Identification of Correlated Qubit Errors for Quantum Computing Error Correction

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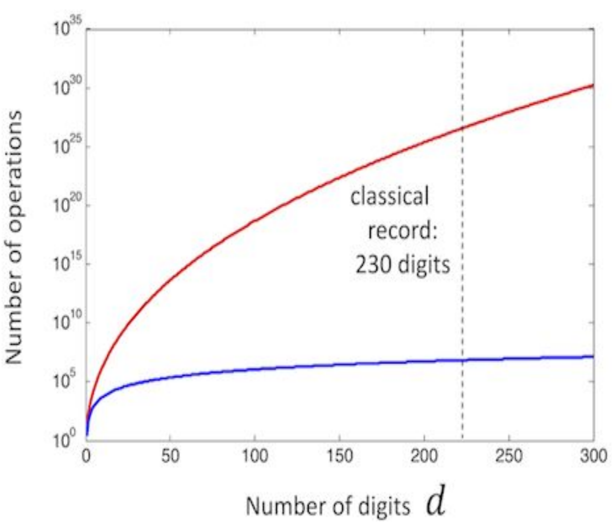
Background / Review of Literature

What is Quantum Computing?

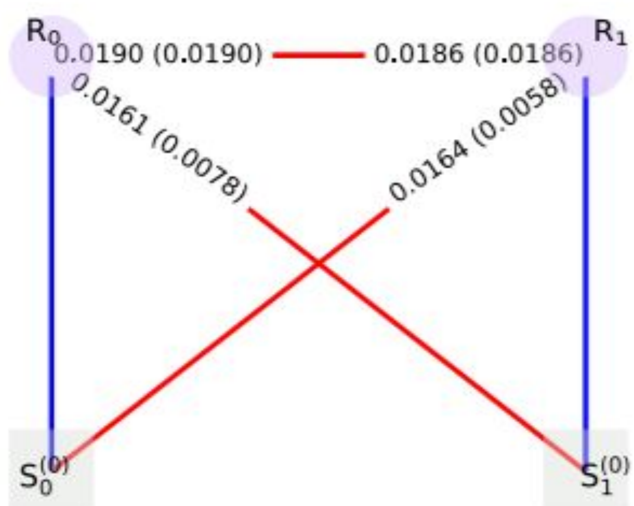
- New emerging technology
- Uses quantum mechanics
  - Superposition
  - Entanglement
  - Interference
- Limited by errors
- Qubit: basic unit of storage for a quantum computer

Applications of Quantum Computing

- Molecular Modeling
  - Battery technology
  - Room temperature superconductors
  - Rapid Drug Development
  - Personalized medicine
- Optimization
  - Electric grid
  - Fleet vehicle routing
- Artificial Intelligence
- Weather Models & Predictions

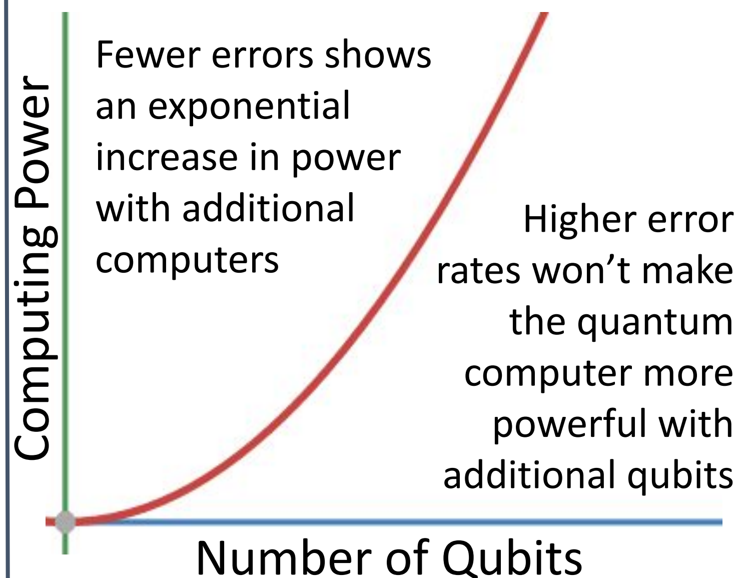


Quantum computers (blue) are much faster than classical computers (red) at factoring large integers (Shor, 1995)



Defined a protocol for detecting crosstalk; validated on a crosstalk simulator (Sarovar et al, 2020)

Crosstalk can cause correlated errors



Quantum computers need successful error correction to achieve their maximum computing power. (Ball, 2018)

Research Question and Definitions

Problem: Correlated qubit errors will make quantum error correction significantly more difficult.

Goal: Determine if qubit errors are correlated on current quantum systems.

Contribution: Develop a method of testing for correlated qubit errors to improve quantum error correction.

Research Question

Are error probabilities $\mathbf{P(q_a)}$ and $\mathbf{P(q_b)}$ independent?

Does qubit adjacency affect independence?

Hypothesis

$\mathbf{P(q_a)}$ and $\mathbf{P(q_b)}$ are correlated when two qubits are adjacent

Null Hypothesis

Qubit error probabilities are independent for both adjacent and nonadjacent qubits

Definitions

$\mathbf{P(q_a q_b) \approx P(q_a)P(q_b)}$: Uncorrelated

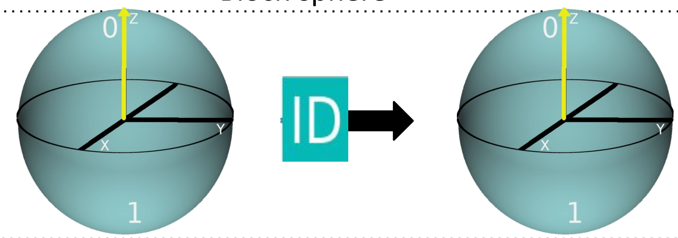
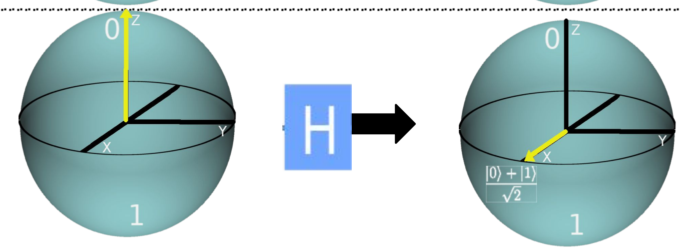
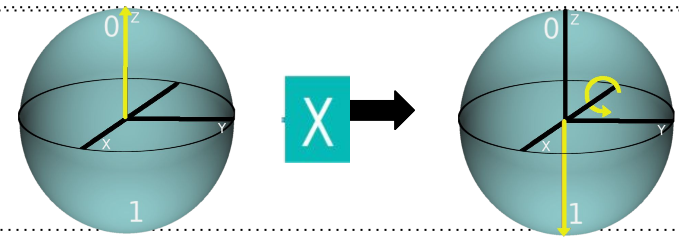
$\mathbf{P(q_a q_b) >> P(q_a)P(q_b)}$: Correlated

- $\mathbf{P(q_a)}$ - Probability of error for qubit ***a*** individually
- $\mathbf{P(q_b)}$ - Probability of error for qubit ***b*** individually
- $\mathbf{P(q_a q_b)}$ - Probability of error for qubits ***a*** and ***b*** together as a pair
- $\mathbf{P(q_a)P(q_b)}$ - Probability of qubit ***a*** times probability of qubit ***b***

- **Adjacency** - Qubit is adjacent if it is directly connected to another qubit (*can be entangled*)
- **Independence** - Qubits do not affect each other's errors
- $\mathbf{P(q_a q_b) \approx P(q_a)P(q_b)}$ - Equation to test for independence of probabilities of errors

Quantum Gates and Circuits

- Quantum gates are quantum computer operators, analogous to classical “and”,”or”, “not” gates.
- Quantum circuits specify the order that the gates are applied to the qubits.

	Symbol	Matrix	Bloch sphere
ID (Identity) gate - Keeps qubit state the same, acting as a delay. No actual gate operation occurs.	ID	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	
H (Hadamard) gate - “Superposition gate”. Puts a qubit in and out of superposition	H	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	
X gate - “Bit flip”. Flips a qubit from |0> to |1> and |1> to |0>, similar to a boolean NOT gate.	X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	

Quantum Circuits

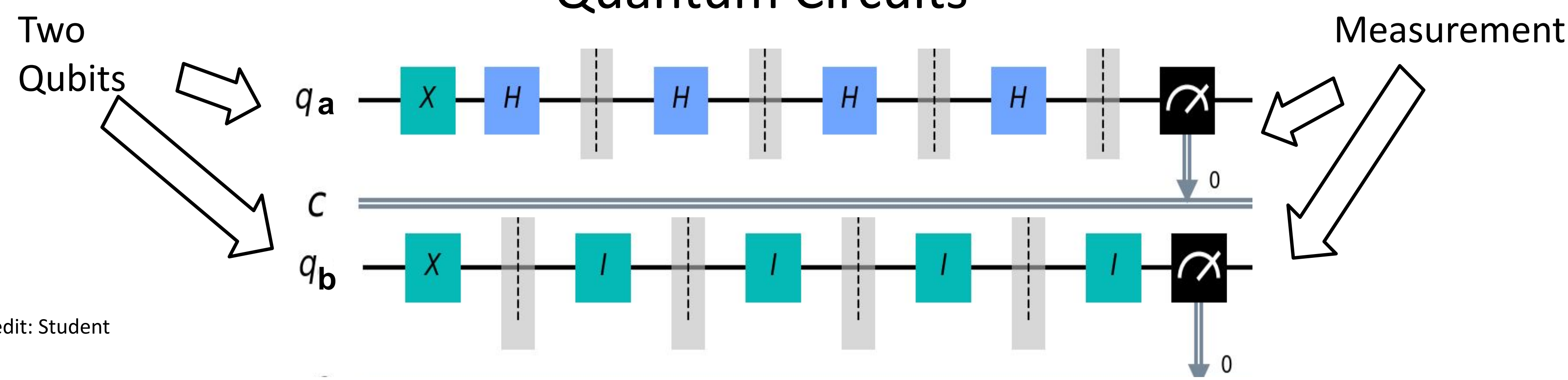


Image Credit: Student

Resources, Variables, and Methods

RESOURCES

- IBM Quantum Experience (open to public)
- IBM Quantum Simulator (open to public)
- Qiskit (Python)
- SciPy (Python)

VARIABLES

- Quantum Computers: Ibmq_valencia, ibmq_santiago, ibmqx2
- Types of Gates: ID, X, H
- Number of Gates: 2, 4, 8, … 128, 256

Step 1 Select a quantum computer, type of gate, number of gates, and qubits ***a*** and ***b***.

Step 2 Run the data collection phase to obtain expected and experimental error probabilities **$P(q_a)$**, **$P(q_b)$**, and **$P(q_a q_b)$** to test for independence until every combination of quantum computer, gate, number of gates, and adjacency is tested**.** (*See next page for details*)

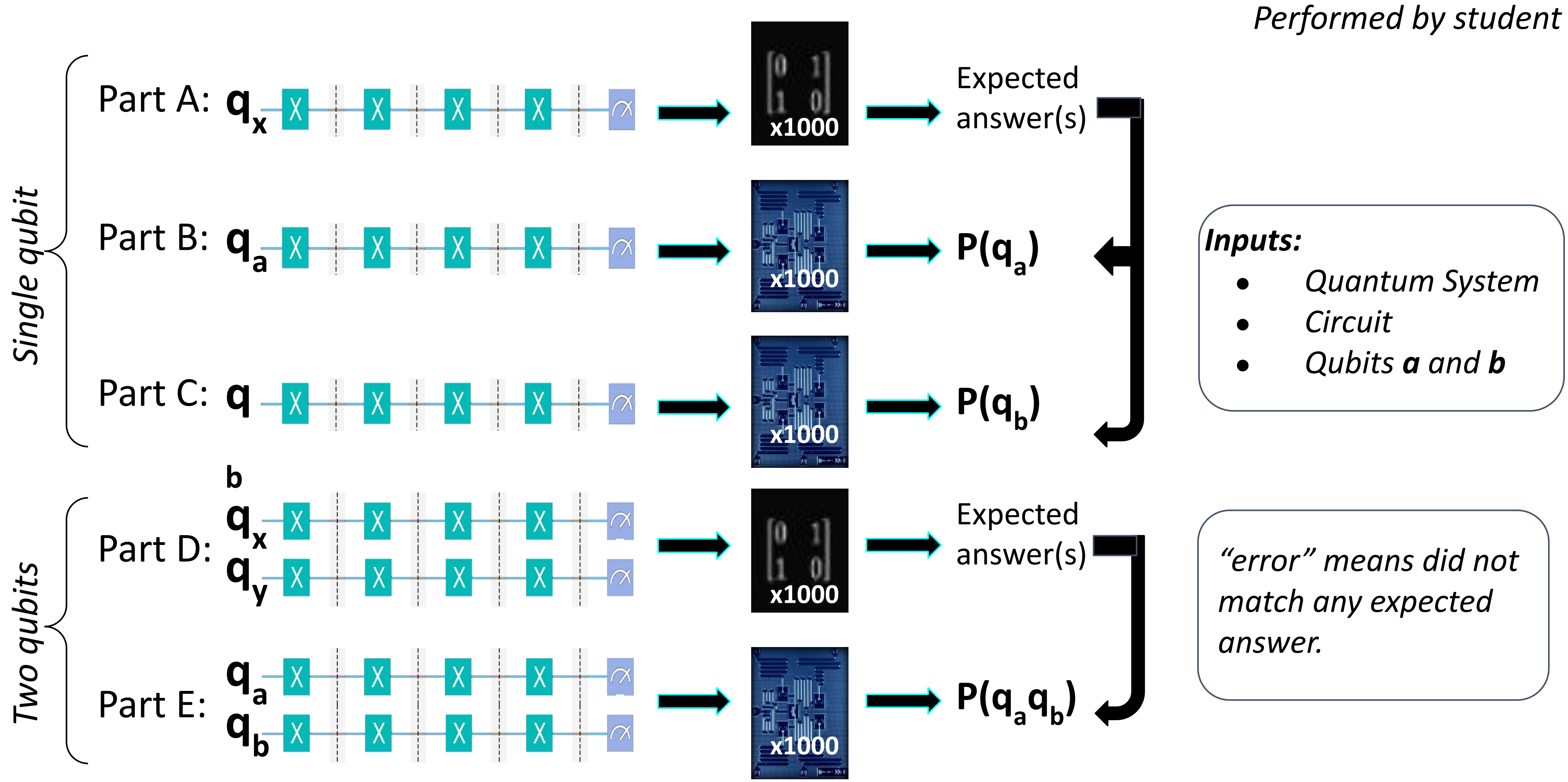
Step 3 Repeat step two thousand times to obtain sufficient data.

Step 4 Record all the data and categorize it based on adjacency, quantum computer, and type of gate.

Step 5 Graph the data and perform a chi-square test to measure significance of correlation.

Repeat procedure thousands of times over 6 months.
15,000 data collection phases and 40 million circuits executed.

Methods: Step 2 in Detail - Data Collection Phase

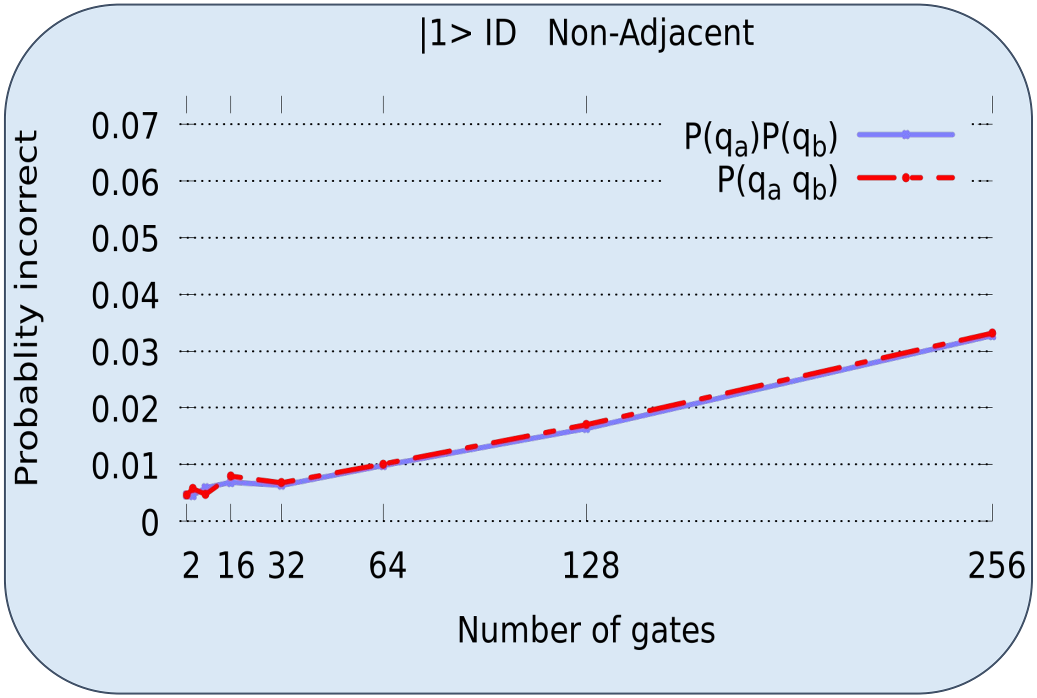


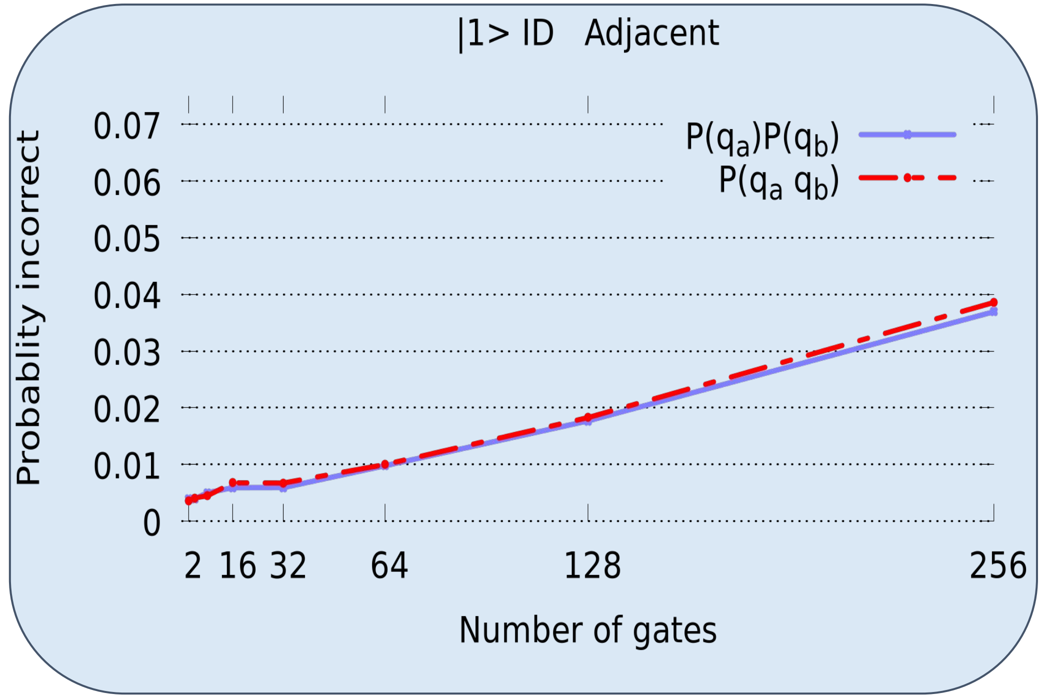
Part A: Execute circuit for arbitrary individual qubit on the simulator to obtain the expected answer
Part B/C: Execute circuit for individual qubits ***a*** and ***b*** on the real quantum computer for the experimental error rates
Part D: Execute circuit for arbitrary qubit pair on the simulator to obtain the expected answers
Part E: Execute circuit for qubit pair ***a*** and ***b*** on the real quantum computer for the experimental error rates
Final Part: $\mathbf{P(q_a)}$, $\mathbf{P(q_b)}$ and $\mathbf{P(q_a q_b)}$ are recorded for use in analysis phase

Findings - ID Gates

Performed by student

ID gate - Identity. State unchanged. No gate operation performed. Errors only from environmental noise.





p-value: 0.3950

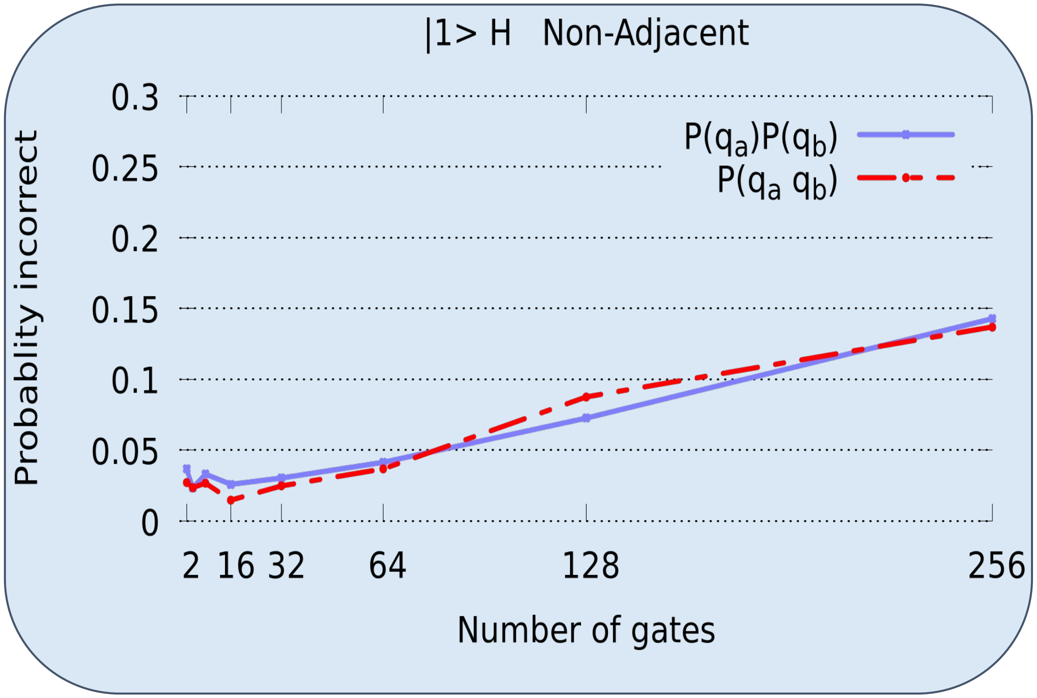
$$\mathbf{P(q_a q_b) \approx P(q_a)P(q_b)}$$

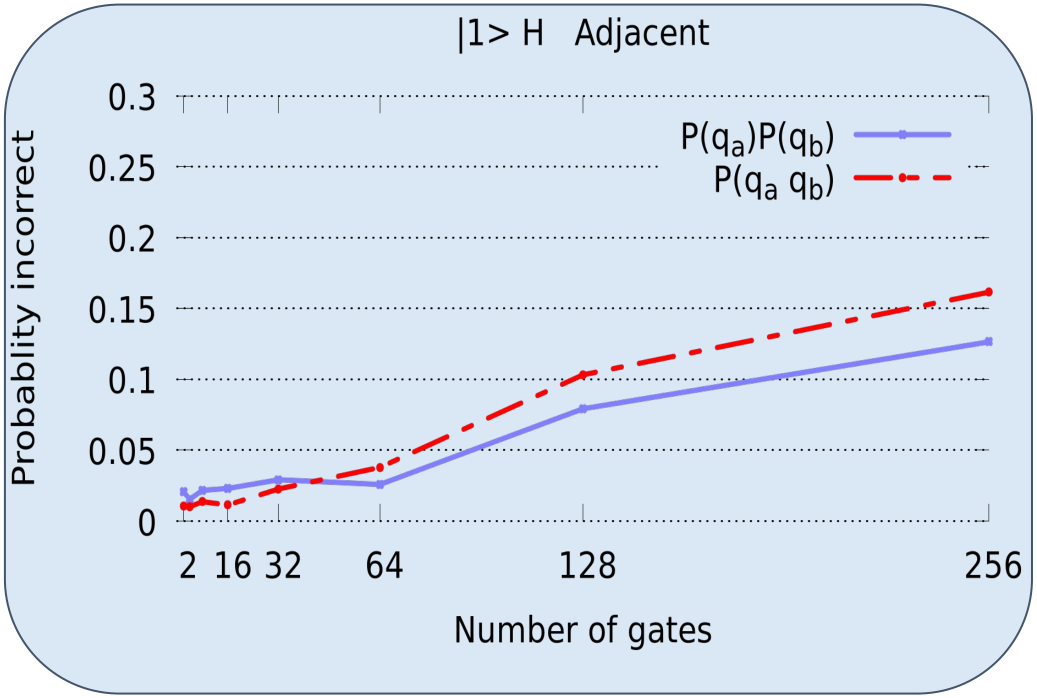
- The graphs show a little difference in the error probabilities.
- The p-value is greater than 0.05; null hypothesis accepted.
- This means that environmental noise is not a significant source of correlated errors.
- **Conclusion:** *Errors from ID gate operations are not correlated.*

Findings - H Gates

Performed by student

H gate - Hadamard. “Superposition gate”. Used to put a qubit in and out of superposition





p-value: 0.0160

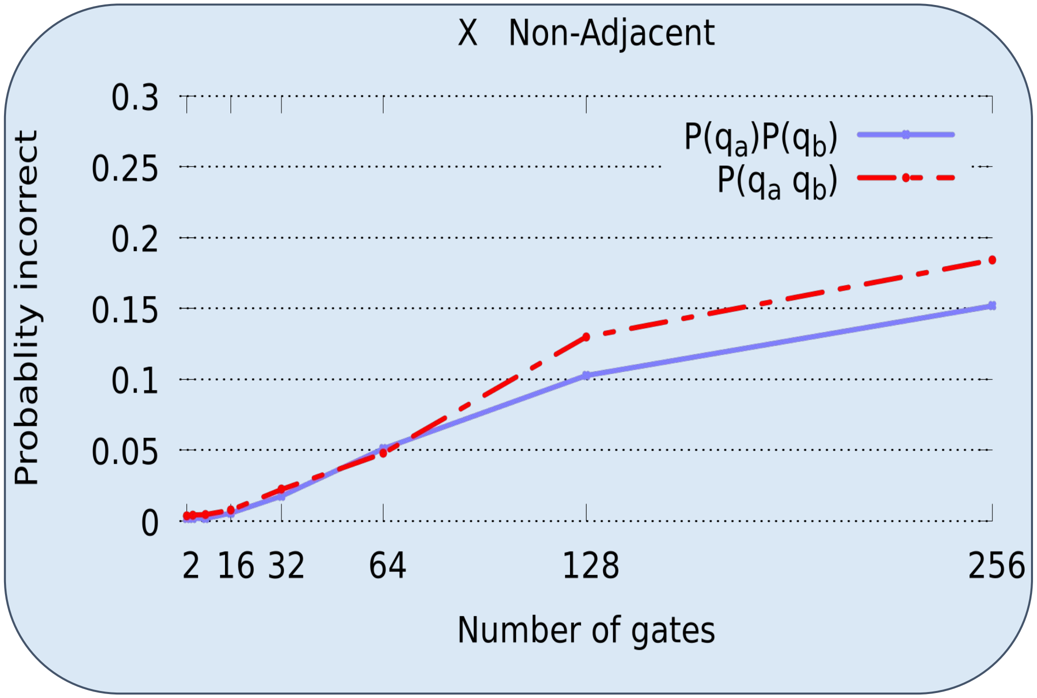
$$\mathbf{P(q_a q_b) >> P(q_a)P(q_b)}$$

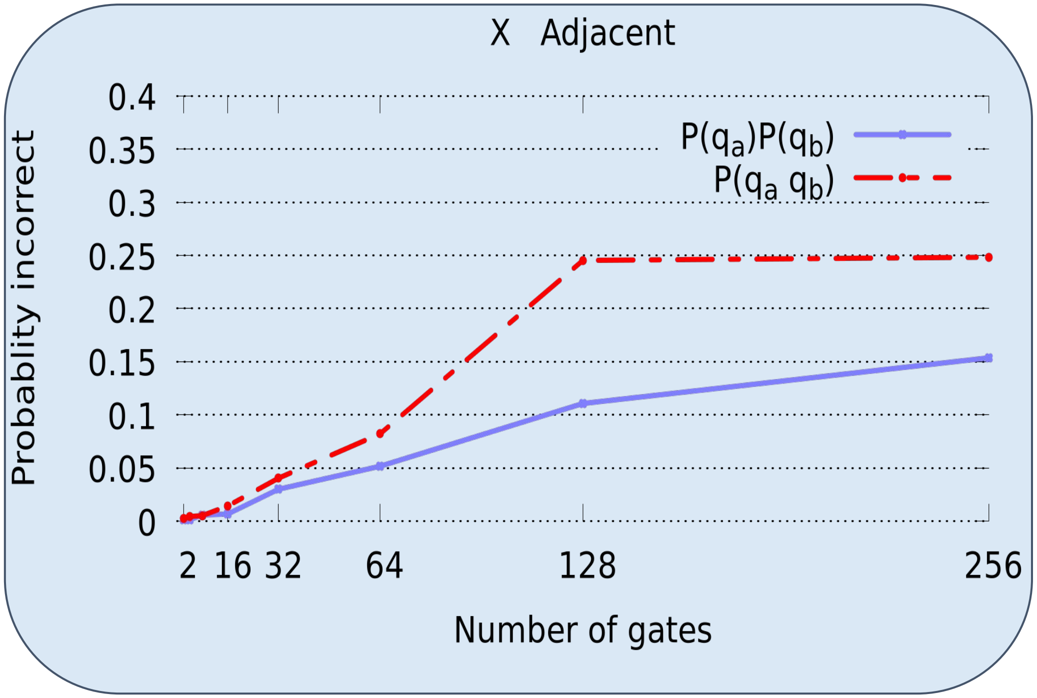
- The adjacent qubits show a small increase in the probability of error from the expected.
- Error rates significantly higher than ID gate and increasing; gate operations are causing errors.
- The p-value is less than 0.05; null hypothesis rejected.
- **Conclusion:** *Errors on H gates are correlated*

Findings - X Gates

Performed by student

X gate - “Bit flip”. 180° rotation about X-axis. Same operation as boolean NOT gate.





p-value: 0.0004

$P(q_a q_b) >> P(q_a)P(q_b)$

- The adjacent qubits show a large increase in the probability of error from the expected.
- Error rates significantly higher than ID gate and increasing; gate operations are causing errors.
- At 128 gates, noise saturates the results, capping error at 25% (two qubits can have 4 potential results).
- The p-value is almost zero; null hypothesis rejected.
- Non-adjacent also shows increase; possibly due to physical proximity of qubits.
- **Conclusion:** *Errors from X gate operations are highly correlated*

Summary of Findings

- Non-adjacent qubits do not cause correlated errors (all results)
- Environmental noise does not cause significant correlated errors regardless of adjacency (ID gate results)
- Adjacent qubits with operations of H and X gates do have correlated errors (H and X gate results)
- Non-adjacent qubits qubits also have some correlated errors, possibly due to physical proximity of the qubits (X gate results)

	Non-adjacent	*Adjacent*
ID	✓	✓
H	✓	✗
X	?	✗

✓ - *No correlated errors.*

✗ - *Correlated errors exist.*

? - *Correlated errors may exist. Data is inconclusive.*

ID gate p-value: 0.3950

H gate p-value: 0.0160

X gate p-value: 0.0004

Conclusion and Future Research

Problem: Correlated errors on quantum computers will make quantum error correction significantly more difficult
Goal: Determine if qubit errors are correlated on current quantum systems
Contribution: Developed a method of testing for correlated qubit errors
Hypothesis: **$P(q_a)$** and **$P(q_b)$** are correlated when two qubits are adjacent

What did my hypothesis hold for?

✗ False: there were no correlated errors for adjacent ID gates
✓ True: adjacent qubits had correlated errors for H and X gates
✓ True: non-adjacent qubits had no correlated errors for ID and H gates
? Unknown: non-adjacent qubits for X gates seemed to be slightly correlated

Conclusion: Correlated qubit errors exist on quantum computers for adjacent qubits but not for non-adjacent qubits

Application: Correlated qubit errors are prevalent on current quantum hardware. In order for quantum computing to succeed, these errors must be significantly reduced. Testing future hardware for correlated qubit errors will help researchers reduce them.

Future Research:

- Investigate if and why X gate operations on non-adjacent qubits have correlated qubit errors.
- Expand my variables to examine other types of gates and on newer and more developed quantum computers
- Experiment with entangled versus non-entangled qubits to determine if entanglement affects correlated errors.

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