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Error correction needs error characterization

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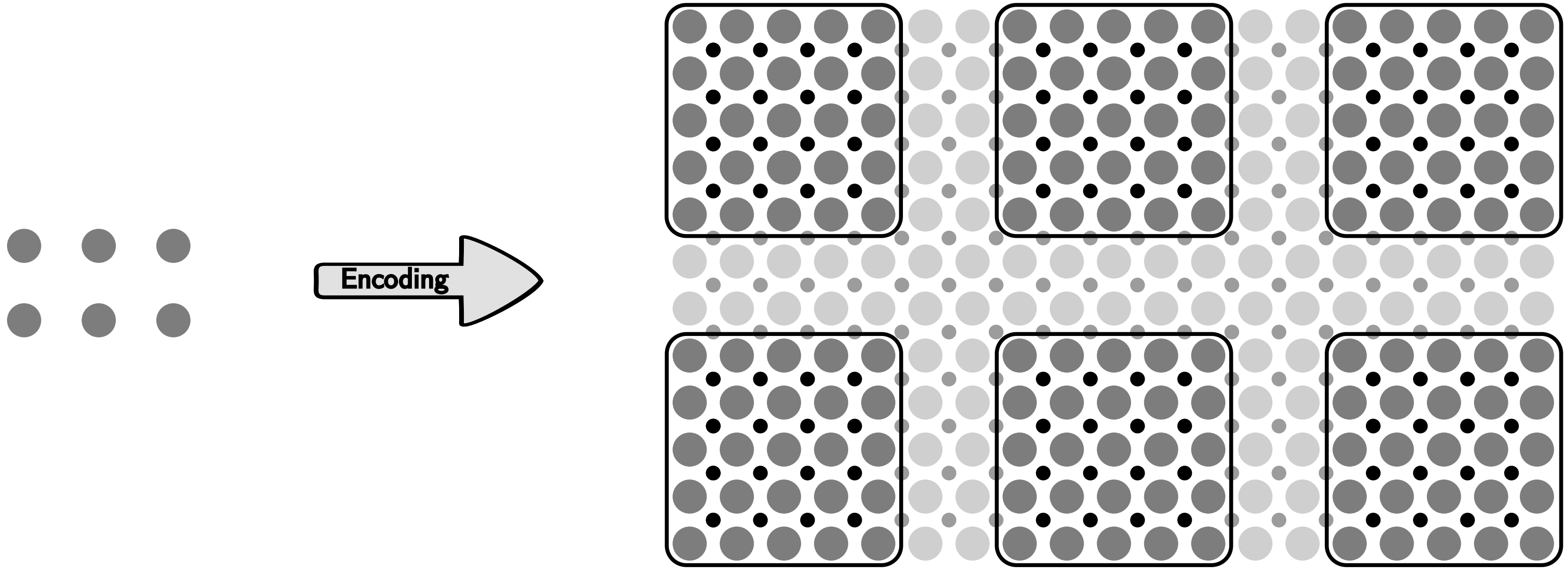
SAND

What limits the performance of quantum computers?

What limits the performance of quantum computers?

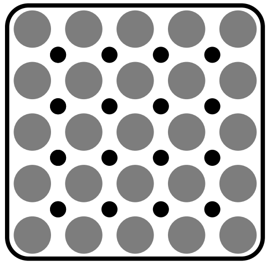
Errors!

What do we do about errors? Error correction!

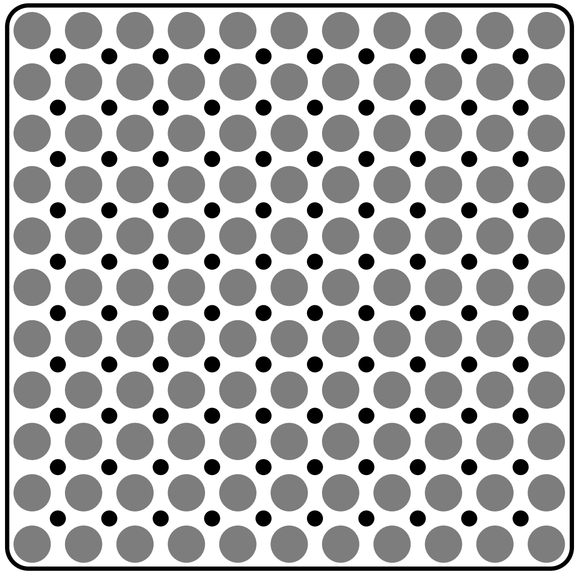


+ lots and lots of large magic state distillation factories to enable universal computation

Higher distance makes for more resilient codes, but at a cost



$d = 5$

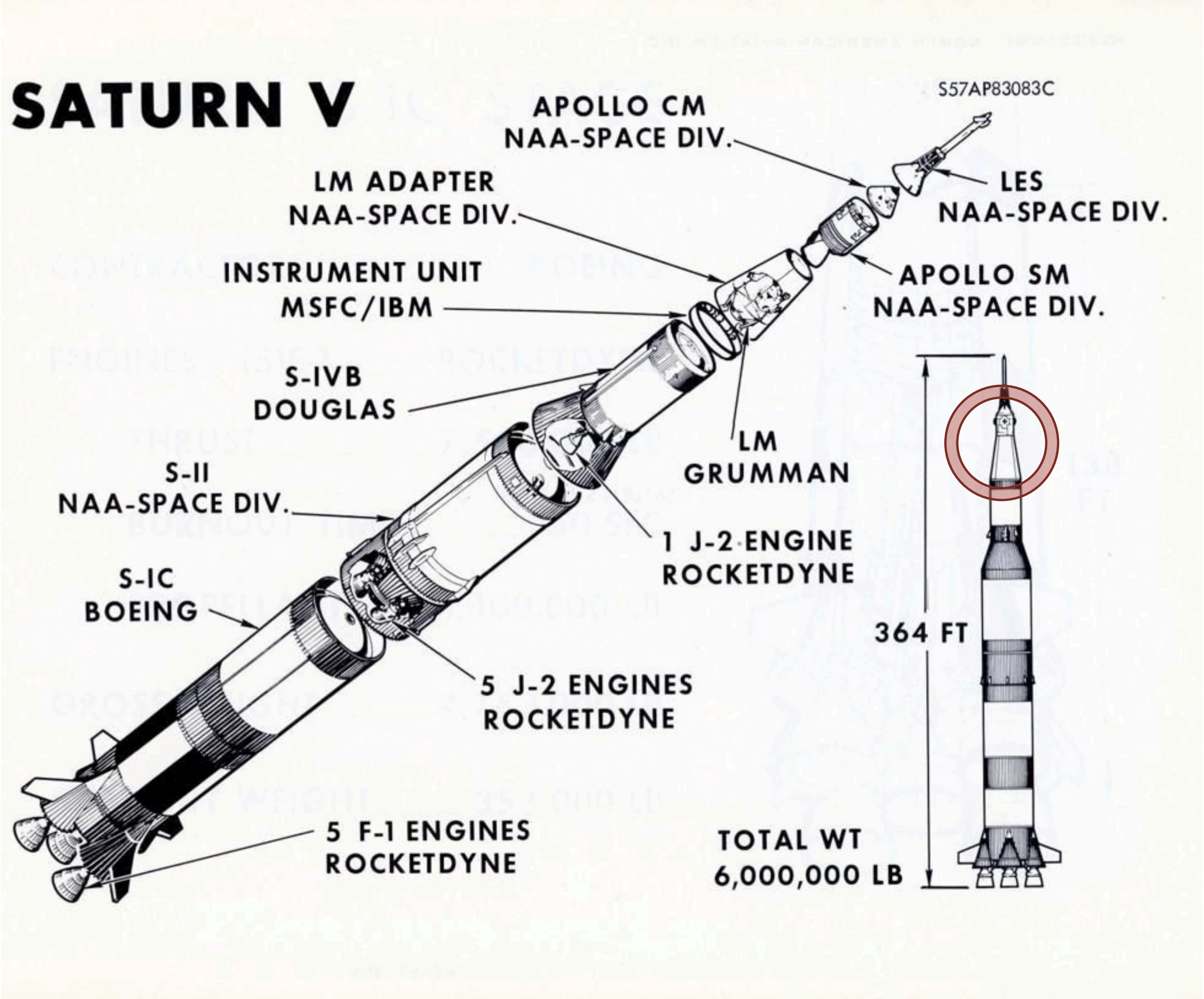


$d = 11$

corrects $\dfrac{d-1}{2}$ errors

Error correction is ***EXPENSIVE***

- The Saturn V was 6 million pounds of infrastructure whose sole purpose was launching 500 pounds of (living) people to the moon.
- Similarly, quantum error correction could require 100’s of physical qubits for each logical qubit.
- Longer computations require more error correction overhead
- Noisy physical qubits require more error correction overhead



Thresholds

- The **threshold** is the error rate below which logical error rate *improves with code distance*.
- Above the threshold, logical error rates *get worse* with increasing distance.
- The closer to the threshold, the bigger the overhead!

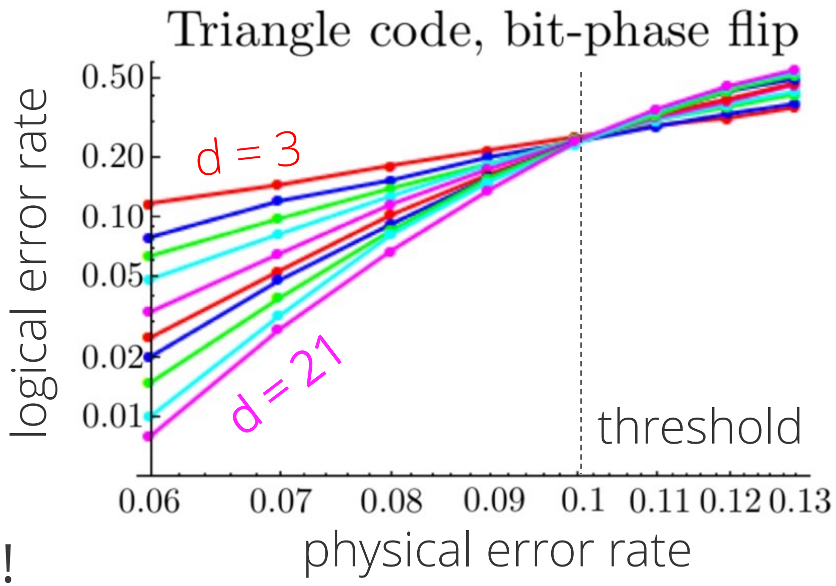


Image adapted from Yoder and Kim, *The surface code with a twist*

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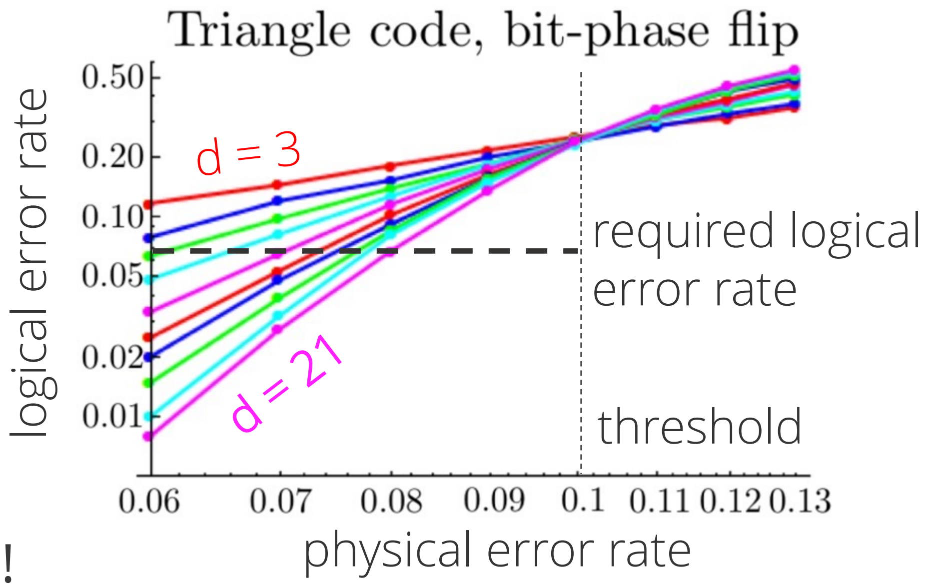

- In this simple example, a **2% absolute change** in the physical error rate (8% to 6%) can lead to an almost **10x reduction** in the error correction overhead for the same logical error rate.

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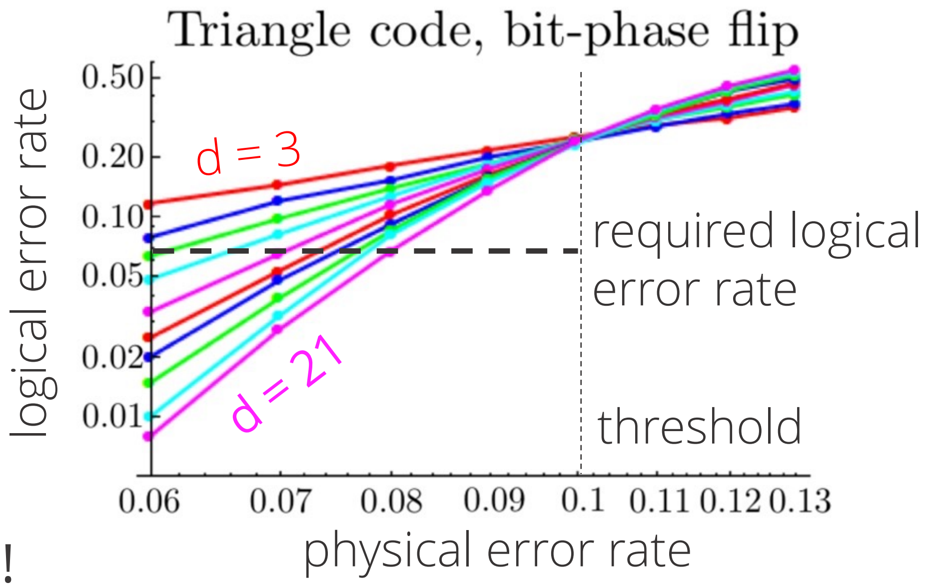
- In this simple example, a **2% absolute change** in the physical error rate (8% to 6%) can lead to an almost **10x reduction** in the error correction overhead for the same logical error rate.
- The further below the threshold you are, the lower your overheads!



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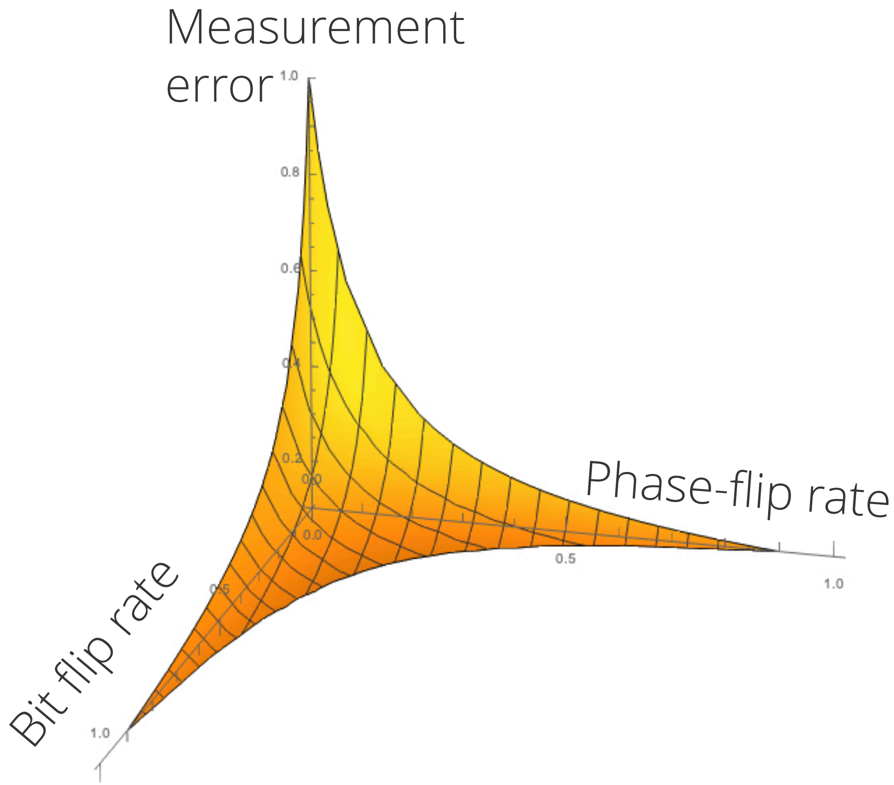
Two ways to get further below threshold

1. The obvious way – **BUILD BETTER QUBITS**
   - Invest millions of dollars into R&D
   - Get a colder fridge
   - Purchase new control hardware
   - Get a colder fridge

2. The less obvious way – Understand your device better
   - Thresholds are typically determined for very unstructured noise models
   - Noise in real hardware has a lot of structure!
   - If the code and decoder are aware of this structure, the **threshold gets higher**!
   - Focus qubit improvements on the noise sources that most meaningfully impact the logical error rate.

Real world thresholds are complicated



- Realistic error models have many parameters.
- This means the threshold is a **surface**, not a point.
- Bias in the noise model can be exploited to get very high thresholds!
  - Some codes treat phase- and bit-flip errors differently
    - Eg., heavy-hex and XZZX codes

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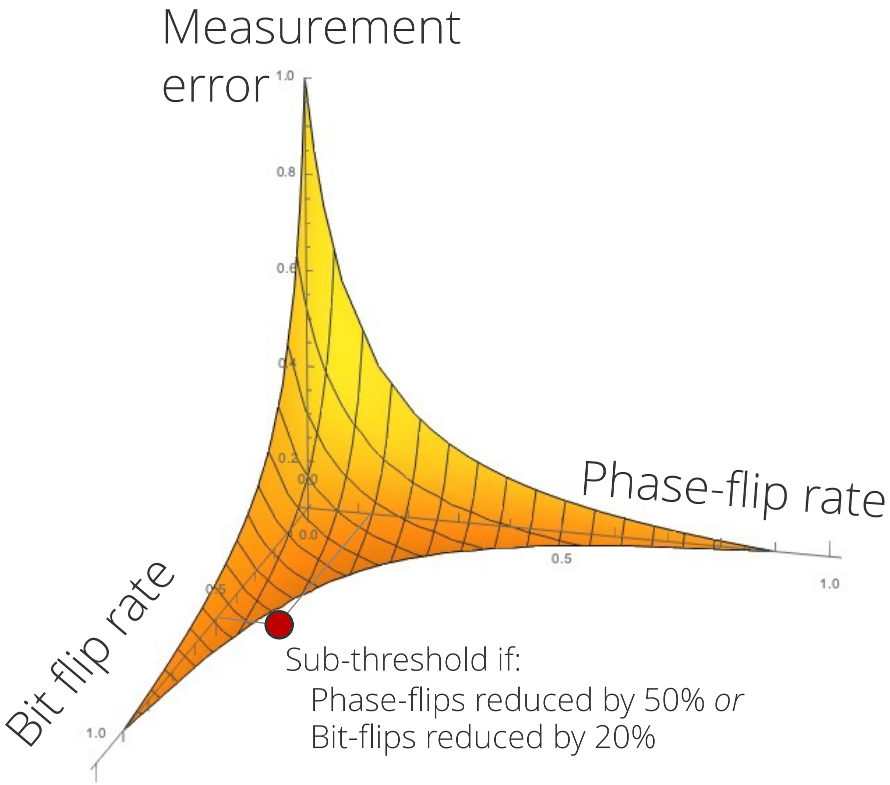

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- Bias in the noise model can be exploited to get very high thresholds!
  - Some codes treat phase- and bit-flip errors differently
    - Eg., heavy-hex and XZZX codes
- Understanding the noise model of your system lets you **optimize your code and hardware** to minimize overhead from error correction!

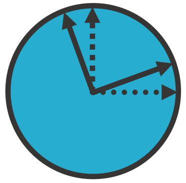
Learning the error model

- There are lots of ways to study the errors in your system
- **Ad hoc methods**
  - One-off experiments that probe specific error models.
- **Randomized benchmarking**
  - Provides a single number that quantifies average gate performance. Often used (abused?) to measure "physical error rate."
- **Process tomography**
  - Constructs a model of a physical gate operation with lots of numbers that tell you about *how* the gate is failing. Assumes perfect measurements and state preparation!
- **Gate set tomography**
  - Constructs a self-consistent model for all gate operations, measurements, and state preparation. Can be expensive (lots of experiment time, lots of postprocessing time). Provides extensive detail about how the system is failing.

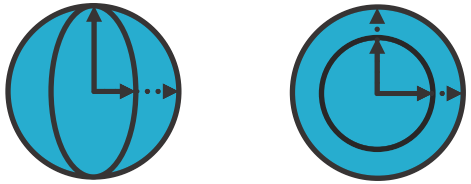
Gate set tomography

- GST specifies a large number of circuits that are designed to amplify many of the most common errors in quantum computers

- A model is built that captures



Coherent over/under-rotation errors
Coherent phase errors



Stochastic bit-flips
Stochastic phase-flips

Also:

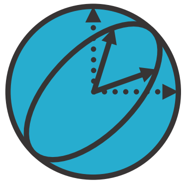
Measurement errors

State-preparation errors

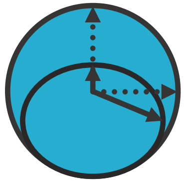
Crosstalk

Dynamic noise processes

Leakage

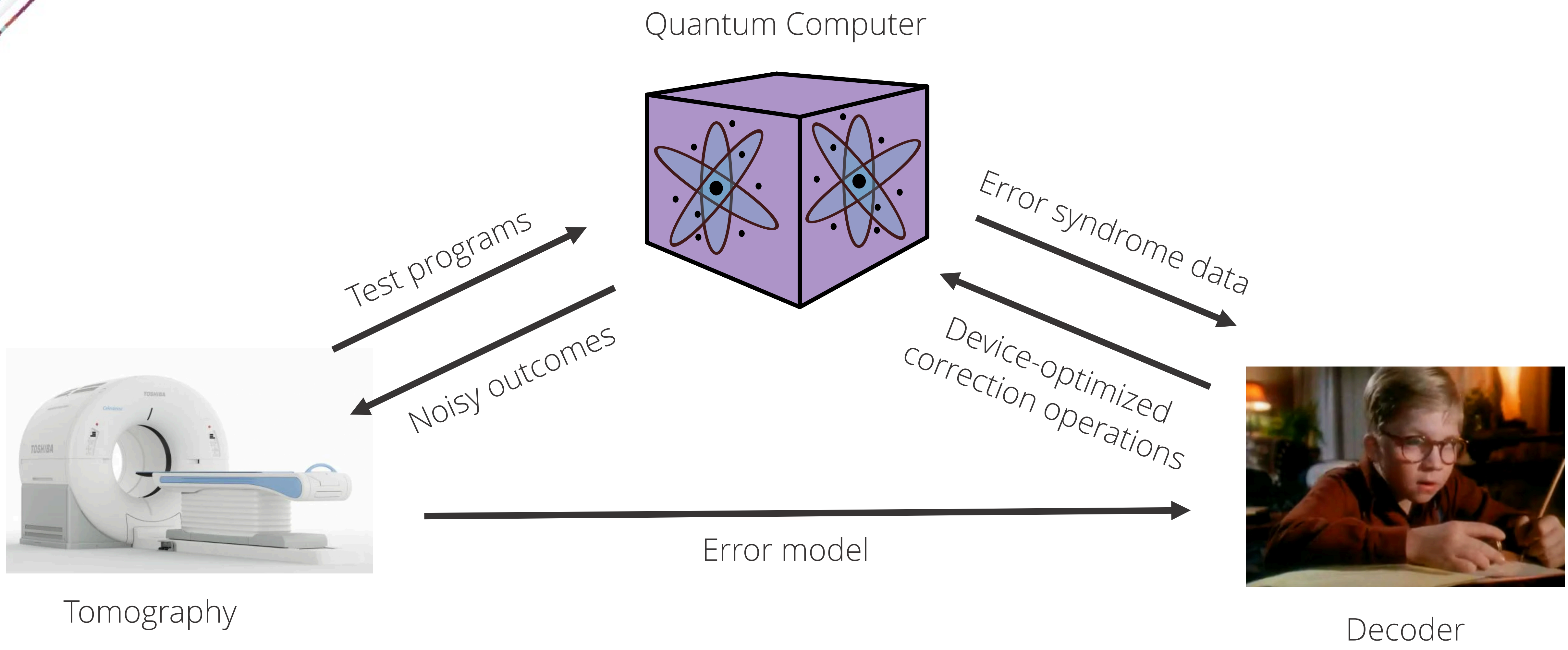


Correlated bit and phase flips



Decay processes

A virtuous cycle!



What do we do with this?

- There's been some great work in developing codes for biased noise. We need more of this!

- The decoders that process classical measurement results should know our best noise model for the device (and how to use it) to correct likely errors

- We need better tools for quickly measuring drifting error rates in large-scale quantum computers

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- We need better tools for quickly measuring drifting error rates in large-scale quantum computers
- **The QPL is hiring staff and postdocs!**
- **Please contact me at qpl@sandia.gov or visit jobs.sandia.gov and search for "*quantum performance*"**