So you want to build a quantum computer ...

Ben Criger [1]

[1]Qutech, TU Delft

February 27, 2018

READYING QUANTUM COMPUTING FOR LIFE'S BIGGEST MYSTERIES

December 1, 2017

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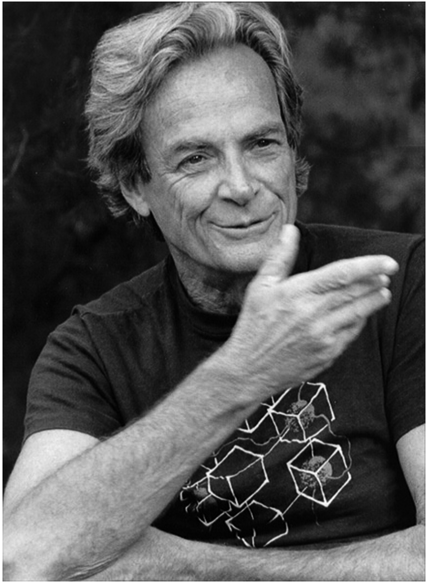
Other possible applications include drug design and materials science (modeling complex structures in nature like proteins) and logistics optimization (finding the most efficient of any number of possible travel routes).

You know the basics



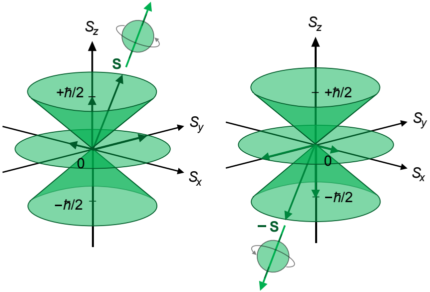
“Nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.”

– Richard Feynman, 1982

You know the basics

What does this mean?

For simplicity, let's consider some *two-level systems* (or *qubits*):



$|\uparrow\rangle \equiv \left|+\frac{1}{2}\right\rangle$ $\quad$ $|\downarrow\rangle \equiv \left|-\frac{1}{2}\right\rangle$

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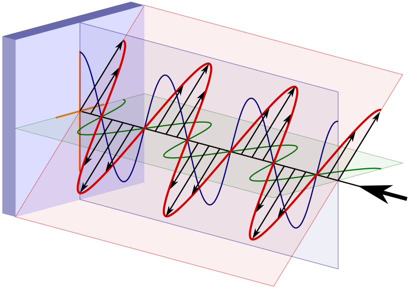

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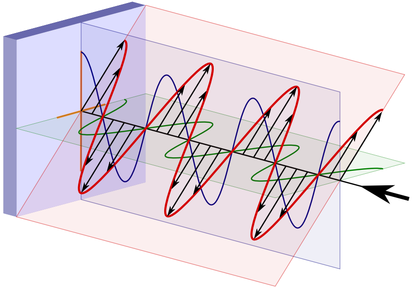
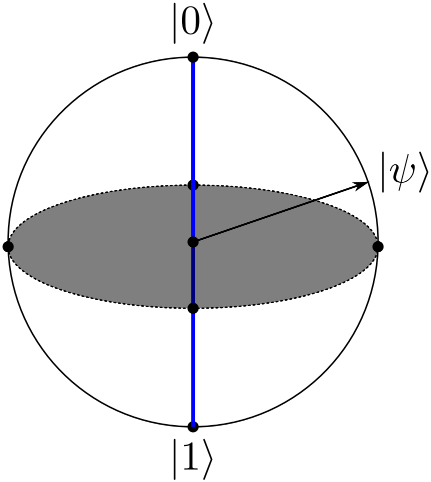


States in these systems are *superpositions* of $|\uparrow\rangle/|\downarrow\rangle$ or $|\text{horizontal}\rangle/|\text{vertical}\rangle$, which we can denote $\alpha|0\rangle + \beta|1\rangle$ or $\begin{bmatrix}\alpha\\ \beta\end{bmatrix}$.

Superposition and its Implications

Superpositions have to be *normalised* ($|\alpha|^2 + |\beta|^2 = 1$) $\therefore \alpha = \cos(\theta)$ and $\beta = e^{i\phi}\sin(\theta)$



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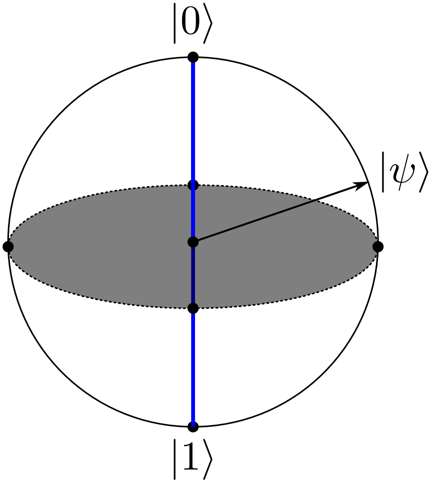

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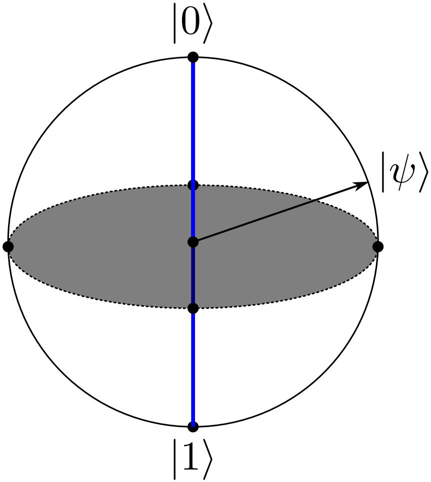

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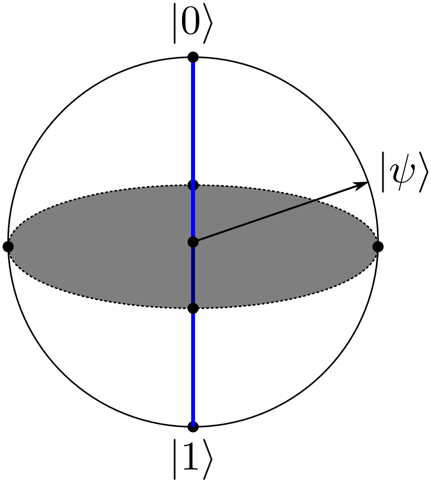

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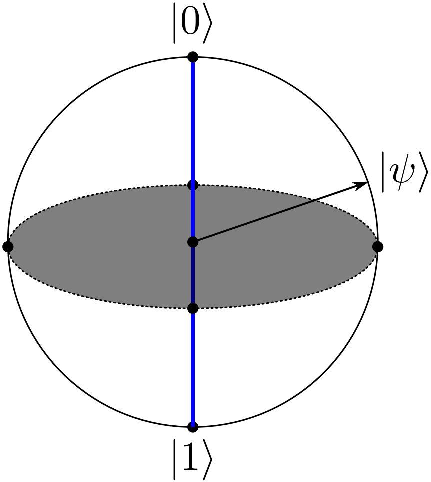

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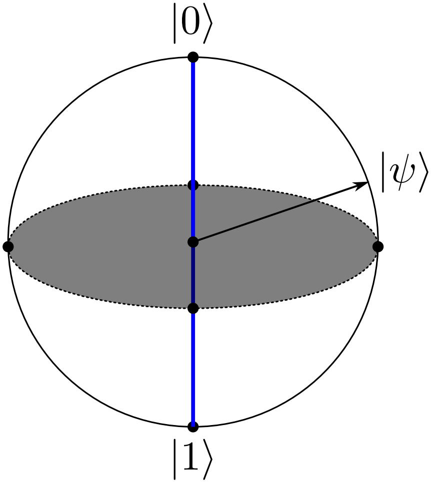

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- *classical states* on the blue axis
- *operations on single qubits* given by rotations on the sphere

Superposition and its Implications

States on multiple qubits are superpositions of basis states:

$$|00\cdots00\rangle\,, |00\cdots01\rangle\,, \ldots, |11\cdots10\rangle\,, |11\cdots11\rangle$$

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Classical computers are exponentially inefficient at simulating quantum mechanics in general.

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In *circuit-based* quantum computing[1], we typically assume that we can:

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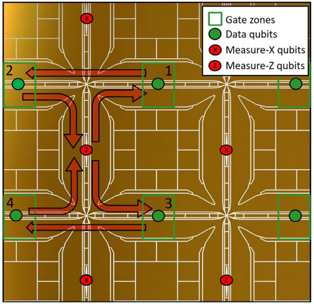
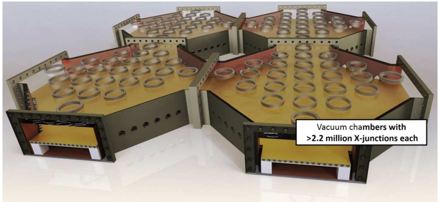
Scale the System Up

The n^{th} qubit shouldn't be much harder to build than the first.





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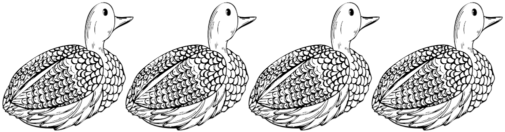
Prepare Initial States

$$|00\cdots 0\rangle =$$ 

Garbage in, garbage out.

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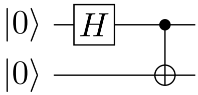
Perform Single- and Two-Qubit Gates

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$\text{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



$$|00\rangle \underset{H_1}{\longmapsto} \frac{|00\rangle + |10\rangle}{\sqrt{2}} \underset{\text{CNOT}}{\longmapsto} \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

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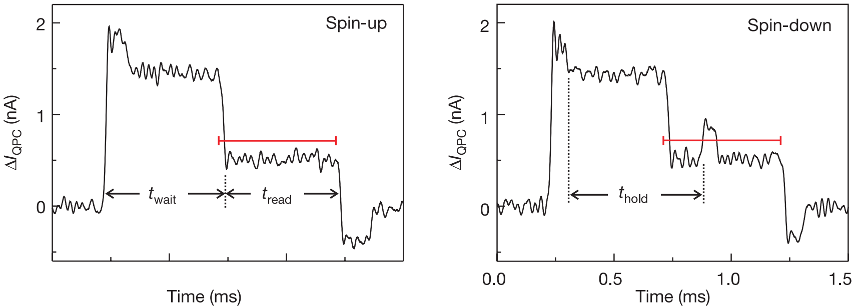
Read Out States

Making classical signals out of quantum states



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Superposition and its Implications

This gives us the power to implement algorithms *in theory*:

Algorithm: Quantum Simulation
Speedup: Superpolynomial
Description: It is believed that for any physically realistic Hamiltonian H on n degrees of freedom, the corresponding time evolution operator e^{-iHt} can be implemented using poly(n,t) gates. Unless BPP=BQP, this problem is not solvable in general on a classical computer in polynomial time. Many techniques for quantum simulation have been developed for general classes of Hamiltonians [25,95,92,5,12,170,205,211,244,245,278,293,294,295,372,382], chemical dynamics [63,68,227,310,375], condensed matter physics [1,99, 145], relativistic quantum mechanics (the Dirac and Klein-Gordon equations) [367,369,370,371], open quantum systems [376, 377,378,379], and quantum field theory [107,166,228,229,230,368]. The exponential complexity of classically simulating quantum systems led Feynman to first propose that quantum computers might outperform classical computers on certain tasks [40]. Although the problem of finding ground energies of local Hamiltonians is QMA-complete and therefore probably requires exponential time on a quantum computer in the worst case, quantum algorithms have been developed to approximate ground [102,231,232,233,234,235,308,321,322,380,381] and thermal [132,121,281,282,307] states for some classes of Hamiltonians. Efficient quantum algorithms have been also obtained for preparing certain classes of tensor network states [323,324,325,326,327,328].

From `https://math.nist.gov/quantum/zoo/`.

Superposition and its Implications

This gives us the power to implement algorithms *in theory*:

Algorithm: Pattern matching
Speedup: Superpolynomial
Description: Given strings *T* of length *n* and *P* of length *m* < *n*, both from some finite alphabet, the pattern matching problem is to find an occurrence of *P* as a substring of *T* or to report that *P* is not a substring of *T*. More generally, *T* and *P* could be *d*-dimensional arrays rather than one-dimensional arrays (strings). Then, the pattern matching problem is to return the location of *P* as a $m \times m \times \ldots \times m$ block within the $n \times n \times \ldots \times n$ array *T* or report that no such location exists. The $\Omega(\sqrt{N})$ query lower bound for unstructured search [216] implies that the worst-case quantum query complexity of this problem is $\Omega(\sqrt{n} + \sqrt{m})$. A quantum algorithm achieving this, up to logarithmic factors, was obtained in [217]. This quantum algorithm works through the use of Grover's algorithm together with a classical method called deterministic sampling. More recently, Montanaro showed that superpolynomial quantum speedup can be achieved on average case instances of pattern matching, provided that *m* is greater than logarithmic in *n*. Specifically, the quantum algorithm given in [215] solves average case pattern matching in $\widetilde{O}((n/m)^{d/2} 2^{O(d^{3/2}\sqrt{\log m})})$ time. This quantum algorithm is constructed by generalizing Kuperberg's quantum sieve algorithm [66] for dihedral hidden subgroup and hidden shift problems so that it can operate in *d* dimensions and accomodate small amounts of noise, and then classically reducing the pattern matching problem to this noisy *d*-dimensional version of hidden shift.

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Difficulties in Quantum Computing

What about implementing algorithms *in practice*?

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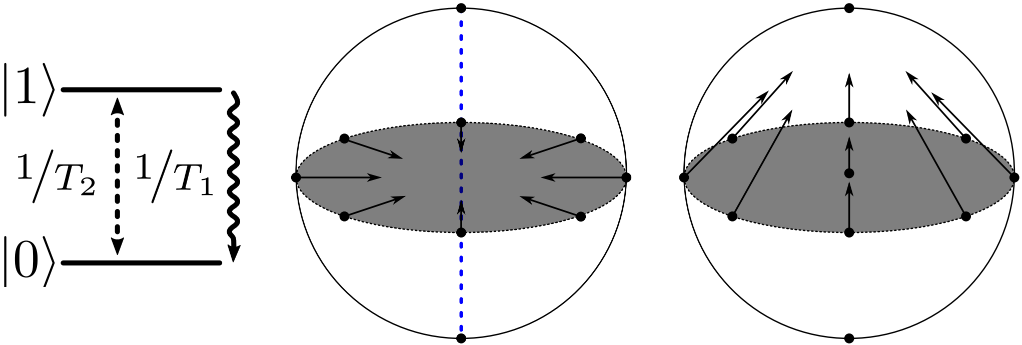

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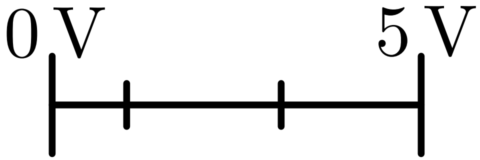

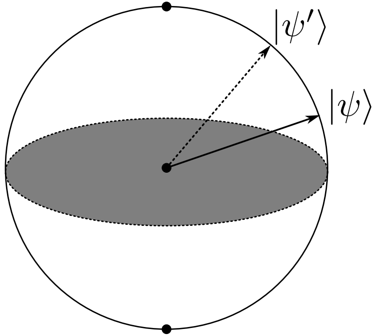

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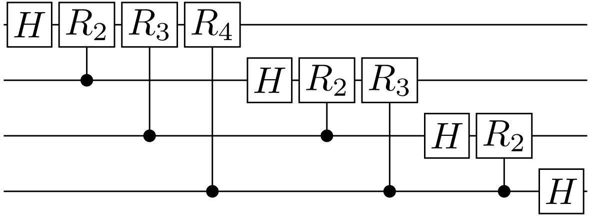
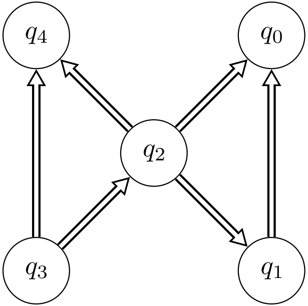
Limited Connectivity

Not all pairs of qubits can participate in a CNOT directly





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$$O\left(N^f \log(\text{poly}(N))\right) < O(N^s) \text{ if } f < s$$

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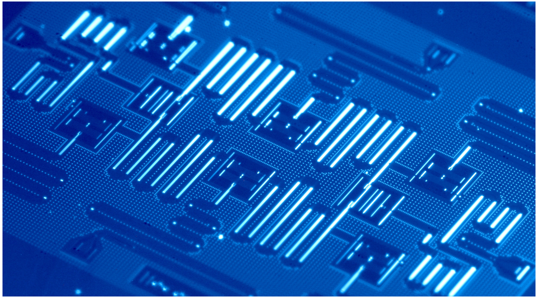

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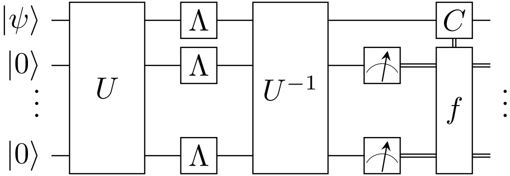

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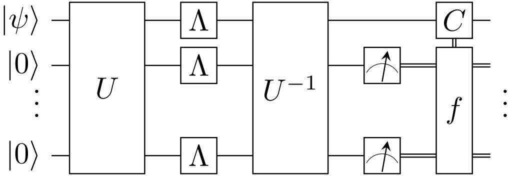

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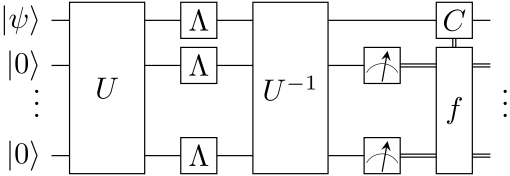

- The states $U|00\cdots0\rangle$ and $U|10\cdots0\rangle$ that span our space of messages are called *code states*
- We usually define these code states to be the *joint* $+1$ *eigenspace* of some operators called *stabilisers*

Aside: Some Brief Examples of Stabilisers

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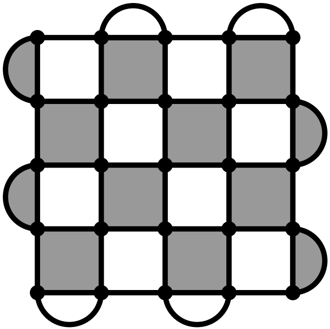
- We call the measurement results a *syndrome*, since they're a list of 'symptoms'.
- Stabiliser states can be mapped to other stabiliser states by H, CNOT and P, and we can simulate them efficiently on classical computers.

The Surface Code

To encode states for transmission, we mostly use this planar code:



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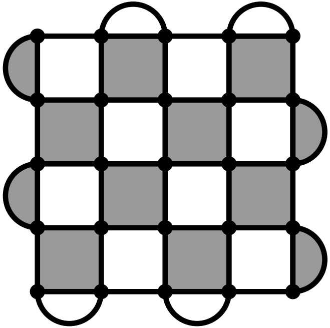

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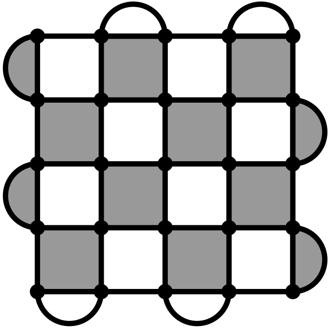

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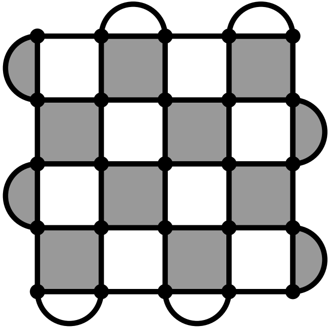
- **White** stabilisers of the form $X^{\otimes 2}$, $X^{\otimes 4}$

The Surface Code

To encode states for transmission, we mostly use this planar code:



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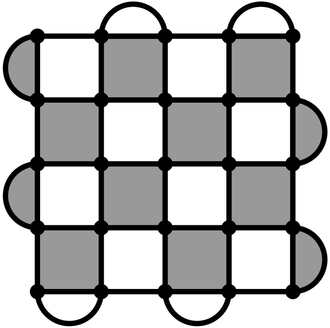

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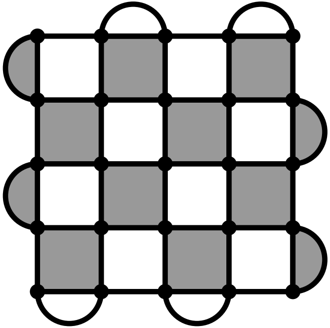

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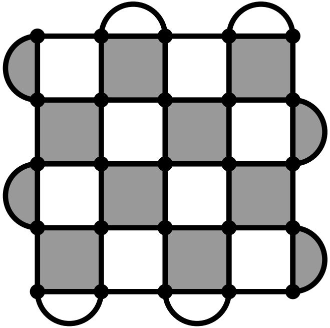

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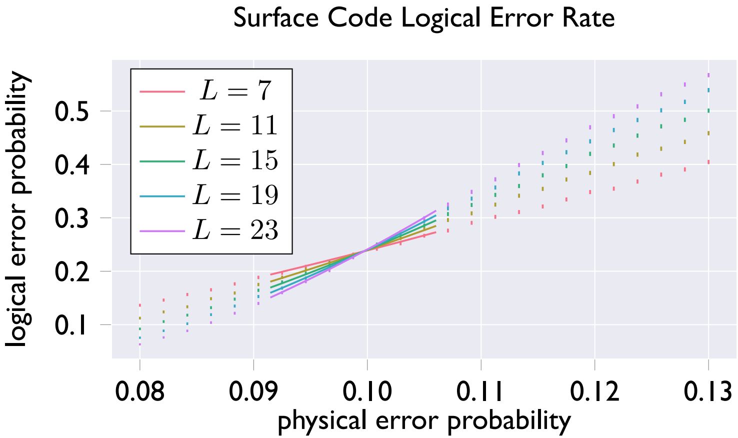

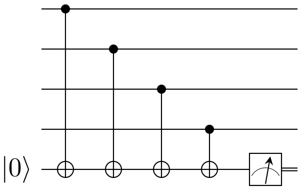

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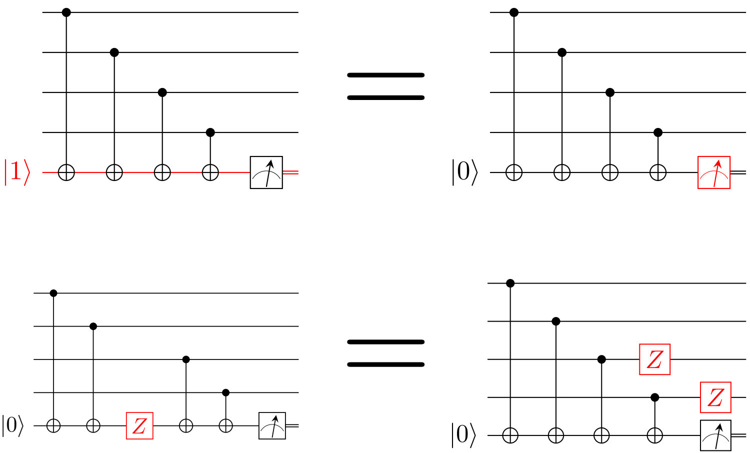
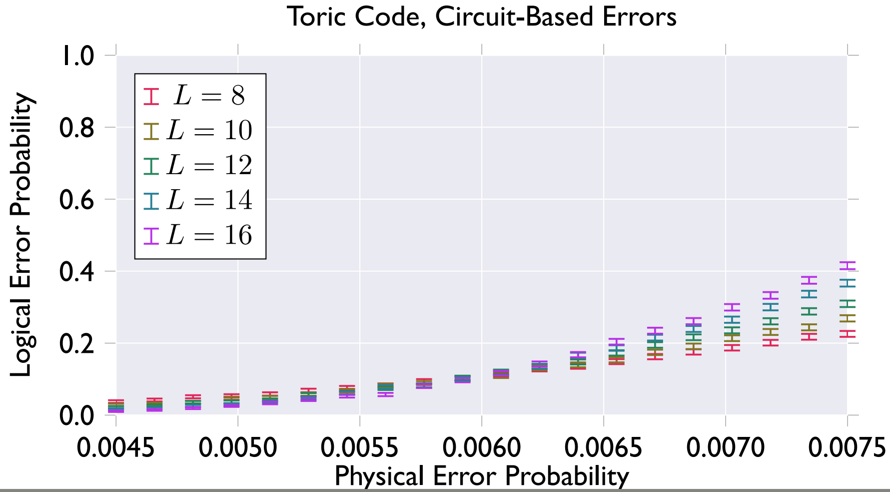


Fault Tolerance in Quantum Memories

By repeating measurements and comparing the results, we can determine which operations are faulty and correct the effect on the data qubits:



My Research

Codes Specialised to Hardware – arXiv:1604.04062v2

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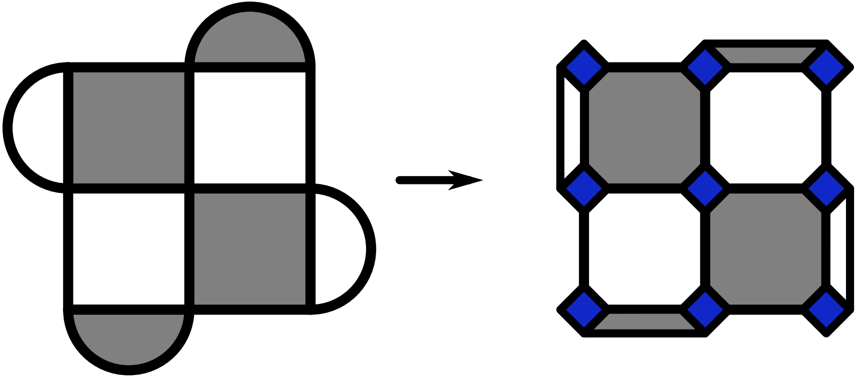

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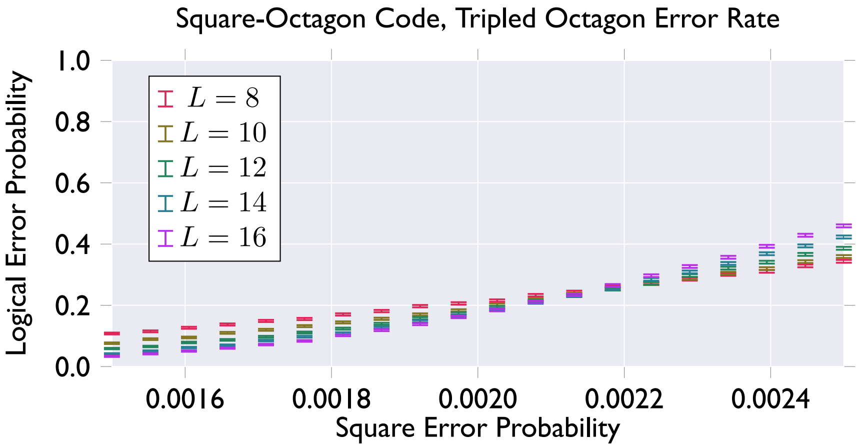

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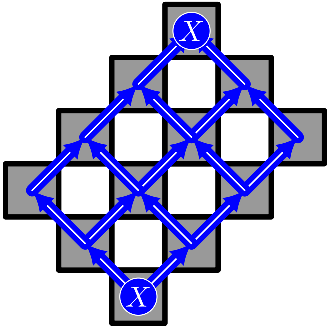

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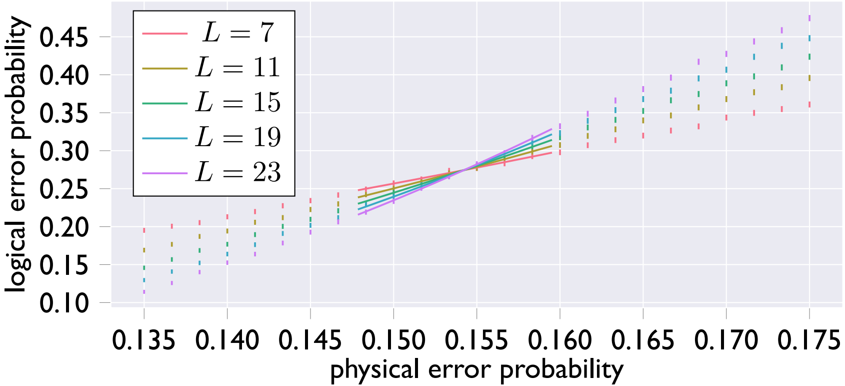
Depolarizing Error Model, without BP/multipath summation



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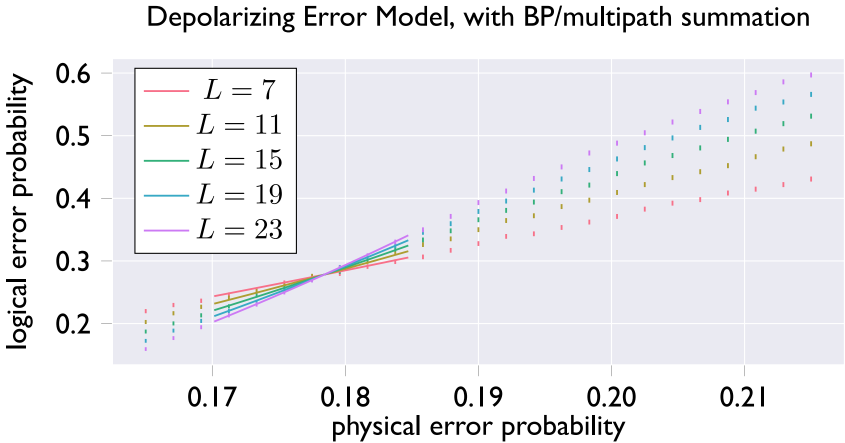

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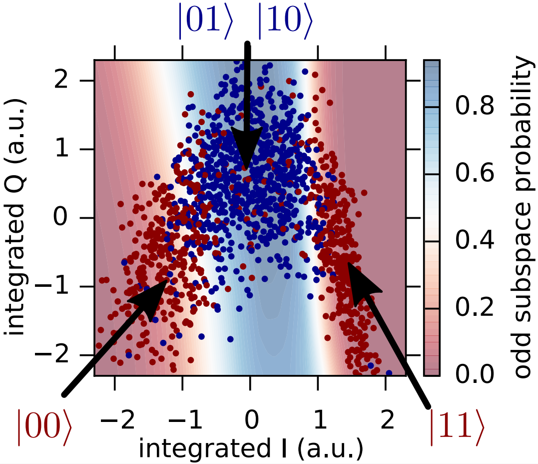

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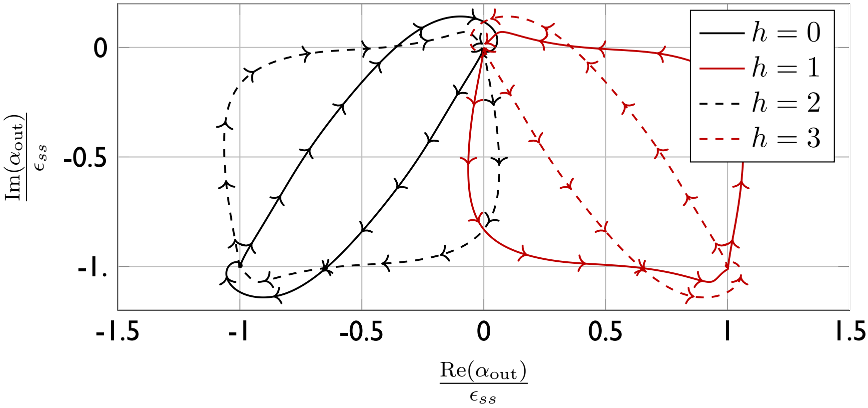

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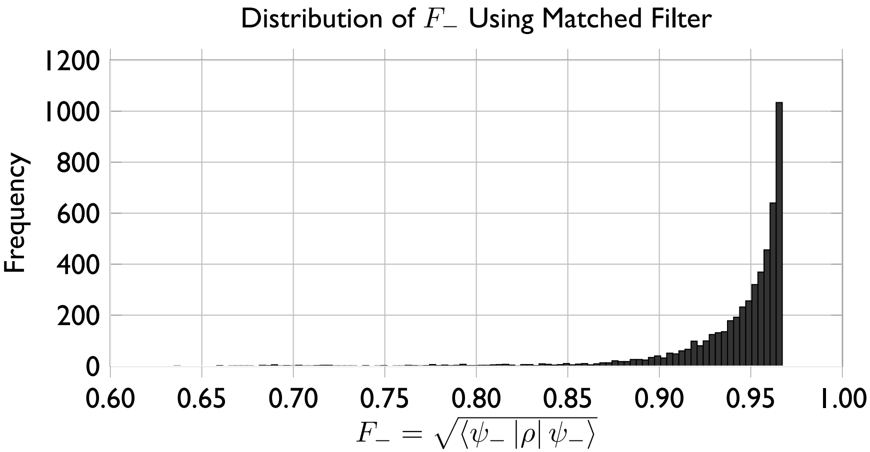

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To Learn More

- QuTech: `qutech.nl` & `qutechacademy.nl`
- Quantum Error Correction & Fault Tolerance: `pirsa.org/C17045`
- These slides: `https://github.com/bcriger/slide_decks`
- My research: `scirate.com/ben-criger/papers`
- My Twitter: `@bcriger`