Dawn in the age of quantum fault tolerance

Professor Stephen Bartlett

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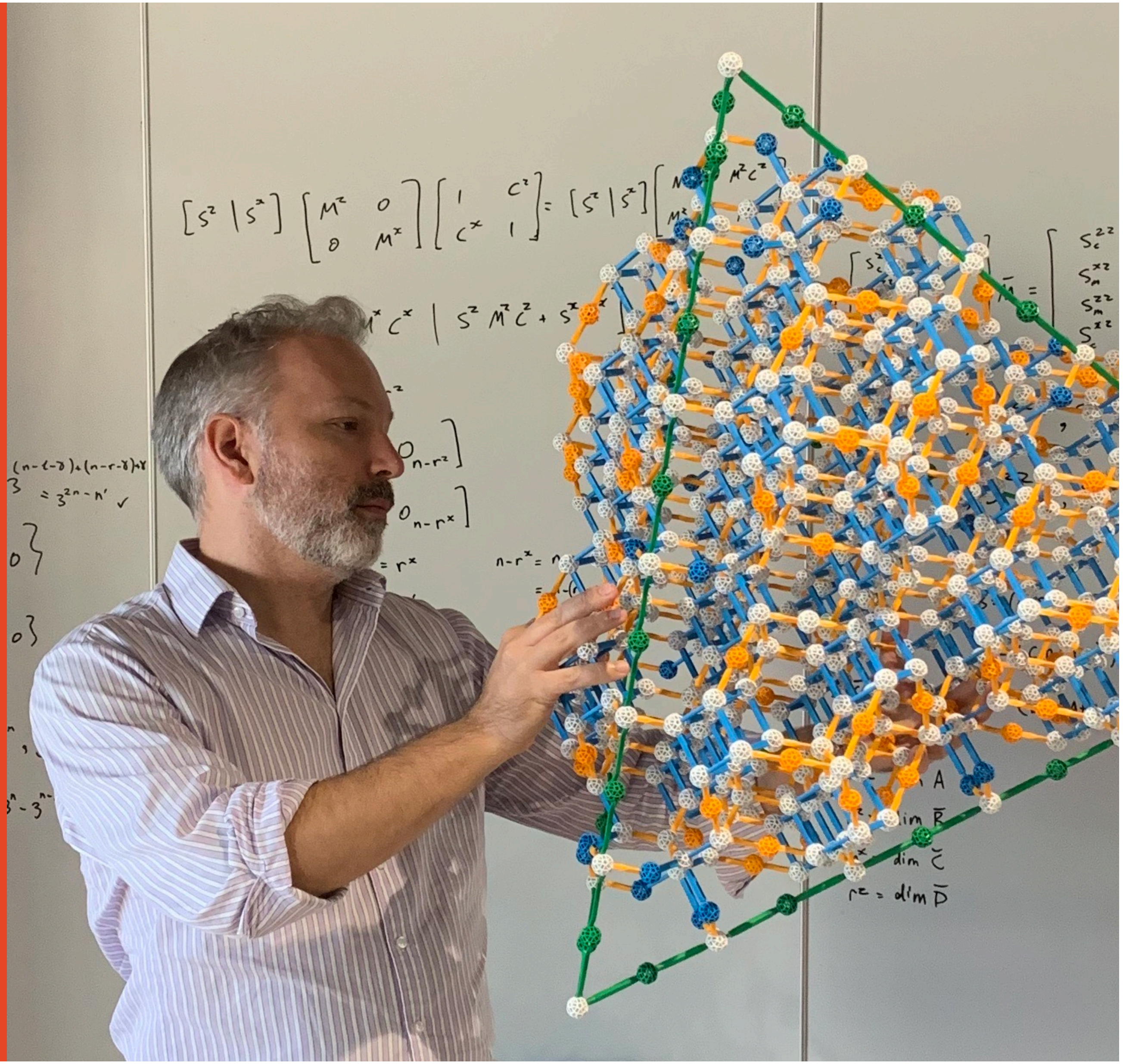

QEC and fault tolerance

An overview

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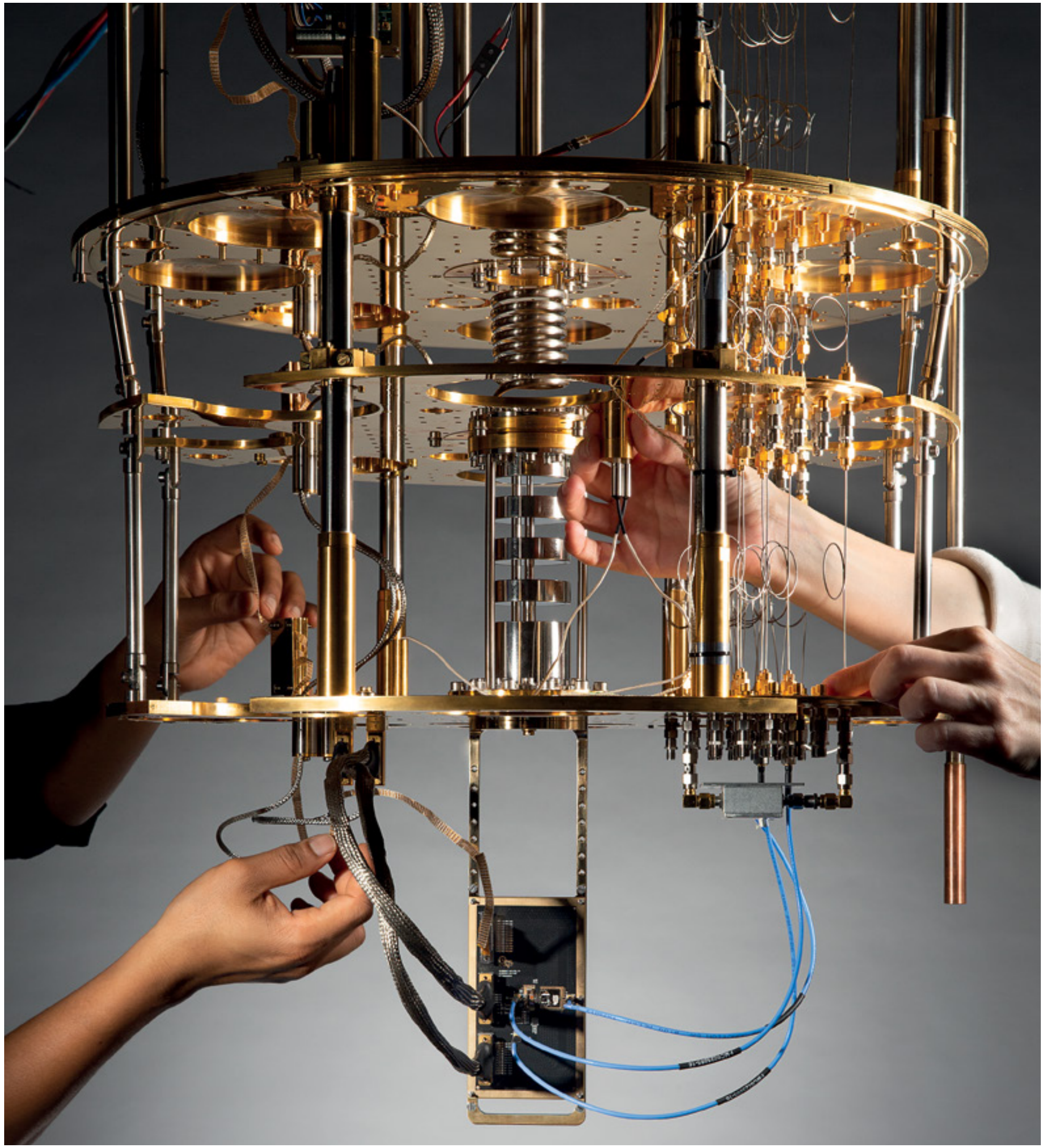
‘Practical’ quantum computing

- Most of the interesting quantum algorithms we want to execute require large quantum circuits & many qubits
- Current qubit technologies fail too frequently (error rates a fraction of a per cent) to execute interesting instances
- Hardware is improving, but is unlikely to close the gap
- *Fault tolerant quantum computing* is a catch-all term, describing architectures to perform large quantum computations using faulty parts

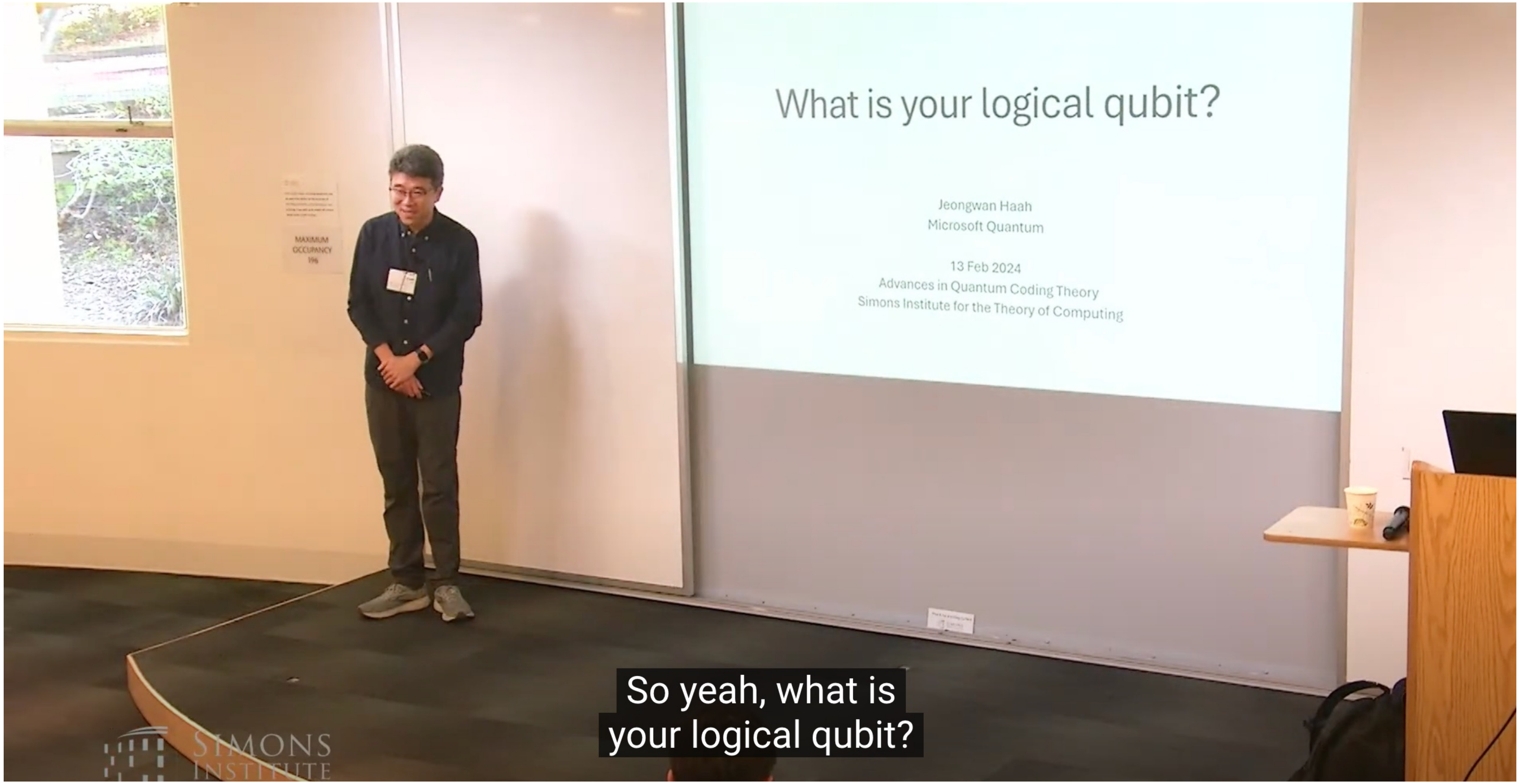


Quantum computing fault-tolerantly

Physical qubits
Noisy: failure rates a fraction of a percent per clock cycle

→ QEC code →

Logical qubits
Near-perfect: failure rates such that whole algorithm succeeds with high probability



https://www.youtube.com/watch?v=l4smz_J8f1E

Quantum computing fault-tolerantly

Physical qubits
Noisy: failure rates a fraction of a percent per clock cycle

→ QEC code →

Logical qubits
Near-perfect: failure rates such that whole algorithm succeeds with high probability

- Is this even possible? Requires physical error rates below a **threshold**.
  - Depends on code, the architecture, and the physical nature of the errors
  - Logic gates including QEC must be performed **fault-tolerantly**, to keep errors correctable (don't allow errors to spread or multiply)
  - Fault tolerance is a property of the **whole circuit**, not just a logical qubit or logical gate

D. Gottesman, Quantum fault-tolerance in small experiments, arXiv:1610.03507

Quantum computing fault-tolerantly

Physical qubits
Noisy: failure rates a fraction of a percent per clock cycle

QEC code

Logical qubits
Near-perfect: failure rates such that whole algorithm succeeds with high probability

Observation (Jeongwan's):
Characterising the 'fault tolerance' of a logical qubit or gate requires care

- Is this even possib… **…hreshold**.
  - Depends … …e of the errors
  - Logic gate… **…antly**, to keep errors corr… …ultiply)
  - Fault tolerance i… …, not just a logical qubit or logical gate

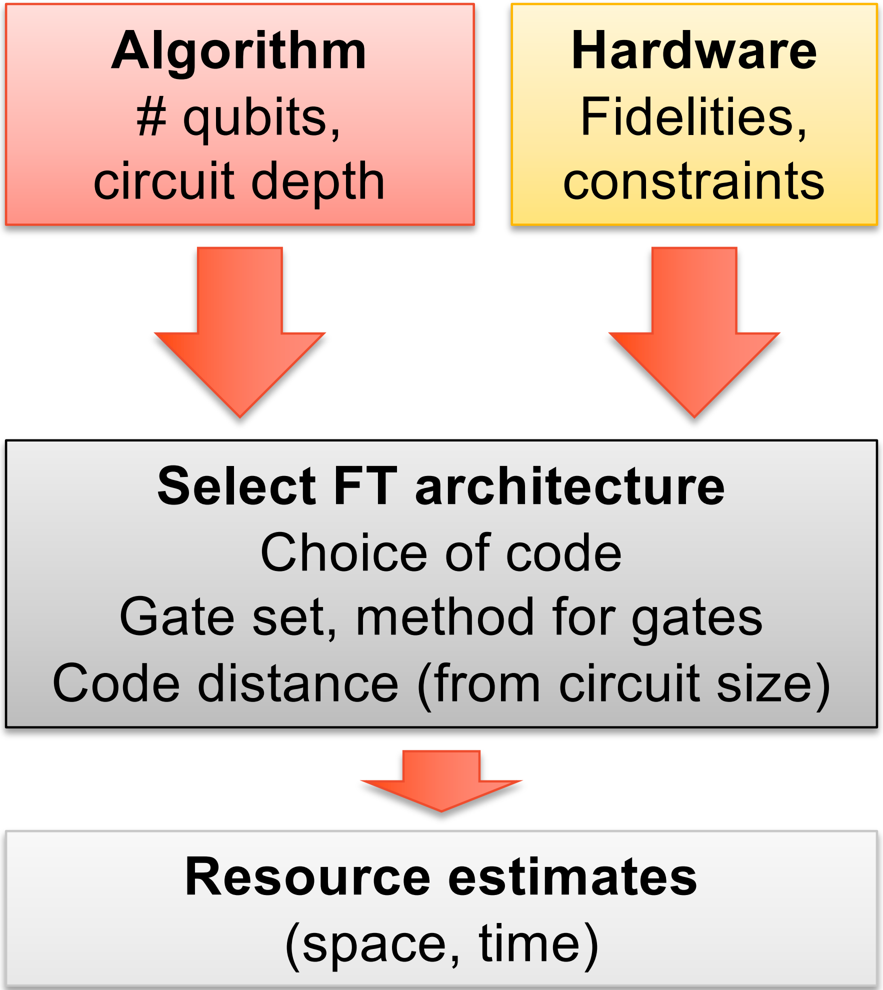
D. Gottesman, Quantum fault-tolerance in small experiments, arXiv:1610.03507

Fault tolerance, overheads, and resources

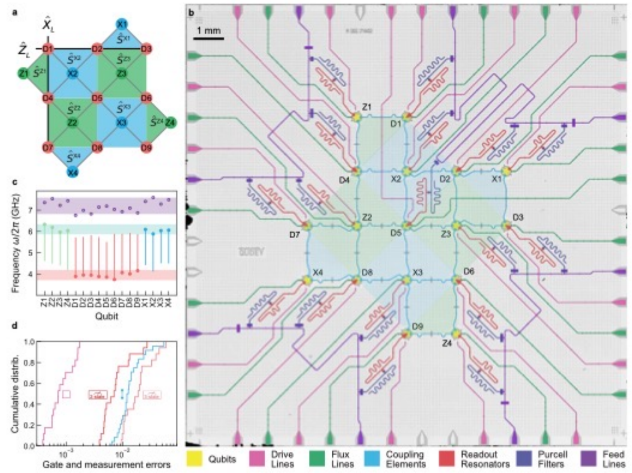
- Step back and take a 'whole circuit' approach

- Threshold theorem states that an algorithm can be executed on (not too) noisy hardware with only a 'small' overhead

- **But what happens in practice?**



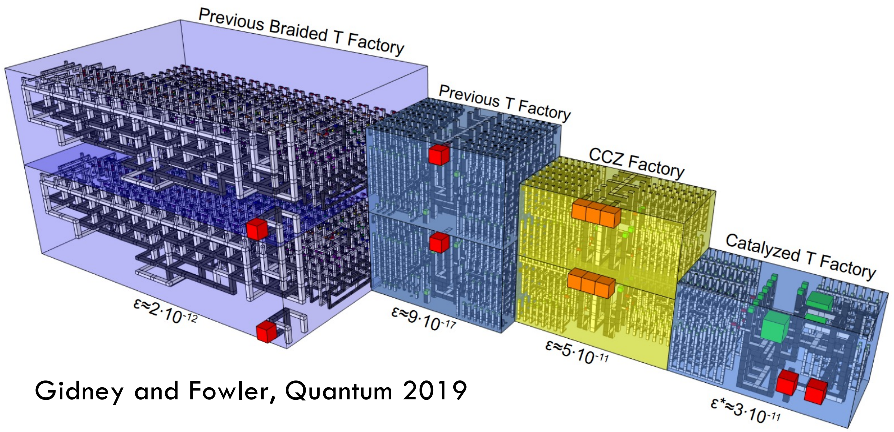
Fault tolerant architectures



Krinner et al, Nature 2022

Tolerance to errors: **quantum error correcting codes**

- ‘Topological’ stabilizer codes in a planar layout (‘on a chip’)
- Nearest-neighbour couplings (no long range couplings required)
- High error thresholds (0.1% - 1% error rates can be tolerated)
- Several hardware platforms now comfortably below threshold
- Bosonic codes offer competitive, even better performance



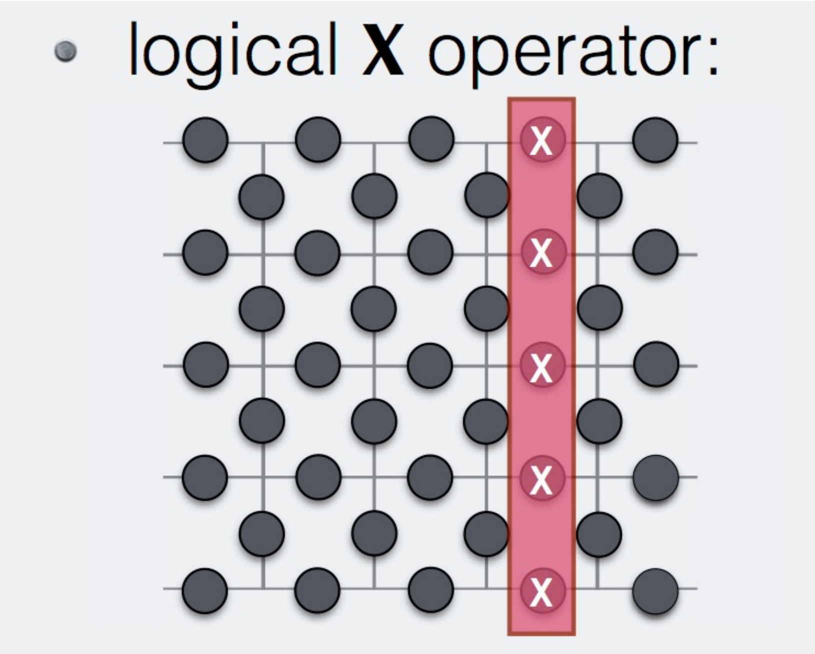
Gidney and Fowler, Quantum 2019

But at a cost: **resource overheads**

- Many candidate codes require thousands, millions of physical qubits to encode a single logical qubit
- Measurements in QEC repeated many times to be reliable
- Resource overheads for logic gates are also astronomical
- e.g. 20 million noisy qubits and 8 hours to run a complex q. algorithm

Main messages: - quantum error correction is becoming possible right now
- using current approaches at scale will be complex and costly

Logic gates



- Logical qubits are spread across many physical qubits in a code
- Performing logic gates requires acting on many physical qubits simultaneously
- **Transversal logic gates**:
  - Apply independent physical gates
  - Naturally fault-tolerant
  - Constant depth (but still require FT QEC)
- **General logic gates**:
  - Complex constructions to make FT
  - e.g. Magic state distillation & injection
  - Significant time overheads

Stabilizer codes: A common class of quantum codes → Many popular codes have only **Clifford gates** as transversal → Circuits with only Clifford gates are not **universal** for QC

Dogma

Clifford logic gates	**Non-Clifford logic gates**
Easy	Hard
Fault-tolerant	Costly FT constructions
"Classical"	"Quantum"

Designing FTQC:

- use classical resources to simulate Clifford logic gates
- focus on low-overhead approaches to non-Clifford logic gates

Dogma

Clifford logic gates
Easy
Fault-tol
“Clas

Non-Clifford logic gates
ctions

Observation:
This simple classification was useful for theoretical development

For FT experiments, we can’t partition things so easily

ifford
logi es

Fault tolerant architectures

Scratching the surface of the surface code

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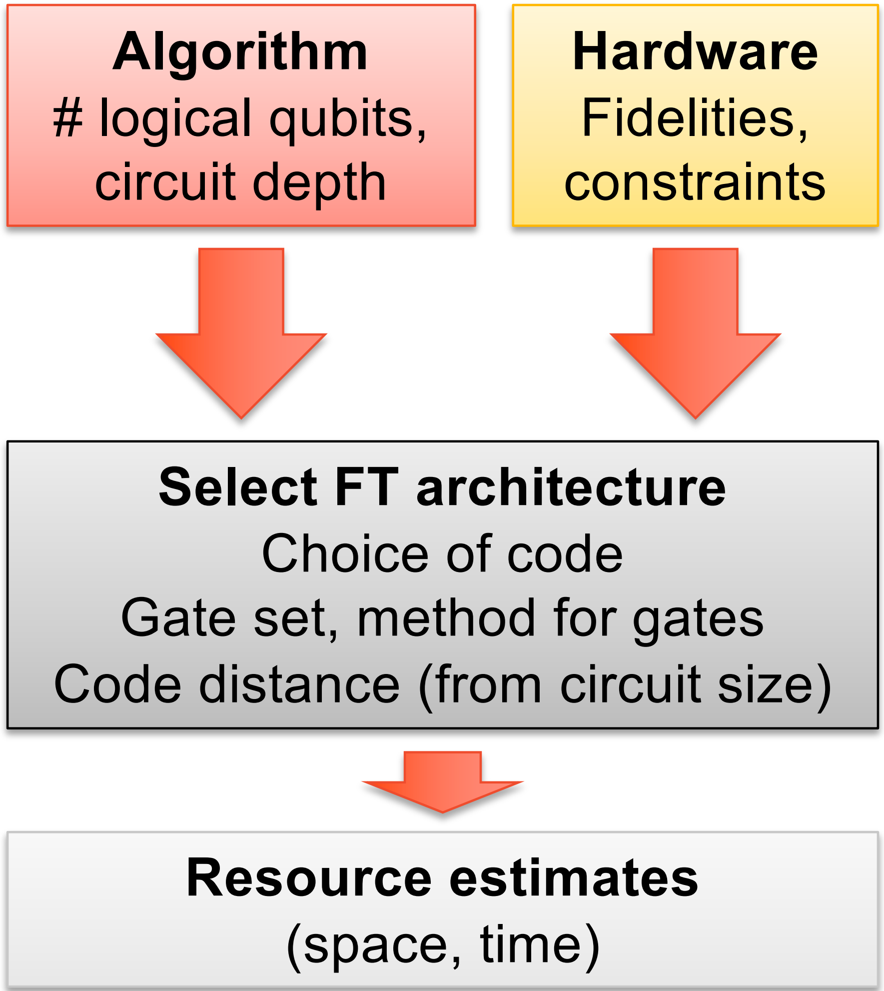
Fault tolerance, overheads, and resources

- Different FTQC approaches lead to overheads that vary by many orders of magnitude

- Common choice of code is the **surface code**, due to high threshold and local 2D layout

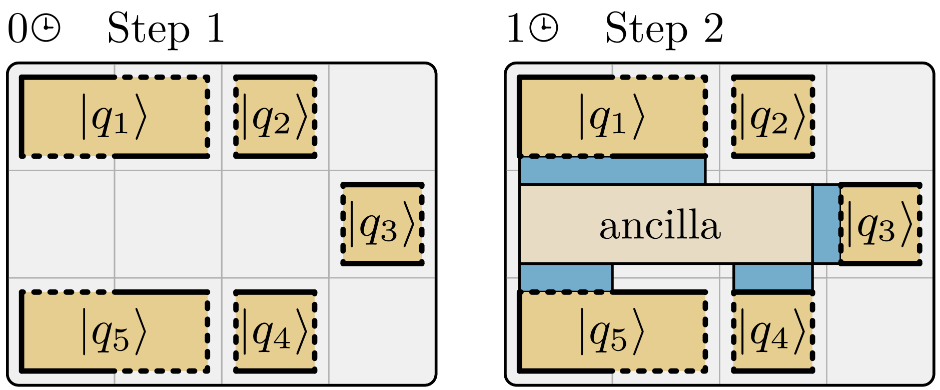
- *Given* the surface code, an approach to gates that offers the *current* lowest overheads is **lattice surgery**



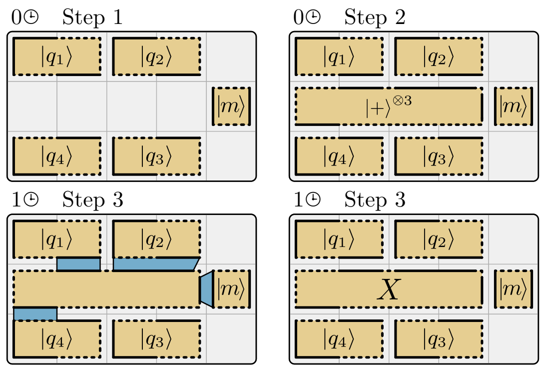
Intro to FTQC with surface codes and lattice surgery

- State of the art: Litinski 2019 (‘A game of surface codes’) with some mods

- Convert logical quantum circuit into ‘Pauli-based computation’
  - Many nontrivial aspects to this step
- Lattice surgery: a method to fault-tolerantly perform multi-logical-qubit Pauli measurements to perform gates
- Options for space vs time tradeoffs
- Data blocks and distillation blocks
  - Lots of assumptions and choices of distillation scheme, and overheads
- Provides a direct way to estimate space and time overheads



(a) Measurement of $Z_{|q_1\rangle} \otimes Y_{|q_2\rangle} \otimes X_{|q_4\rangle} \otimes Z_{|m\rangle}$



Intro to FTQC with surface ... ry

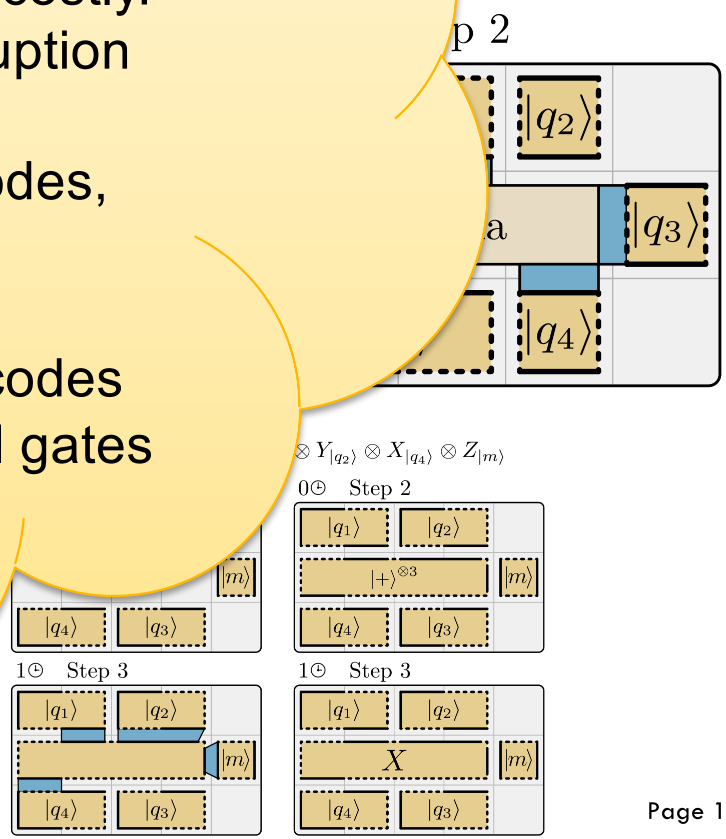
- State of the ar ... ome mods
- Convert logical ... based comp ...
  - Many ...
- Lattice surg ... tolerantly pe ... Pauli measure ...
- Options for s ...
- Data blocks c ...
  - Lots of assum ... distillation scheme ...
- Provides a direct way to es ... ac ... and time overheads

Observation:

Surface code is particularly costly.
Lots of opportunity for disruption

More exotic topological codes,
qLDPC codes

More work to be done on codes
with non-Clifford transversal gates

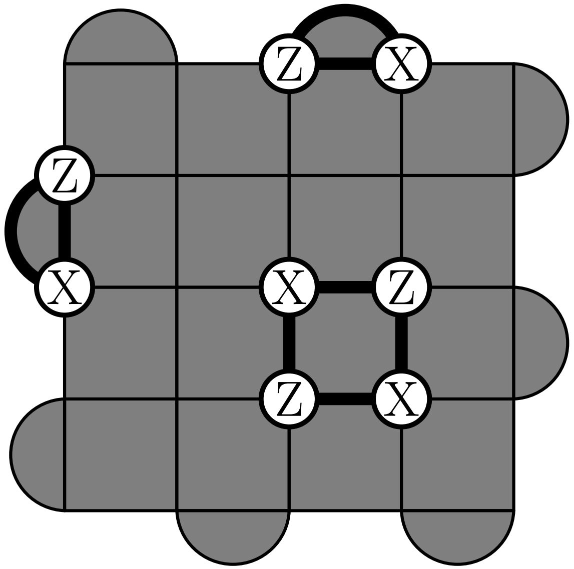


Lowering the overheads

FTQC with LDPC, ASAP

Topological codes vs qLDPC codes

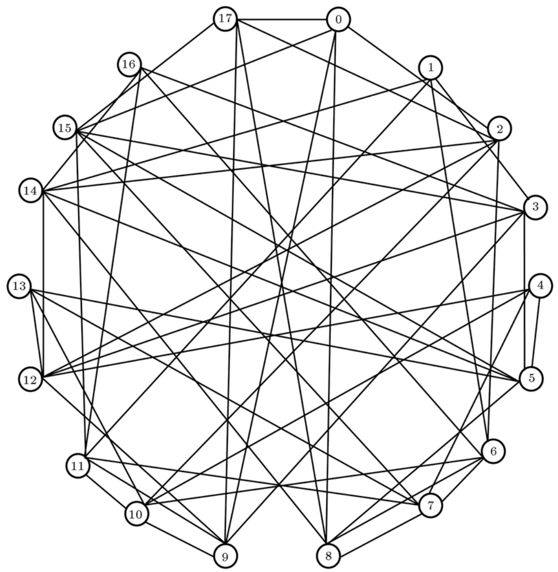
Surface code has local check operators



More protection with larger systems

Encodes one logical qubit no matter how big

qLDPC codes remove the locality constraint



More protection with larger systems

Encodes many logical qubits, growing with size

Recent breakthrough: good codes!

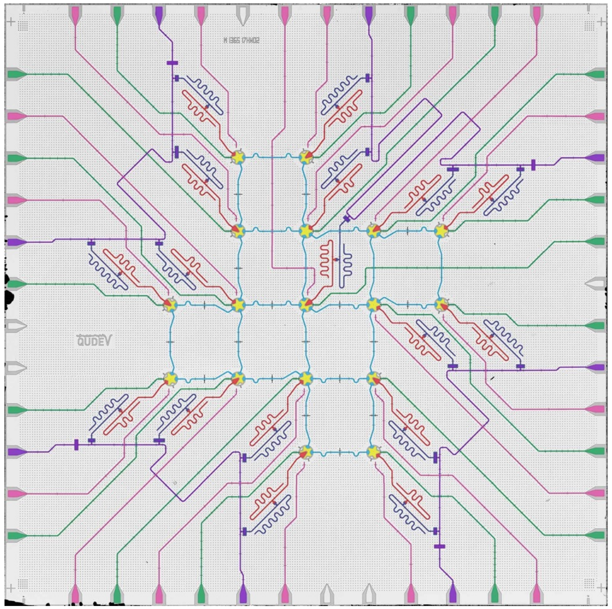
k	d	Code
2	$\sqrt{n}$	Kitaev toric
2	$\sqrt{n\sqrt{\log n}}$	Freedman-Meyer-Luo
$\Theta(n)$	$\sqrt{n}$	hypergraph product
$\sqrt{n}/\log n$	$\sqrt{n}\log n$	high-dimensional expander (HDX)
$\sqrt{n}$	$\sqrt{n}\log^c n$	tensor-product HDX
$n^{3/5}/\mathrm{polylog}(n)$	$n^{3/5}/\mathrm{polylog}(n)$	fiber-bundle
$\log n$	$n/\log n$	lifted-product (LP)
$\Theta(n)$	$\Theta(n)$	expander LP
$\Theta(n)$	$\Theta(n)$	quantum Tanner
$\Theta(n)$	$\Theta(n)$	Dinur-Hsieh-Lin-Vidick

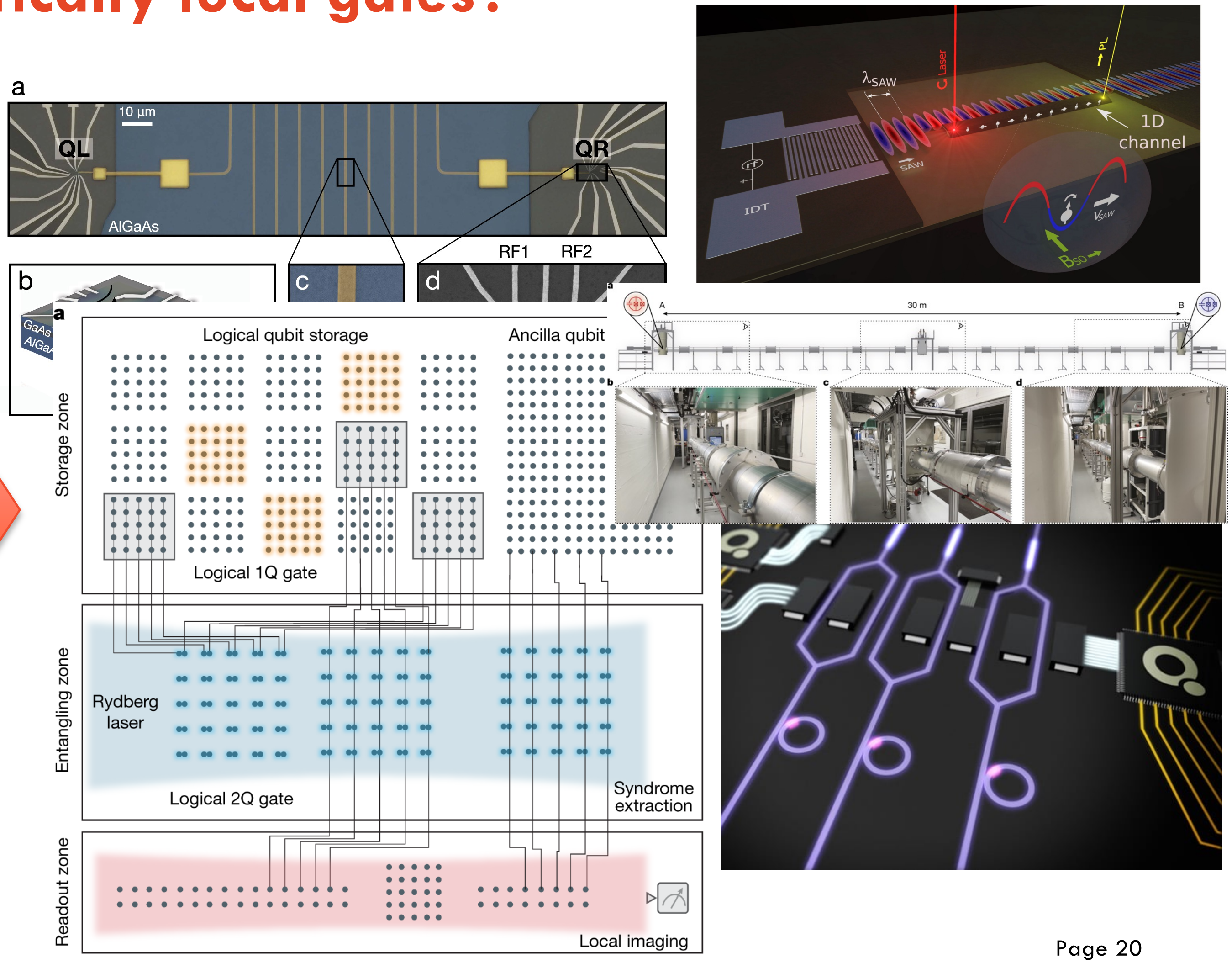
Table I: Notable QLDPC codes; c is a positive integer.

Yay!

From EC Zoo https://errorcorrectionzoo.org/c/qldpc

Don’t we need geometrically local gates?





But…

- Is there a low-overhead architecture based on a high-rate qLDPC code?

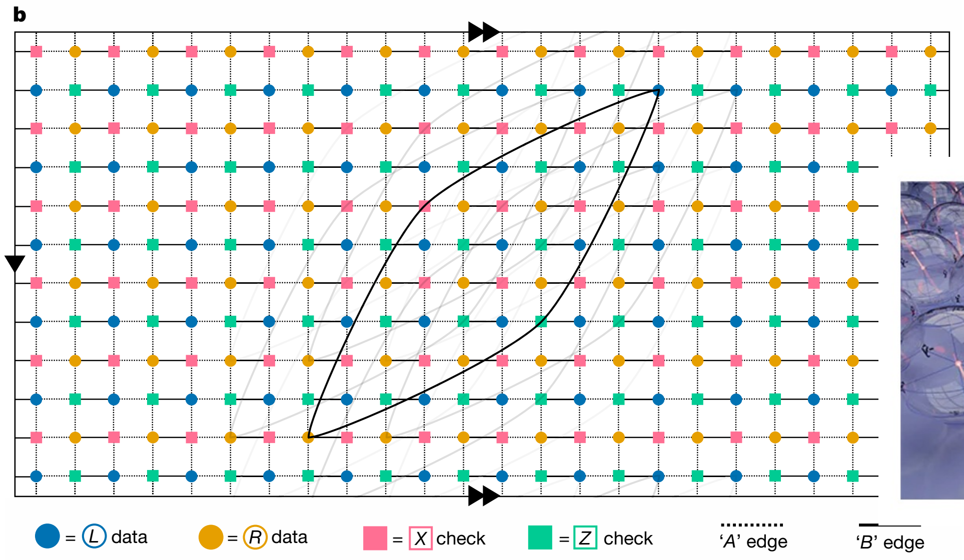
D. Gottesman, Fault-Tolerant Quantum Computation with Constant Overhead, arXiv:1310.2984

- The ingredients are there:
  - codes that satisfy Gottesman's criteria ☑
  - reasonably high thresholds and fast decoders ☑

- But focus has been on asymptotics. What about in practice?

qLDPC codes and FTQC

- Recent proposals look to use qLDPC codes in currant and future hardware to reduce overheads
- What are the actual gains in the relevant regimes?
- What long-range connectivity is needed, or most useful?



Article

High-threshold and low-overhead fault-tolerant quantum memory

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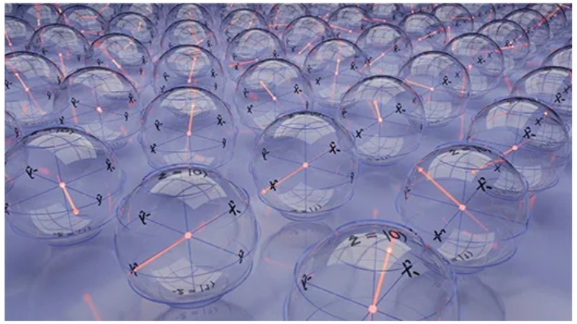
Sergey Bravyi[1], Andrew W. Cross[1], Jay M. Gambetta[1], Dmitri Maslov[1]✉, Patrick Rall[2] & Theodore J. Yoder[1]

Constant-Overhead Fault-Tolerant Quantum Computation with Reconfigurable Atom Arrays

Qian Xu,[1,*] J. Pablo Bonilla Ataides,[2,*] Christopher A. Pattison,[3] Nithin Raveendran,[4] Dolev Bluvstein,[2] Jonathan Wurtz,[5] Bane Vasić,[4] Mikhail D. Lukin,[2] Liang Jiang,[1,†] and Hengyun Zhou[2,5,‡]

[1]*Pritzker School of Molecular Engineering, The University of Chicago, Chicago 60637, USA*
[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[3]*Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, CA 91125*
[4]*Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721, USA*
[5]*QuEra Computing Inc., 1284 Soldiers Field Road, Boston, MA, 02135, US*



QUANTUM COMPUTING

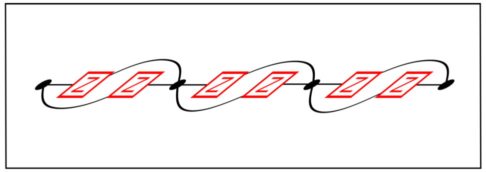
New Codes Could Make Quantum Computing 10 Times More Efficient

By CHARLIE WOOD | AUGUST 25, 2023 | 6

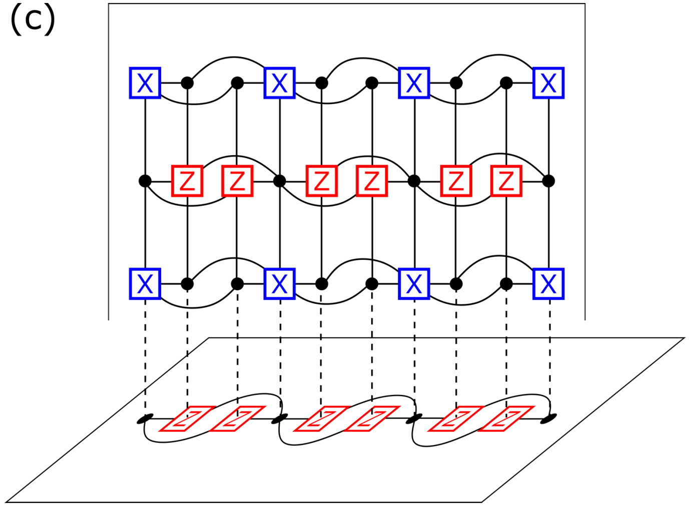
Quantum computing is still really, really hard. But the rise of a powerful class of error-correcting codes suggests that the task might be slightly more feasible than many feared.

qLDPC codes and FTQC – logic gates

- Still work to do to construct FTQC with LDPC codes including logic gates
- We have a new way of doing FT gates by generalizing **lattice surgery**



(c)



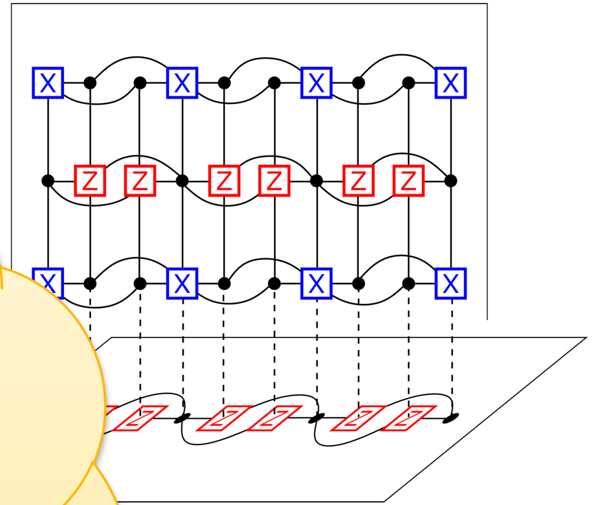
k	d	Parallelism	Code family	n_{data}	n_{anc}	n_{tot}
18	8	2	Hyperbicycle	294	500	800
			Surface	1152	128	1300
50	14	2	Hyperbicycle	900	1400	2300
			Surface	9800	300	10000
	16	20	Hypergraph	1922	5000	7000
			Surface	12800	2000	15000
578	16	578	Hypergraph	7938	120000	130000
			Surface	150000	75000	225000
		68	Hypergraph	7938	15000	23000
			Surface	150000	10000	160000

TABLE I. Estimates of the overhead required to perform a round of logic, including those qubits needed to encode the data as well as additional ancilla qubits required to perform fault-tolerant gates. We use LDPC codes constructed in [39, 40], which all have initial check weights of no more than 10. We denote the number of logical qubits as k and the distance of the code as d. Comparisons are made against the surface code with the same distance. Here, 'parallelism' denotes the number of logical qubits that can be acted upon non-trivially in one round of error correction, and which determines the number of required ancilla qubits. The number of data, ancillary, and total physical qubits needed to perform one round of logical measurements with error correction are denoted n_{data}, n_{anc}, and n_{tot}, respectively. We do not include any ancilla qubits that may be used for error syndrome extraction.

Cohen, Kim, Bartlett, Brown
Science Advances 2022

qLDPC codes and FTQC – logic gates

– Still work to do to construct FTQC with LDPC codes including logic gates
– We have a new way of doing FT[illegible] generalizing **lattice surgery**



Observations (qLDPC):

Low-overhead architectures for FTQC based on qLDPC codes are within reach

Connectivity is front and centre; unlikely to find a good 'once-size-fits-all' architecture

				[illegible]0
				[illegible]000
578	1[illegible]	[illegible]	[illegible]	[illegible]25000
			[illegible]	23000
			10000	160000

TABLE I. Estimates of the overh[illegible] erform [illegible] uding those qubits needed to encode the data as well as additional ancilla qubits [illegible] m fault-tolerant gates. We use LDPC codes constructed in [39, 40], which all have initial check weights of n[illegible] We denote the number of logical qubits as k and the distance of the code as d. Comparisons are made agains[illegible] de with the same distance. Here, 'parallelism' denotes the number of logical qubits that can be acted upon [illegible] one round of error correction, and which determines the number of required ancilla qubits. The number of [illegible] ry, and total physical qubits needed to perform one round of logical measurements with error correction are denoted [illegible] n_{anc}, and n_{tot}, respectively. We do not include any ancilla qubits that may be used for error syndrome extraction.

Cohen, Kim, Bartlett, Brown
Science Advances 2022

Lowering the overheads 2

Don’t waste my time

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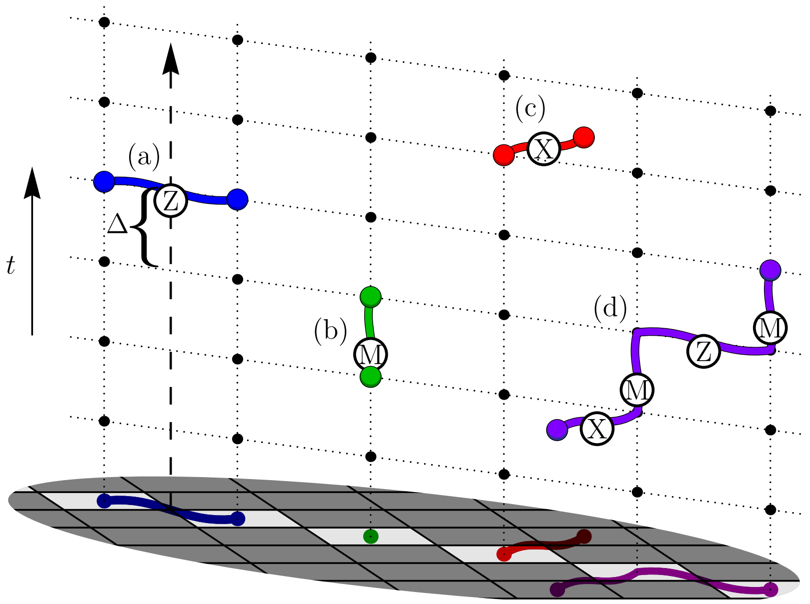
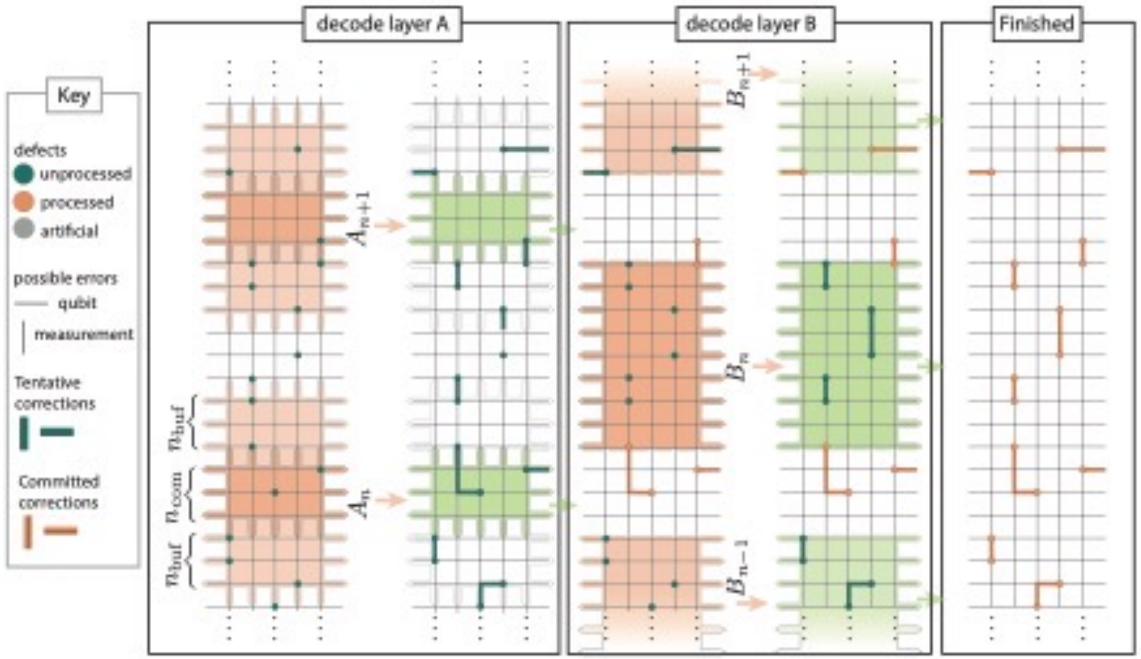
Repeated syndrome measurements

- Surface code (and many others) require accurate syndrome measurements
- 'Standard' approach is to repeat syndrome extraction many (d) times



Bonilla Ataides et al., Nature Comms 2021



Skoric et al., Nature Comms 2023

Repeated syndrome meas

- Surface code (and r ... rements
- 'Standard' approa ... es

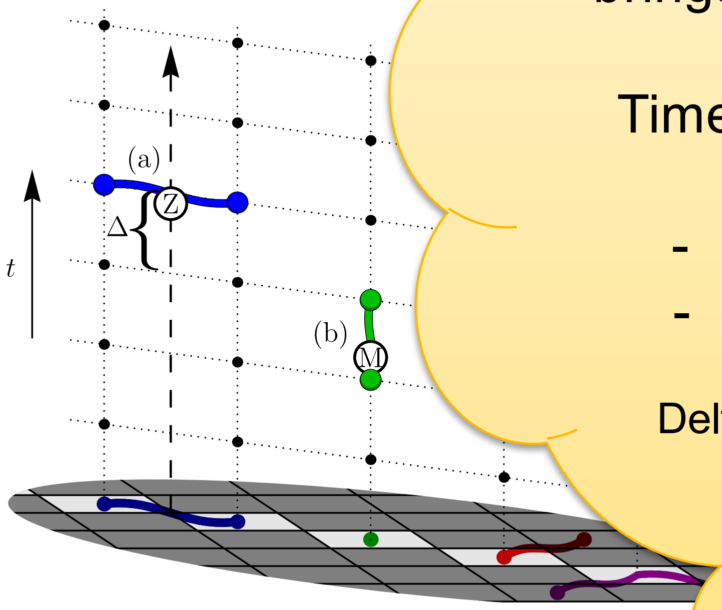
Observations
(FT syndrome extraction):

Repeated measurements brings large time overheads

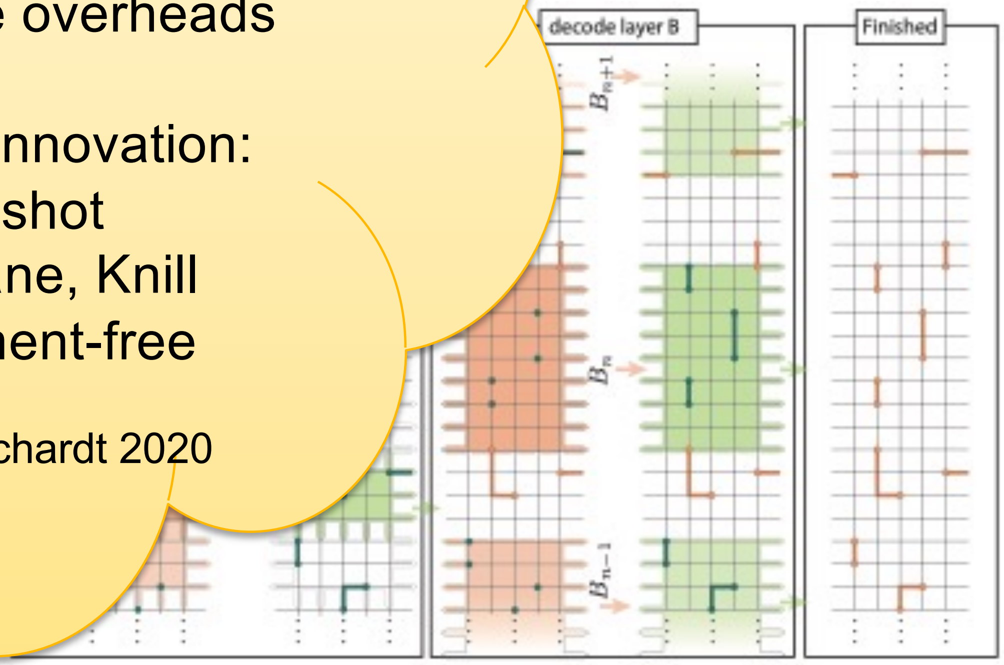
Time for some innovation:

- single shot
- Shor, Steane, Knill
- measurement-free

Delfosse and Reichardt 2020



Bonilla Ataides et al., Nature Comms



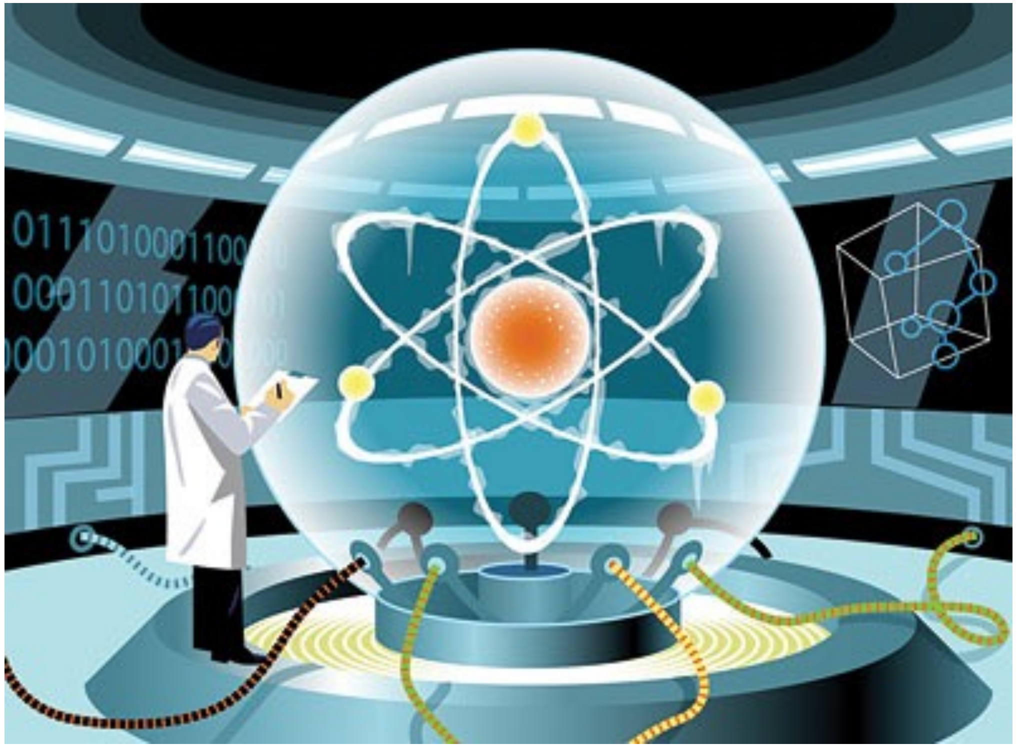
Skoric et al., Nature Comms 2023

So where does that leave us?

- Quantum error correction will be incredibly challenging, but current estimates for resource overheads are likely pessimistic

- QEC is not a piece of quantum software to run, but a full-stack approach to integrate with hardware and control

- Plenty of opportunities for university-based researchers to innovate



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