Quantum Search Simulator: Full Project Documentation with Code Snippets

1. Project Title

Quantum Search Simulator: A Comprehensive Study and Simulation of Grover's Algorithm

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2. Abstract

This project simulates Grover's Algorithm on classical hardware using Qiskit. Grover's Algorithm provides a quadratic speedup for unstructured search problems compared to classical linear search. The project includes oracle and diffusion construction, iterative Grover operations, probability amplification, interactive visualization, and performance analysis. It is suitable for academic research, hackathons, and potential publication.

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3. Introduction

Classical search algorithms require O(N) time for unstructured datasets. Grover's Algorithm reduces this to $O(\sqrt{N})$ using quantum superposition and interference. This project simulates Grover's Algorithm, compares it with classical search, and provides educational and research-oriented insights.

3.1 Motivation

Large unstructured datasets demand efficient search algorithms. Simulating quantum algorithms demonstrates quantum speedup and provides educational and research value without requiring physical quantum hardware.

3.2 Objectives

- Implement Grover's Algorithm on a classical simulator
- Construct oracles for target identification
- Apply diffusion operators and iterative Grover steps
- Compare quantum search with classical search
- Visualize probability distributions and amplitude amplification
- Provide interactive interfaces (CLI/GUI)
- Document theoretical foundations, complexity analysis, and experimental outcomes

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4. Background

4.1 Classical Search

```python
# Classical Linear Search Example
def classical_search(dataset, target):
    steps = 0
    for item in dataset:
        steps += 1
        if item == target:
            return steps
    return steps

# Example usage
dataset = ['000','001','010','011','100','101','110','111']
target = '101'
print(classical_search(dataset, target))
```

4.2 Quantum Computing Basics

- **Qubits:** Quantum information units
- **Superposition:** Multiple state evaluation
- **Entanglement:** Correlation between qubits
- **Interference:** Amplifies correct outcomes

4.3 Grover's Algorithm Overview

1. Initialize qubits in superposition
2. Apply oracle to mark the target state
3. Apply diffusion operator
4. Repeat ~π/4√N times
5. Measure qubits

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5. Mathematical Foundations

5.1 Oracle Function

$$f(x) = \begin{cases} 1 & x = x^* \\ 0 & x \neq x^* \end{cases}$$

Quantum oracle: $U_f|x\rangle = (-1)^{f(x)}|x\rangle$

5.2 Diffusion Operator

$$D = 2|s\rangle\langle s| - I, \quad |s\rangle = \frac{1}{\sqrt{N}}\sum_{x}|x\rangle$$

5.3 Grover Iteration

$$G = DU_f$$

Amplitude after r iterations:

$$sin((2r+1)\theta)|x^*\rangle + cos((2r+1)\theta)|non-solutions\rangle, \quad sin(\theta) = 1/\sqrt{N}$$

5.4 Complexity Analysis

- Classical: O(N)
- Quantum: O(√N) → Quadratic speedup

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6. Project Architecture

6.1 Modules

1. Classical Search Module
2. Quantum Search Module
3. Comparison Module
4. Visualization Module
5. User Interface Module
6. Data Handling Module

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7. Implementation Details

7.1 Classical Search

See section 4.1 code snippet above.

7.2 Quantum Search (Grover Simulation)

```
from qiskit import QuantumCircuit, Aer, execute
from qiskit.visualization import plot_histogram
import matplotlib.pyplot as plt

def grover_oracle(qc, target):
    n_qubits = len(target)
    for i, bit in enumerate(target):
```

```
        if bit == '0':
            qc.x(i)
    qc.h(n_qubits - 1)
    qc.mct(list(range(n_qubits - 1)), n_qubits - 1)
    qc.h(n_qubits - 1)
    for i, bit in enumerate(target):
        if bit == '0':
            qc.x(i)

def grover_search(target):
    n_qubits = len(target)
    qc = QuantumCircuit(n_qubits, n_qubits)
    qc.h(range(n_qubits))  # superposition
    grover_oracle(qc, target)
    # Diffusion operator
    qc.h(range(n_qubits))
    qc.x(range(n_qubits))
    qc.h(n_qubits - 1)
    qc.mct(list(range(n_qubits - 1)), n_qubits - 1)
    qc.h(n_qubits - 1)
    qc.x(range(n_qubits))
    qc.h(range(n_qubits))
    qc.measure(range(n_qubits), range(n_qubits))

    backend = Aer.get_backend('qasm_simulator')
    result = execute(qc, backend, shots=1024).result()
    counts = result.get_counts()
    return counts

# Example usage
counts = grover_search('101')
print(counts)
plot_histogram(counts)
plt.show()
```

7.3 Visualization

- Histogram of measurement counts
- Line plots of classical steps vs quantum success probability
- Optional amplitude animation

7.4 User Interface

- CLI prompts for dataset, target, iterations
- GUI with Tkinter or web interface with Flask
- Display circuits, plots, comparisons

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8. Experimental Setup

- Dataset sizes: N = 4, 8, 16, 32
- Target configurable
- Simulate classical vs quantum search
- Record probabilities and steps
- Generate graphs

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9. Results and Analysis

- Classical search scales linearly
- Quantum search scales ~$\sqrt{N}$ iterations
- Amplitude amplification visible in probabilities
- Visualizations demonstrate quantum advantage

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10. Extended Features

- Multiple target searches
- Text and encrypted datasets
- Runtime and iteration metrics
- Optional IBM Quantum Experience execution

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11. Future Scope

- Larger datasets, more qubits
- Other quantum algorithms (Shor, VQE)
- Integration with AI datasets
- Publication and conference potential

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12. Tools and Technologies

- Python 3.10+
- Qiskit, Matplotlib/Plotly
- Tkinter or Flask for UI
- Jupyter Notebook for exploration

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13. Timeline (6 Months)

Month	Tasks
1	Project architecture, classical search, initial Grover implementation
2	Quantum search, oracle and diffusion construction
3	Visualization of amplitudes and probabilities
4	User interface development, multiple targets support
5	Extended features: text/encrypted datasets, performance metrics
6	Documentation, report, presentation, testing

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14. Conclusion

The Quantum Search Simulator demonstrates Grover's Algorithm, providing quadratic speedup over classical search. The project integrates simulation, visualization, and interactive exploration, making it suitable for hackathons, publications, and FYP submission.

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15. References

1. Grover, L. K. (1996). A fast quantum mechanical algorithm for database search. *Proceedings of the 28th Annual ACM Symposium on Theory of Computing*, 212–219.
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