Summary of Key Concepts

Quantum Error Correction

Week of February 25th, 2024

Resources

- QXQ YLC Week 18 Homework Notebook [STUDENT].ipynb
- QXQ YLC Week 18 Lab Notebook [STUDENT].ipynb

Key Terms

Key Term	Definition
Quantum Error Correction (QEC)	A set of techniques to protect quantum computers from errors, often relying on quantum properties since classical approaches don't tend to work.
Error Correcting Codes	The main idea in both classical and quantum error correction is to encode information in a way that protects it from some or all errors. These encodings are called error correcting codes.
Logical Qubit	A qubit, potentially represented by multiple physical ones, that is used within an algorithm or protocol.
Physical Qubit	A qubit that is physically part of hardware, potentially used with other physical qubits to represent a logical one.
Auxiliary Qubit	An extra qubit (physical or logical) used to help perform a computation or error correction, but that is not part of the input or output.
Classical Repetition Codes	One logical bit is encoded by repeating its state across many physical bits.
Quantum Repetition Codes	One logical qubit is encoded by repeating its state across many physical qubits.
Syndrome Measurement	A measurement that says if an error has occurred.

Lecture

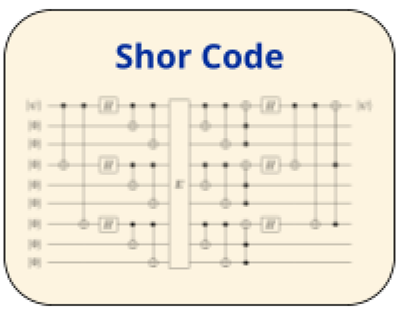
Learning Objectives

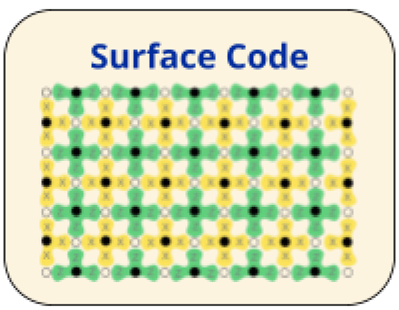
1. Recognize what quantum error correction is and why it is important.
2. Recognize what a repetition code is.
3. Recognize the terms: logical vs. physical qubits and error detection vs. correction.

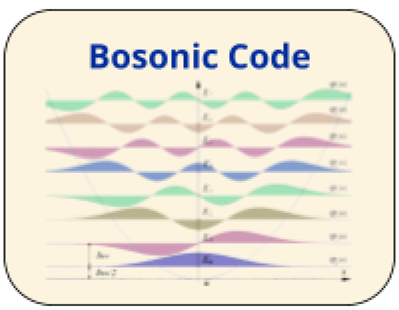
Key Ideas

1. **Quantum Error Correction (QEC)** is a set of techniques to protect quantum computers from errors, often relying on quantum properties since classical approaches don't tend to work. QEC's ultimate goal is enabling fault tolerant quantum computing.

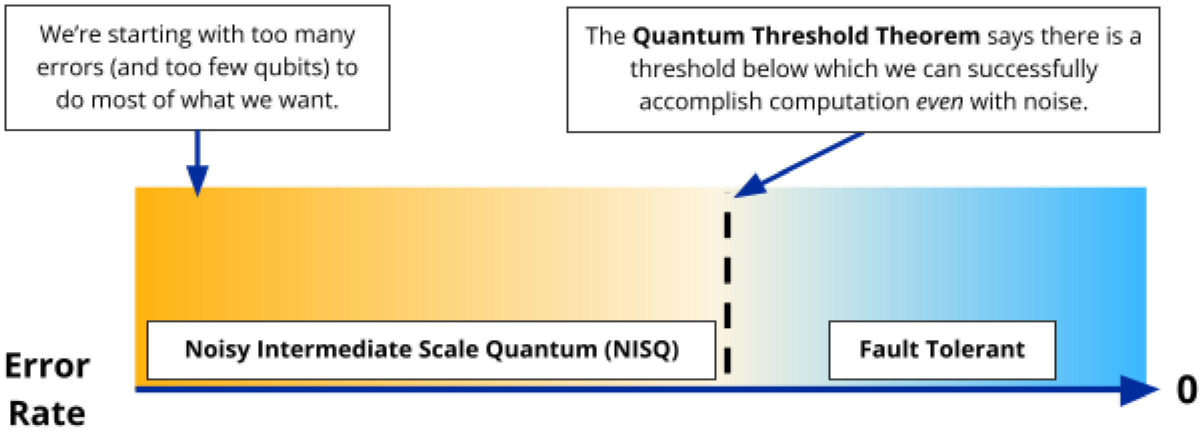
2. The main idea in both classical and quantum error correction is to encode information in a way that protects it from some or all errors. These encodings are called **error correcting codes**. Famous examples include:



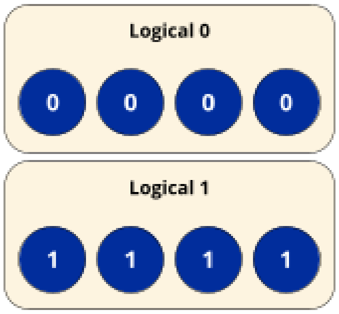




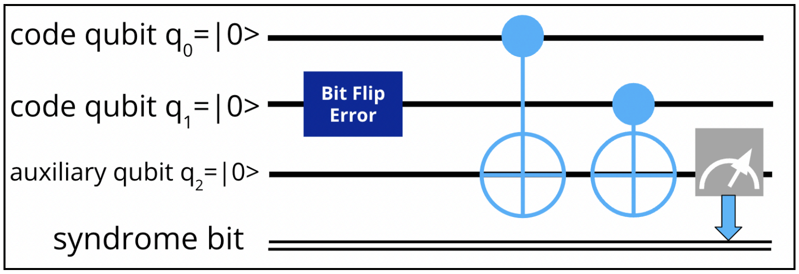
3. When considering the rate of errors incurred by computers and their size, current day quantum devices are considered **Noisy Intermediate Scale Quantum (NISQ) devices**, while the ultimate goal is to build quantum devices capable of working successfully even in the face of errors–known as **Fault Tolerant devices**.



4. **Classical repetition codes** simply repeat the information of one bit across many bits. For example, here is a 4 bit repetition code:



5. **Quantum repetition codes** encode one logical qubit using many physical qubits. Although similar in idea to classical repetition code, they need to be built differently due to the nature of quantum states. For example, here is one way to build a 3 bit repetition code:



6. Cutting edge quantum error correction algorithms focus on using fewer auxiliary qubits to detect and correct any type of errors. Understanding each one requires certain theoretical concepts and asking questions such as:
    a. Do our theoretical codes actually work like we expect on the hardware we have?
    b. Which errors are more prevalent on which architectures?
    c. What hardware makes error correction more feasible?

   d. What do qubits need to be able to do in order to implement quantum error correction?
   e. What is the minimum amount of times we need to run a circuit in order to get a reliable result?
   f. How much error correction should be built into hardware versus software?

7. Learning new codes can be daunting. But you can start by breaking down any Quantum Error Correction scheme into 5 parts that can be distinct steps *or* different parts of the same code at a given time:
   a. **Encoding**: Encode logical states and gates into physical states and gates.
   b. **Sending over Noisy Channel**: The physical state is exposed to noise and may incur errors.
   c. **Error Detection:** Any errors in the state are detected and diagnosed using the error syndrome.
   d. **Error Correction**: Any errors in the state are corrected.
   e. **Decoding**: The final physical state is interpreted logically.

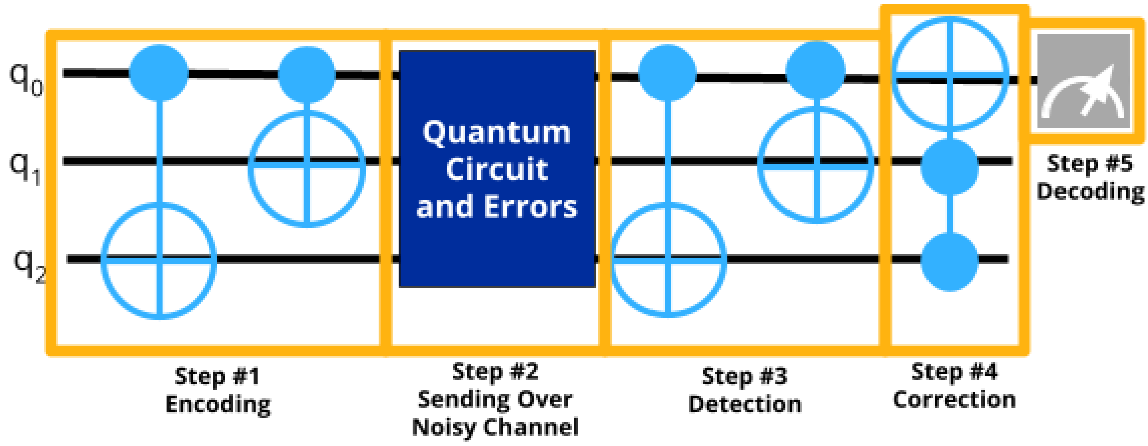
Lab

Learning Objectives

1. Recognize how to implement a bit flip code using cirq.
2. Recognize how to test an error correcting code using cirq generally and with noise models.

Key Ideas

1. In lab, we explored a different way to implement a bit flip code that does not require a syndrome measurement to correct errors:



2. One of the keys behind this code is the use of the **Toffoli gate** in Step #4. This is the 3-qubit Controlled Controlled X gate, also called the Toffoli gate. It is the same as a CX but with two control qubits that must both be 1 to flip the target.
3. One of the first codes able to correct any (single qubit) error is the Shor Code. It expands upon this bit-flip code and the phase-flip code in the homework.