CSCI 4140
Dealing with Errors

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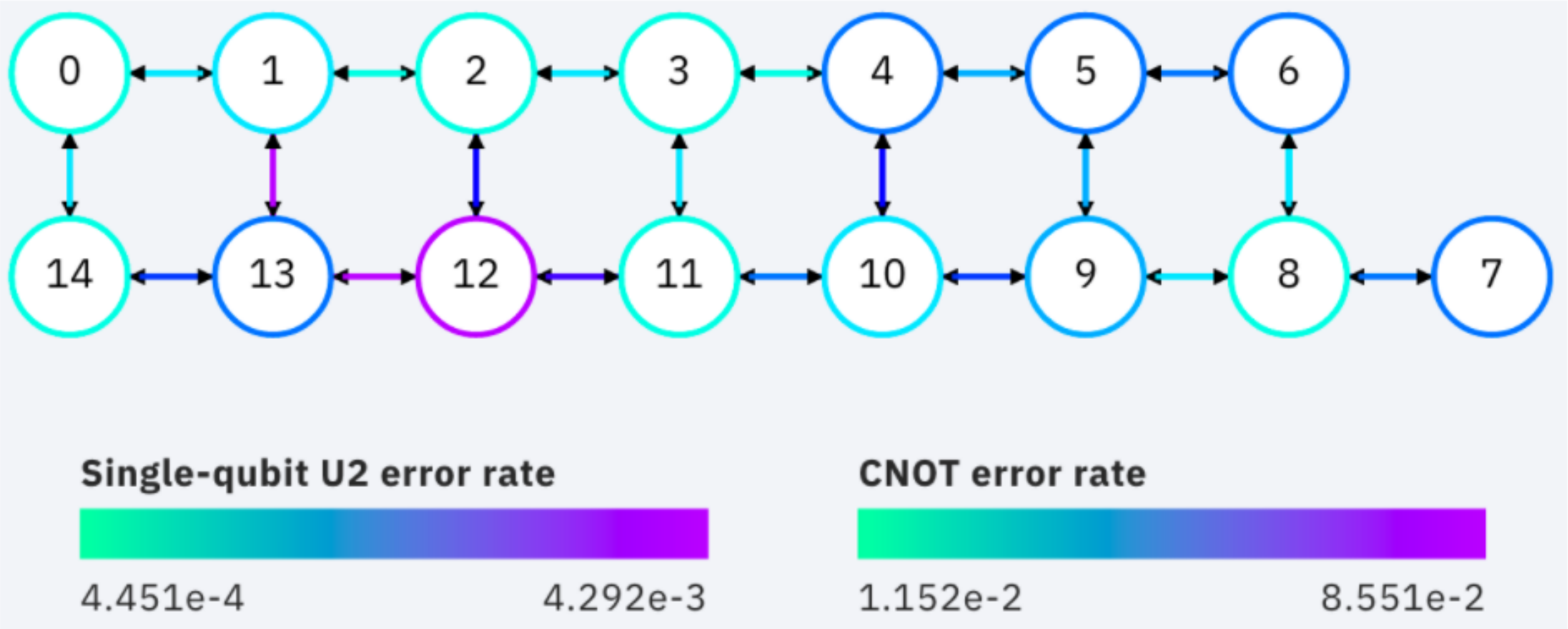
Introduction

- In discussing algorithms we always assumed our qubits were perfect, there was no noise
- We call these logical qubits
- Real quantum computers unfortunately have noise, they have physical qubits
- If we run some of our algorithms on real quantum computers they will fail, they can’t deal with the noise in physical qubits

Introduction

- The error rates measured for the 16 qubit Melbourne computer:



Introduction

- Given that some of our algorithms require a large number of gates, for example anything using the quantum Fourier transform, these error rates are a problem
- There are three possible solutions to these problems:
  - Build better qubits, with much lower error rates
  - Develop algorithms that work on noisy physical qubits
  - Develop ways of fixing errors while the algorithms run
- We need to work on all three

Building Better Qubits

- If the main problem is errors in the qubits we need to build better ones
- This is clearly what we are trying to do
- There is some excellent research in this area that hasn’t made it into production yet
- Doing a better job of pulse shaping and monitoring the impact of pulses on qubits
- This can reduce errors by a factor of 100 or more

Algorithms that Tolerate Noise

- This is an interesting idea, in some sense counter to what we do in computer science
- Do our algorithms need to be exact? We are already dealing with floating point approximations and inaccuracies in input data
- Can we build algorithms that can tolerate noise and errors?
- This is important outside of quantum computing, for example self driving cars
- Requires a different way of thinking

Algorithms that Tolerate Noise

- This is something we need to explore further, and could be a main application of quantum computers
- Example: the computational holography algorithms I work on can tolerate 5% to 10% error without a problem
- Do we need an exact solution? Or is one that is 1% off good enough
- Example: scheduling is very difficult
- Instead of attempting an optimal solution, produce one that is good enough and then hand tune

Error Correction

- This is our hope, we can live with physical qubits if there is some way of putting them together to form a logical qubit
- This problem is much harder than most people think it is
- The common thought is once we have enough physical qubits, it will be easy to construct logical qubits
- This just isn’t the case
- There has been a lot of research on this, but there have been very few if any demonstrations of it actually working

Error Correction

- Why is this so hard?
- We can do error correction with classical bits, we just need to add a few extra bits to detect errors, and a few more if we want to correct them, this has been known for decades
- But, we can read a classical bit without destroying it
- We can copy classical bits, but we can’t copy qubits
- We can try things like simple replication, which we have seen in the lab
- Unfortunately, there are problems with this

Error Correction

- Replication catches what we call bit flips, a |0> is converted to a |1>, for example
- On the Bloch sphere this is a 180 degree rotation, but what happens if the rotation is less than 180 degrees, after all this is a drastic change?
- This produces a superimposed state and its unlikely that we will catch there error
- If the error is small, like 10 degrees, but is repeated many times, this could result in a major problem
- So, there are errors that replication codes can’t detect

Error Correction

- What happens when we apply gates to replication codes?
- Things like CNOT work okay, but we have problems with rotations
- Rotation gates convert our replicated states into Bell states
- To be a bit contrary, how does replication differ from running the circuit multiple times?
- The one good thing about replication is it doesn’t need a lot of extra qubits, compared to other approaches
- It is something we could think of running on our existing quantum computers

Error Correction

- There are more sophisticated error correction codes
- A good example of this is surface codes, which are based on parity
- Surface codes can detect a much wider range of error and can be used with all gates (we think)
- But, they are much more complicated and require many more physical qubits
- A surface code on our largest quantum computer would only result in one or two logical qubits, not very useful

Error Correction

- If we have a code that detects errors, how are we going to correct them?
- This is very important, but very little has been done on this
- The codes can usually detect the qubit that is causing the problem, but now we need to be able to change it to the correct value
- But, we are going to be using qubits and gates that are noisy, so we don’t know whether we have actually corrected the error, or whether an error occurred when we attempted to do the correction
- We need error correction for our error correction

Error Mitigation

- For the time being maybe the best we can do is error mitigation, techniques that reduce the error level, but don't eliminate them
- We saw this with measurement error mitigation
- We could significantly reduce the error, but there was still some error remaining
- This may be a more profitable approach, at least in the near term
- If we can characterize how errors impact our algorithms, this might be good enough

Cat Qubits

- Cat states have been studied in theoretical quantum mechanics since around 1935, recently quantum computing researchers have started studying them
- A regular qubit can be viewed as a 2D vector space, the qubits live on the Bloch sphere
- Cat qubits can be viewed as a 4D vector space, go from having 2 basis vectors to 4 basis vectors
- The idea is that there will be extra redundancy in cat qubits, thought is one cat qubit is as good as 4 regular qubits

Cat Qubits

- The mathematics and quantum physics get a bit deep, but we will look at the basic idea
- We can rewrite a regular qubit in the following way

$$|\psi_{\alpha}^{(0)}\rangle = c_0|0\rangle_L + c_1|1\rangle_L = c_0|\mathscr{C}_{\alpha}^{(0 \bmod 4)}\rangle + c_1|\mathscr{C}_{\alpha}^{(2 \bmod 4)}\rangle,$$

- Where

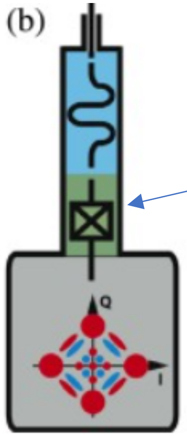
$$\begin{aligned}
|\mathscr{C}_{\alpha}^{(0 \bmod 4)}\rangle &= \mathscr{N}_0(|\alpha\rangle + |-\alpha\rangle + |\mathrm{i}\alpha\rangle + |-\mathrm{i}\alpha\rangle),\\
|\mathscr{C}_{\alpha}^{(1 \bmod 4)}\rangle &= \mathscr{N}_2(|\alpha\rangle - |-\alpha\rangle - i|\mathrm{i}\alpha\rangle + i|-\mathrm{i}\alpha\rangle),\\
|\mathscr{C}_{\alpha}^{(2 \bmod 4)}\rangle &= \mathscr{N}_1(|\alpha\rangle + |-\alpha\rangle - |\mathrm{i}\alpha\rangle - |-\mathrm{i}\alpha\rangle),\\
|\mathscr{C}_{\alpha}^{(3 \bmod 4)}\rangle &= \mathscr{N}_3(|\alpha\rangle - |-\alpha\rangle + i|\mathrm{i}\alpha\rangle - i|-\mathrm{i}\alpha\rangle).
\end{aligned}$$

Cat Qubits

- We have that

$$\mathcal{N}_0 \approx \mathcal{N}_1 \approx \mathcal{N}_2 \approx \mathcal{N}_3 \approx 1/2$$

- And $|\alpha\rangle$ is a coherent state of complex amplitude α

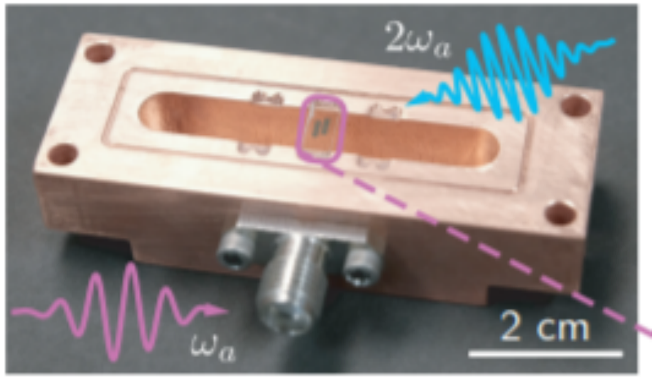


Traditional transmon acting as a syndrome

Cat qubit in resonator chamber

Cat Qubits

- There are several groups working on implementing cat qubits
- Need to be able to construct them, then be able to perform gates on them
- Implementation of a single cat qubit



Summary

- Dealing with errors is one of the main challenges in quantum computing
- The initial idea was that with enough physical qubits we can construct logical qubits
- This may not be as easy as we thought
- Error mitigation may be the near term approach
- May need to dive deeper into quantum mechanics to come with a better solution, the cat qubit is a start in that direction