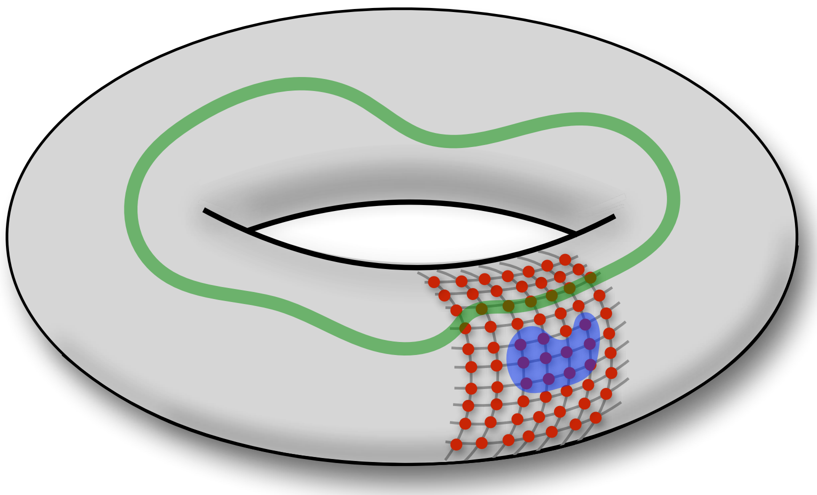
Quantum fault tolerance and error correction

Aleksander Kubica

aws Caltech

Yale University



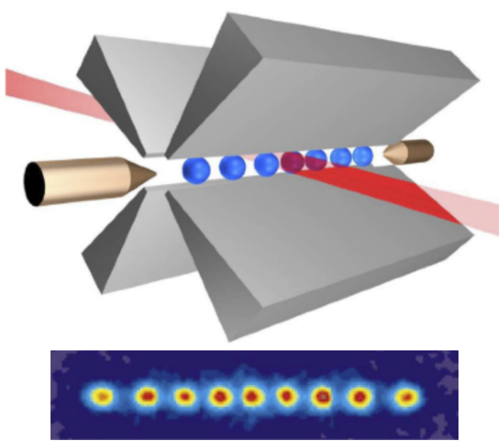
ASPLOS Workshop

April 28, 2024

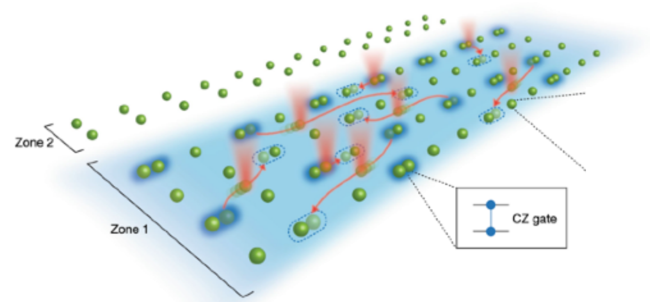
Quantum computers

- A ~~million~~ billion dollar challenge—how to build a quantum computer?

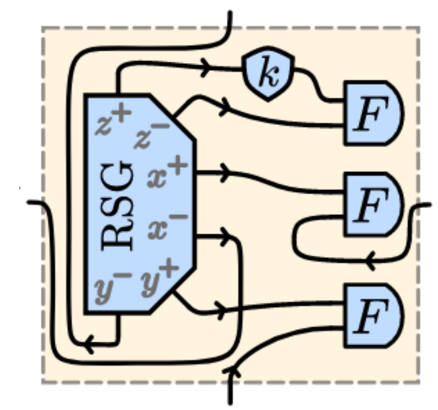
- Different architectures:



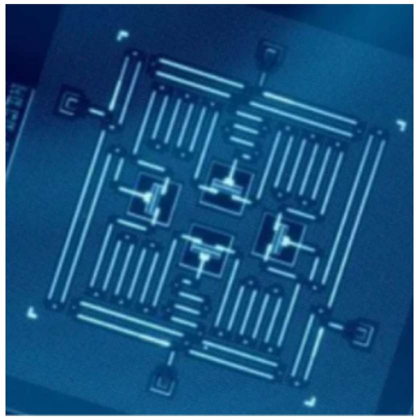
Eltony+, *Quant. Inf. Proc.* (2016)



Bluvstein+, Nature (2022)



Bombin+, *arXiv:2103.08612*



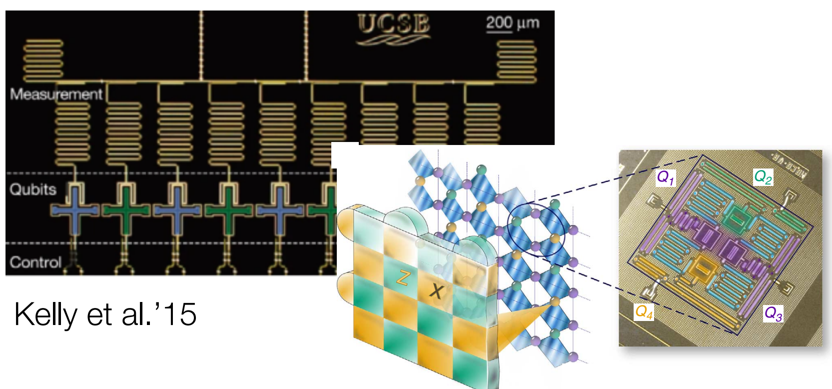
Gambetta+, *npj Quant. Inf.* (2017)

- Reliable processing of quantum information is extremely difficult!

- Indispensable concepts [Shor95,Steane96]:
  (i) quantum error correction, (ii) fault-tolerant methods.

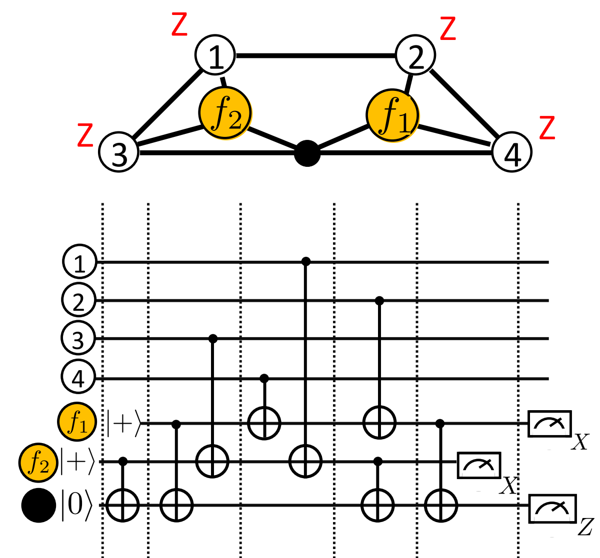
A path to fault-tolerant quantum computers

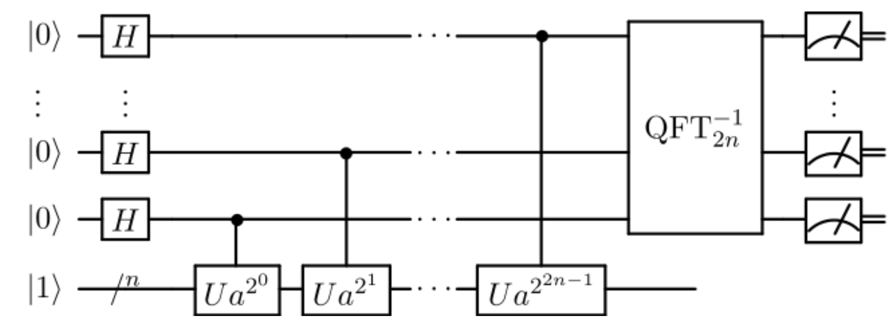
physical system & operations → quantum error correction (QEC) → quantum algorithms



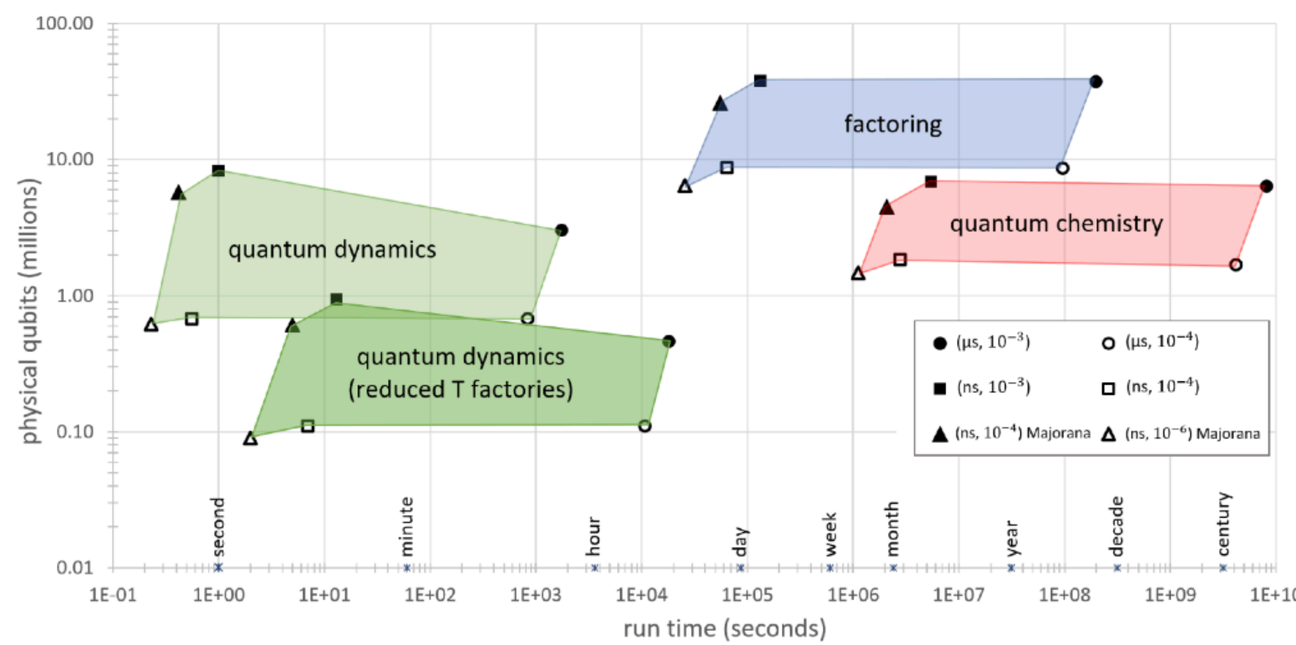
Kelly et al.'15

Córcoles et al.'15





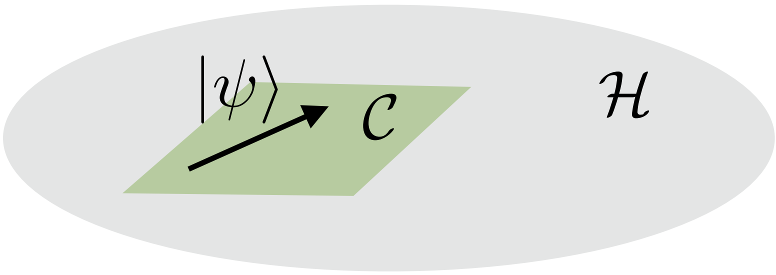
- Quantum algorithms require:
  - — error rates $\sim 10^{-10} - 10^{-15}$,
  - — fast logical clock speed.
- The space & time overheads of QEC are a major roadblock!



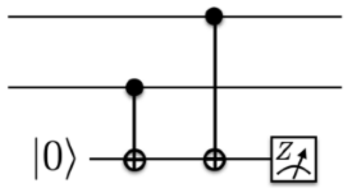
Beverland et al.'22

Quantum error correction

- Quantum code = a subspace of the Hilbert space.
  Errors take the encoded state $|\psi\rangle$ outside $\mathscr{C}$.



- Detecting & correcting errors:



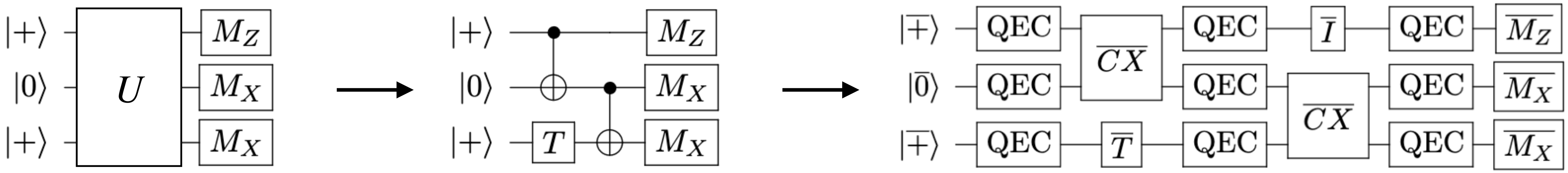
parity-check measurements → 1 0 1 1 0 0 … decoding algorithms → $I\ X\ X\ Z\ \ldots$

- The decoding problem is computationally hard [Iyer,Poulin15].

- Processing of classical information needs to:
  — be fast to avoid the backlog problem [Terhal15],
  — handle many errors & have good performance.

Fault-tolerant computation

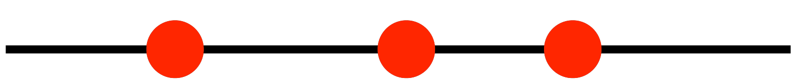
- We want to run quantum algorithms!



- Implementation of any unitary U w/ a universal set of gates, e.g., $\{H, T, CX\}$.

- Fault-tolerant computation on encoded information:
  — logical operations interleaved w/ QEC.

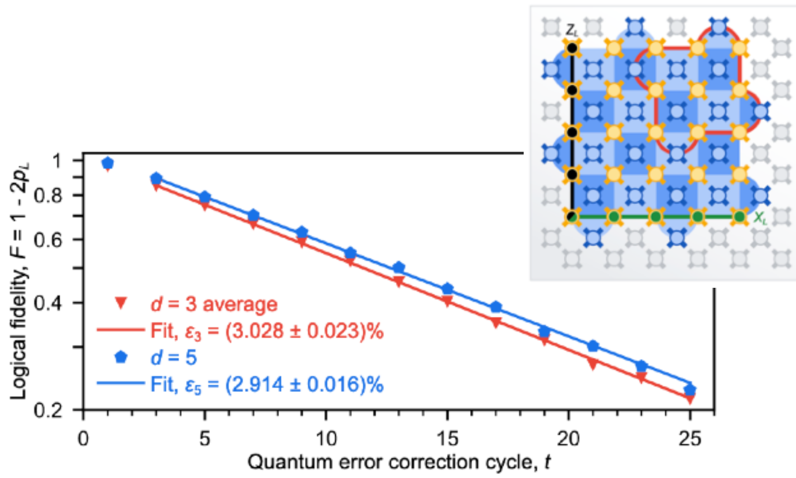
- Transversal gates & const.-depth circuits:
  — easy to implement & fault-tolerant,
  — limitations, e.g., the Eastin-Knill theorem.



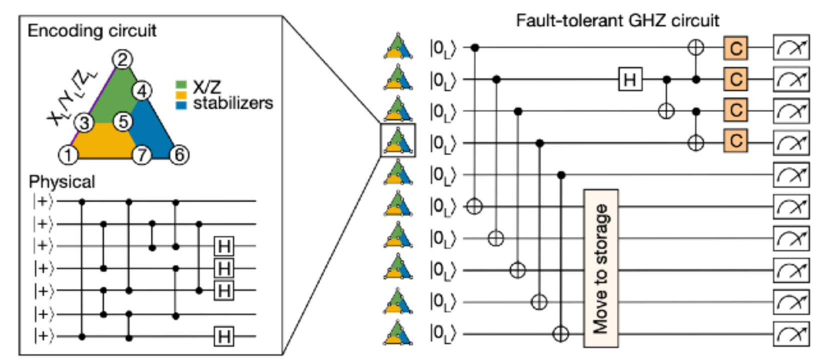
$$\overline{U} = \ldots \otimes U_{i-1} \otimes U_i \otimes U_{i+1} \otimes \ldots$$

Summary

- Exciting times—the dawn of QEC & fault tolerance.



Google Quantum AI, Nature (2023)



Bluvstein et al., Nature (2024)

- Reducing the overhead of QEC:
  — qubit overhead, e.g., better QEC codes,
  — time overhead, e.g., single-shot QEC.

- Many questions still remain open.

- Integration in the quantum computing stack.

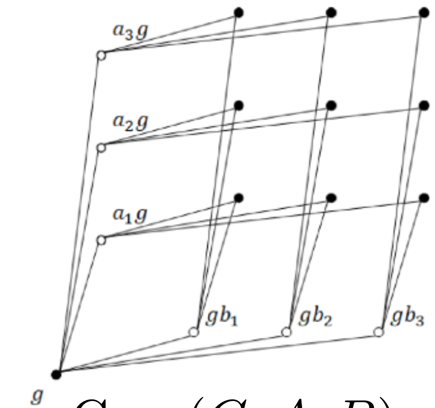
quantum codes

hardware realizations

logical operations

Challenges & opportunities

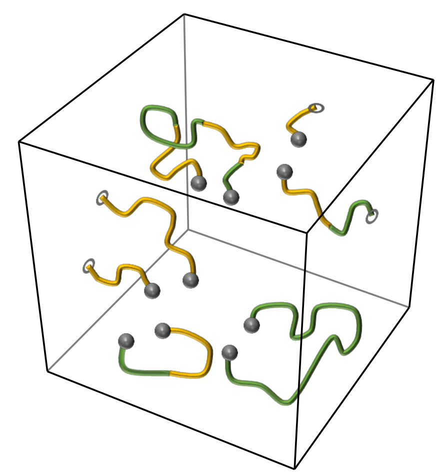
- Reducing the qubit overhead:
  — limitations on codes w/ geometrically-local checks,
  — quantum low-density parity-check (LDPC) codes,
  — …



$\mathrm{Cay}_2(G, A, B)$

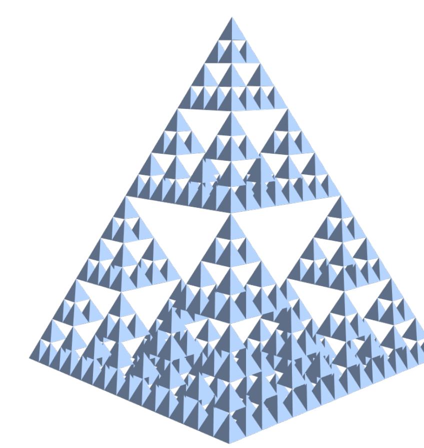
Gu et al., Comm. Math. Phys. (2024)

- Reducing the time overhead:
  — single-shot QEC,
  — transversal gates,
  — …



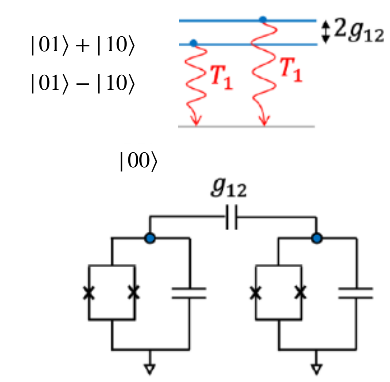
Kubica, Vasmer, Nat. Comm. (2022)

- Solving the decoding problem:
  — self-correcting quantum memories,
  — practical decoding algorithms,
  — …



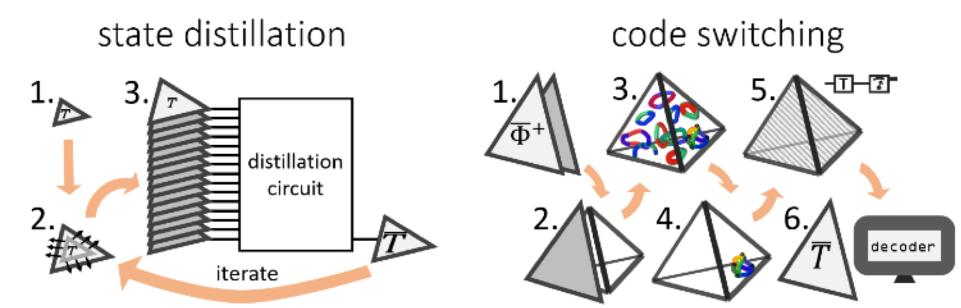
Challenges & opportunities, cont.

- Implementation on quantum hardware:
  - — exploiting noise bias, e.g., erasure qubits,
  - — solving different optimization problems,
  - — …



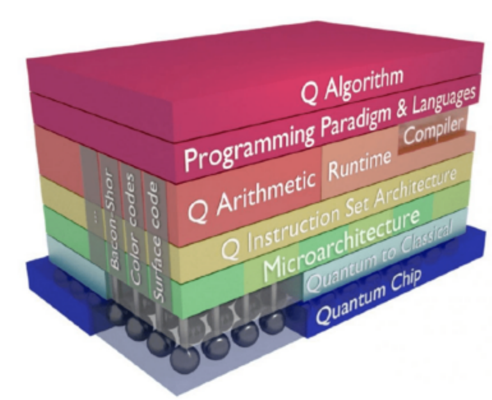
Kubica et al., PRX (2023)

- Implementation of logical operations:
  - — alternatives to magic state distillation,
  - — constructing novel QEC codes,
  - — …



Beverland et al., PRX Quantum (2021)

- Integration in the quantum computing stack:
  - — fault-tolerant compilation of algorithms,
  - — solving the routing problem,
  - — …



source: QuTech webpage