Noise Noise and More Noise

Task 2 - QOSF

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Introduction :

One of the main challenges in quantum computing is the noise in current devices. In this task, you will create a simple noise generator and assess its effect. You can use any framework you like (Qiskit, Cirq, etc..)

The quantum addition circuit, implemented using the Draper adder, was transformed into a specific gate basis suitable for execution on quantum hardware. Once transformed, noise was systematically introduced to simulate realistic operational conditions. The noise levels were categorized as low, moderate, and high, corresponding to error probabilities of p 1 (single-qubit errors) and p2 (two-qubit errors).
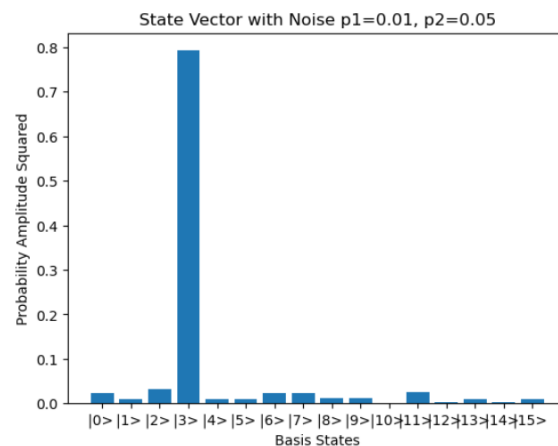

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Results for noise levels p1=0.01, p2=0.05:
Outcome 0011: 809 times
Outcome 0010: 24 times
Outcome 1011: 20 times
Outcome 0110: 17 times
Outcome 1111: 15 times
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Outcome 0111: 21 times
Outcome 0000: 30 times
Outcome 1001: 14 times
Outcome 1101: 10 times
Outcome 0101: 12 times
Outcome 1100: 1 times
Outcome 1000: 9 times
Outcome 0001: 10 times
Outcome 1110: 2 times
Outcome 0100: 5 times
Outcome 1010: 1 times
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Noise in quantum computing can manifest in various ways, impacting the accuracy and reliability of quantum operations. Here's how noise affects the results
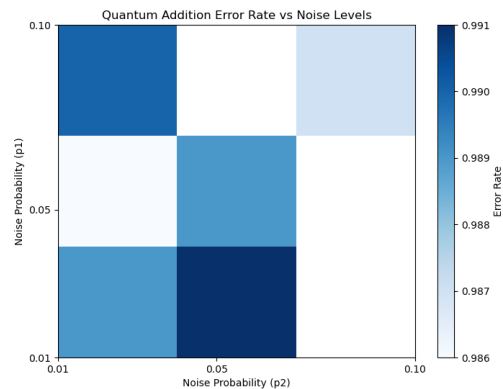
Noise Levels Applied:

- **Low Noise Levels** (e.g., p1=0.01,p2=0.01)

- **Moderate Noise Levels** (e.g., p1=0.05,p2=0.1)

- **High Noise Levels** (e.g., p1=0.2,p2=0.3)

1. How Does the Noise Affect the Results?

As noise is introduced to a quantum circuit, the probability of achieving the intended outcome decreases. Noise causes the circuit's final quantum state to diverge from its ideal configuration, leading to measurement errors.
With more noise, the likelihood of observing the correct result diminishes, which is especially significant for algorithms where precise states are crucial for accuracy.

The introduction of noise had a profound impact on the results of the quantum addition circuit:

Heat Map Mentioning the Error rate with comparison of both probabilities p1 and p2

As noise levels increase (both $p1$ and $p2$), the probability of applying incorrect gates increases.
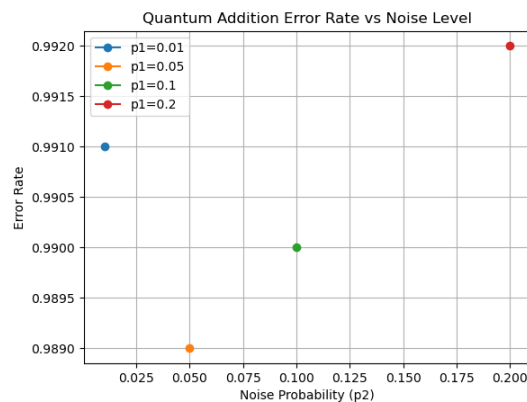
Plot showing error rate with respect to the noise probability p2 the 2-qubit gate noise probability

Results may become less predictable, showing a spread of potential outcomes rather than one clear answer. For instance, when adding 3 and 5, increased noise may cause the circuit to output values like 6,4,7 or 1, depending on the noise's impact.

- **Low Noise Levels**:
  - The circuit produces results close to the correct sum, with a measurement histogram showing a prominent peak at the expected result.
  - Minor deviations occur, but the overall probability distribution remains centered around the accurate sum.

- **High Noise Levels**:
  - The output distribution becomes scattered, lacking a distinct peak at the correct sum.
  - Increased noise affects a larger proportion of gates, particularly two-qubit gates, disrupting entangled states and leading to significant errors.

- **Error Accumulation**:
  - Errors accumulate with increased circuit depth and gate count, particularly in two-qubit gates that can propagate errors across entangled states.
  - In deep circuits like the Draper adder, which utilizes Quantum Fourier Transform (QFT), errors can significantly impact the reliability of outcomes.

2. Is There a Way to Decrease the Effect of Noise?

Several strategies can be implemented to mitigate the effects of noise on quantum circuits:

- **Error Correction Techniques**:
  - **Surface Code** and **Shor's Code** can be utilized to protect logical qubits by encoding them across multiple physical qubits. While resource-intensive, these methods provide robust error correction capabilities. These are particularly promising for practical implementations, providing a way to correct errors by leveraging redundancy in qubit arrangements.

- **Error Mitigation Strategies**:
  - **Zero Noise Extrapolation**: This technique runs the circuit under various noise levels and extrapolates the results to predict the outcome under ideal (zero-noise) conditions.
  - **Probabilistic Error Cancellation**: This method leverages error profiles to partially cancel out noise effects in the measurement results.

- **Circuit Optimization**:
  - **Reducing Two-Qubit Gates**: As two-qubit gates are more prone to errors, minimizing their use through circuit simplification can significantly enhance performance.

- **Noise-Aware Transpilation**: Adapting the circuit to align with the native gate set of the hardware reduces the likelihood of error-prone conversions.

- Feedback and Control: Implementing adaptive feedback systems allows for real-time adjustments based on detected errors during computation. This can help in correcting errors dynamically as they occur.

3. How Does the Number of Gates Used Affect the Results?

The number of gates, particularly the presence of two-qubit gates, has a significant impact on the circuit's susceptibility to noise.
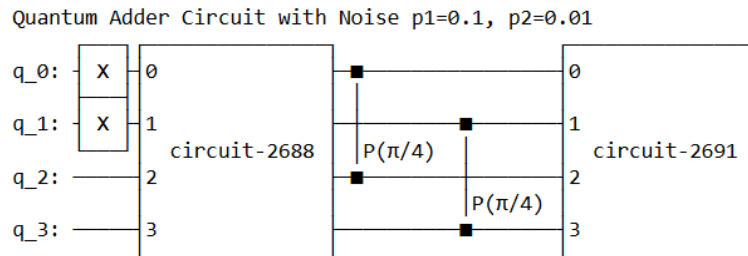
Quantum Circuit With a noise Implementation

The number of gates in a quantum circuit directly impacts its susceptibility to noise, especially in complex operations like the Draper adder that require a high gate count for components like the Quantum Fourier Transform (QFT).

- **Error Accumulation:** Every additional gate presents an opportunity for noise to disrupt the computation. This effect is particularly notable with two-qubit gates, which have higher error rates than single-qubit gates. For example, if each gate has a 1% error rate, a circuit with 100 gates has a high cumulative probability of encountering at least one error, which can significantly impact the outcome.

- **Circuit Depth and Complexity:** Longer circuits with more sequential gates increase the probability of error propagation, as errors can spread further in deep circuits. As circuit depth grows, qubits must remain in a superposition state for longer, which heightens the risk of **decoherence**—where qubits lose their quantum properties due to environmental interactions. This effect is compounded in circuits composed of many consecutive two-qubit gates, leading to complex error patterns that can be difficult to predict or correct.

- **Trade-offs with Computation Accuracy:** Complex circuits like the Draper adder, with numerous gates, are more vulnerable to noise-induced inaccuracies. Each additional gate heightens the risk of measurement errors. Although simplifying the circuit by reducing gate count can enhance noise resilience, it may also compromise computational efficiency. Therefore, balancing circuit complexity with error resilience is critical to achieving accurate and reliable results in practical quantum computing.