = -H_{\text{stab}} - \lambda H_{\text{gauge,X}} - (1 - \lambda)H_{\text{gauge,Z}}, \quad 0 \leq \lambda \leq 1. \]

\( \lambda = 1 \): Color code with Z-type string ops and X-type surface ops.
\( \lambda = 0 \): Color code with X-type string ops and Z-type surface ops.

What behavior as \( \lambda \) varies?
1) No phase transition.
2) One critical point.
3) Two (or more) critical points. Properties of intermediate phase?

An unconventional topological phase? Haah’s 3D cubic code as a cautionary example.
Adiabatic quantum computing at nonzero temperature?

What is the right (theoretical) question to ask?

Probably not the right question: Can we simulate the ideal Hamiltonian using a local physical Hamiltonian? (Logical operators have high weight.)

Instead (Crosson): Is there a time-independent local Hamiltonian whose Gibbs state (at nonzero temperature) is a reliably decodable history state, and can be efficiently prepared by slow Hamiltonian deformation?

Follow the principles of self correction, e.g. the 6D color code of Bombin et al. A tricky issue is checking the logical measurements needed for computational universality.

The clock, too, must be robustly encoded.

If it works, so what?
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