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Implementation of Grover's Search Algorithm for Tectonic Activity Detection in an Unsorted Seismic Database

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Abstract: One application of Grover's Search Algorithm to large, unsorted databases can be found in seismic data, which is a collection of data with no specific order or structure that continues to grow over time. The Grover's algorithm was implemented to detect tectonic activity in Indonesia based on earthquake magnitude and depth parameters. The data used consists of 5000 earthquake events in Indonesia from 2019 to 2024, obtained from United States Geological Survey (USGS). The target criteria were defined as earthquakes with a magnitude $\geq \mathbf{5}\ \boldsymbol{M_w}$ and a depth $\leq \mathbf{70}$ km. The research focused on the amplitude amplification mechanism through the application of a quantum oracle and a quantum diffusion, which increased the probability of finding target data in each iteration. The implementation was carried out using Python and Qiskit. Simulation results showed that both Grover's algorithm and the classical search method successfully identified 353 target data points. However, Grover's algorithm required only 3 iterations, whereas the classical method required 5000 iterations. The distribution of target data indicates dominant tectonic activity in North Maluku, papua, and the western Sumatra subduction zone. Grover's algorithm further demonstrates a computational advantage thorugh a quadratic speedup, reducing the time complexity from $\boldsymbol{O}(\boldsymbol{N})$ in the classical approach to $\boldsymbol{O}(\sqrt{\boldsymbol{N}})$ in the quantum approach.

Keywords: Amplitude amplification; Grovers's search algorithm; Grover's simulation; Seismic database; Qiskit

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Introduction

Grover's algorithm was introduced by Lov Grover of Bell Labs in 1996 as one of the early quantum computing algorithms that demonstrated the superiority of quantum computing over classical computing in the case of searching for an element in a large unsorted database (Jozsa, 1999; K. Grover, 1994; Preskill, 2021). By utilizing the principles of quantum mechanics, Grover's algorithm achieves a quadratic advantage in terms of time complexity, namely $\boldsymbol{O}(\sqrt{\boldsymbol{N}})$, whereas classical search algorithm have a time complexity of $\boldsymbol{O}(\boldsymbol{N})$ (Creemers,2025).

One implementation of Grover's search algorithm for a large unsorted database can be found in seismic data, which is a collection of data without a specific order or structure that continues to grow over time (Qiu et al., 2024; Wong, 2022; Zhahir et al., 2025). This data is used to monitor tectonic activity based on vibrations recorded in a given region. However, not all data is used to monitor tectonic activity that has the potential to cause significant impacts (Damayanti et al., 2020; Erlangga, 2020; Faizah, 2015). Therefore, specific parameters are needed to identify the target data. In this research, the parameters used include earthquake magnitude and depth.

The process of searching for target data in an unsorted seismic database is performed through simulation of Grover's algorithm using Qiskit, with a focus on changes in amplitude at each iteration step of the algorithm (Pattanayak, 2021). Amplitude plays a role in determining the probability of finding target data. Thus, Grover's algorithm works by increasing the amplitude of the target state and decreasing the amplitude of the non-target state through an amplitude amplification mechanism (Tonchev & Danev, 2024). To demonstrate the superiority of Grover's algorithm, a comparison was made with a classical search algorithm on the same case. This comparison was used to analyze the time complexity of each method, revealing the quadratic advantage of Grover's algorithm over classical search.

Methods

The seismic data is secondary data obtained from the United States Geological Survey (USGS), specifically from the Preliminary Determination of Epicenter (PDE) catalog managed by the National Earthquake Information Center (NEIC). The data used covers the period from 2019 to 2024 and was obtained in Comma-Separated Values (CSV) format through the official USGS portal. The parameters used are earthquake magnitude with a threshold of $\geq 5\ M_w$, earthquake depth $\leq 70\ Km$, and location coordinate (longitude and latitude) (Erlangga, 2020; Rahayu et al., 2025). The seismic data obtained from the USGS covers an area of Indonesia with coordinates ranging from $94{,}219$ to $140{,}801$ in longitude, and $-10{,}71$ to $5{,}734$ in latitude. Based on this observation area, a total of $5{,}000$ earthquakes event records were obtained and used as the initial dataset (United States Geological Survey, 2026).

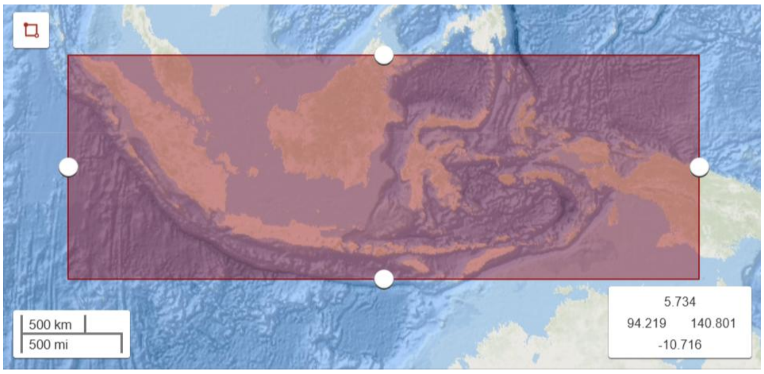

Figure 1. Observation Area

Based on the observation area shown in Figure 1, a total of 5,000 earthquake event data were obtained and used as the initial dataset for analyzing the distribution of seismic events. The dataset meeting the target criteria is subsequently visualized using the density map method in QGIS (Quantum Geographic Information System), a software application for processing, analyzing, and visualizing location-based data.

To demonstrate the mechanism of Grover's algorithm, a random sampling method was employed to select a subset of 64 earthquake events from the dataset. The random sampling method was selected because each data point has an equal probability of being selected, ensuring that the subset selection is not based on specific characteristics and can preserve the general characteristics of the original dataset. The sample size of 64 was selected because it satisfies ($N = 2^6 = 64$), allowing the search space to be represented using six qubits in Grover's algorithm. Using the entire dataset to visualize the mechanism of Grover's algorithm would yield a larger search space and a more complex amplitude plot, making the amplitude amplification process difficult to analyze visually. Therefore, the subset of 64 earthquake events was specifically processed using Python to generate amplitude plots illustrating the amplitude amplification process, while maintaining the magnitude and depth threshold criteria for determining the target data.

The earthquake dataset was processed for implementation in a quantum algorithm. The data, obtained in Comma-Separated Values (CSV) format, was imported into the Python programming environment using the Pandas library (Bose & Verma, 2025; Niels & chu, 2010), so it could be used as input for quantum computing simulations using Qiskit (Listiyanto, 2025). Next, a subset of data was extracted from the main dataset (random sampling), and target indices were determined based on specified parameters, as shown in Figure 2.

```
df = pd.read_csv("data_riset_gempa.csv",  sep=';')

# subset
subset = df.sample(64).reset_index(drop=True)

# syarat threshold
target_indices = [
    i for i, row in subset.iterrows()
    if row['mag'] >= 5 and row['depth'] < 70
]
```

Figure 2. Initialization of the Target Index

This target index is used as the basis for designing the oracle function in the classical algorithm and Grover's algorithm. The classic search algorithm process is performed by iterating over each row of data in the subset being used (Pan et al., 2019). At each iteration, the variable *quary_count* is incremented to represent the number of checks performed by the algorithm. If the data meets the conditions specified by *classical_oracle*, it is stored in the list *target_data* as the search result. The program code for the classical algorithm is shown in Figure 3.

```
def classical_oracle(row):
    return row['mag'] >= 5 and row['depth'] < 70


# Linear search (brute force)
target_data = []
query_count = 0

for i, row in subset.iterrows():
    query_count += 1

    if classical_oracle(row):
        target_data.append(row)
```

Figure 3. Oracle (Black Box) of Classical Algorithm.

Furthermore, the implementation of Grover's algorithm in the Qiskit simulation. Grover's algorithm operates using a key operator—the Grover operator—which consists of a *quantum_oracle* and a *diffusion_oracle. The quantum oracle flags states that meet predetermined* criteria via phase inversion, as is shown in the following code Figure 4.

```python
def quantum_oracle(n, target_indices):
    oracle = QuantumCircuit(n, name='Oracle')

    for idx in target_indices:
        b = format(idx, f'0{n}b')[::-1]

        for i, bit in enumerate(b):
            if bit == '0':
                oracle.x(i)

        oracle.h(n - 1)
        oracle.mcx(list(range(n - 1)), n - 1)
        oracle.h(n - 1)

        for i, bit in enumerate(b):
            if bit == '0':
                oracle.x(i)
```

Figure 4. Quantum Oracle of Grover's Algorithm.

In the *quantum_oracle* process, the target data undergoes a phase change through the application of multi-controlled Z gates. The goal is to distinguish the target data from the non-target data. Meanwhile, the *quantum_diffusion* works by applying a multi-controlled Z gate to all data (Portugal, 2024). The code for the *quantum_diffusion* is shown in Figure 5.

```python
def quantum_diffution(n, target_indices):
    dif = QuantumCircuit(n, name='Diffution')

    # X-gate untuk semua qubit
    dif.h(range(n))
    dif.x(range(n))


    # Menerapkan multi controlled Z-gate untuk semua qubit
    dif.h(n - 1)
    dif.mcx(list(range(n-1)), n - 1)
    dif.h(n - 1)

    # X-gate untuk semua qubit
    dif.x(range(n))
    dif.h(range(n))
```

Figure 5. Diffusion Oracle of Grover's Algorithm.

The combination of the *quantum_oracle* and *quantum_diffusion* operations forms the Grover operator. Grover's algorithm is implemented in a Qiskit-based quantum computing environment with the aim of observing changes in amplitude after a series of repeated iterations of the Grover operator until the optimal number of iterations is reached. The optimal number of iterations is determined using the following Equation (1).

$$k = \sqrt{\frac{N}{M}}, \tag{1}$$

where N is the total number of states and M is the number of states that satisfy the criteria (target) (Aburto Moccia et al., 2025).

```
optimal = int(np.sqrt(N / M))

simulator = Aer.get_backend("statevector_simulator")

for i in range(optimal):
    qc.append(quantum_oracle(n, target_indices), range(n))
    qc.append(quantum_diffution(n, target_indices), range(n))
```

Figure 6. Diffusion Oracle of Grover's Algorithm.

Results and Discussion

To visualize the amplitude amplification process in Grover's algorithm, 64 data points were randomly selected from a datset of 5,000 events using random sampling. At the initial stage, all selected data points had an equal amplitude of approximately 0,13, obtained by rounding the theoretical amplitude of $\frac{1}{\sqrt{N}}$, where $N = 2^6 = 64$. As shown in Figure 2, which is referred to as the initial state.

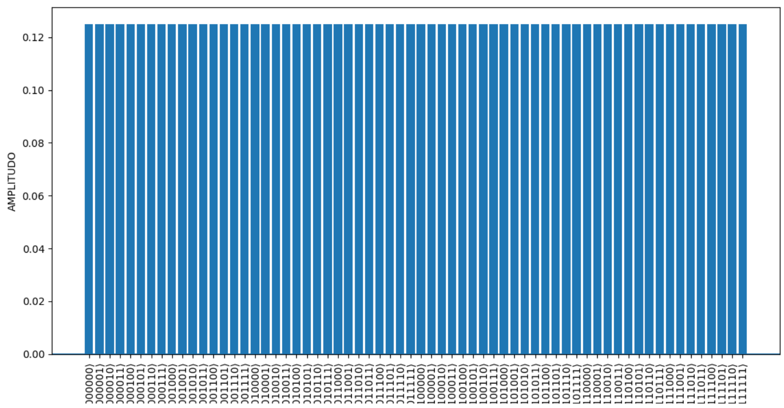

Figure 7. Initial State.

Afterward, the initial state is subjected to a quantum oracle, which causes the target data state to undergo a phase reversal so that its amplitude becomes negative.

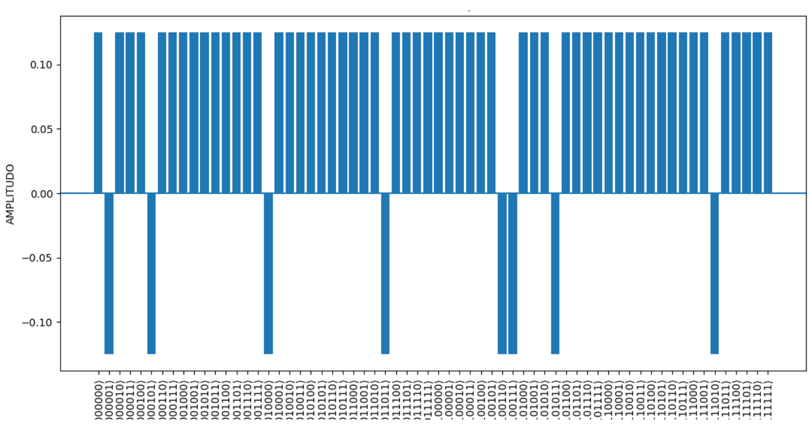

Figure 8. Amplitude After *quantum_oracle* is Applied.

In Figure 8, there are 8 target states that undergo phase inversion, resulting in negative amplitudes. This causes the average amplitude value to decrease. Next, the diffusion operator shown in Figure 4 acts to invert the amplitude of each state relative to the average amplitude value. This is what causes the non-target state, which was originally $0{,}13$ in Figure 3, to change to $-0{,}06$ as shown in Figure 4. Thus, the diffusion operator not only inverts the non-target amplitude but also accounts for the change in the average of all states. In addition to altering the non-target states, the diffusion operator also causes the target amplitude to move further away from zero, reaching a value of $-0{,}31$.

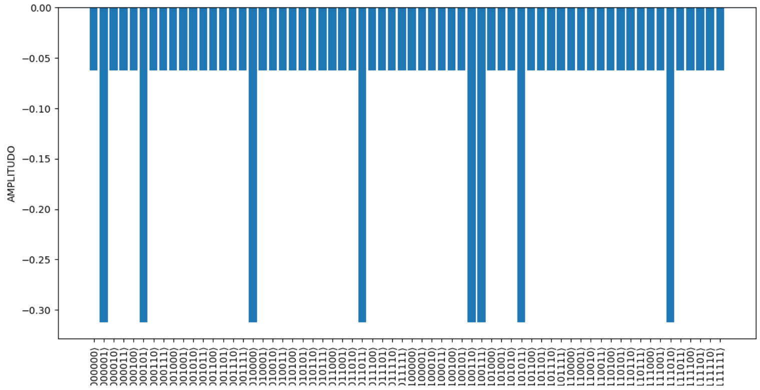

Figure 9. Amplitude Modified by quantum_diffusion.

Figure 8 and Figure 9 show the Grover operator steps that make up the first iteration in this research. These steps are repeated until the amplitude of the target state reaches its maximum value.

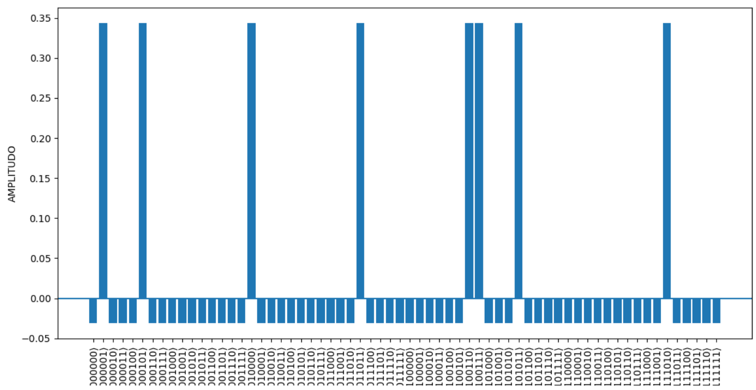

Figure 10. Second Iteration.

Figure 10 shows the results of the second iteration of Grover's algorithm. At this stage, the amplitude of the target state has increased to approximately $0{,}34$, while the amplitude of the non-target state is around $-0{,}03$. These conditions indicate that the amplitude amplification process is proceeding in accordance with the principles of Grover's algorithm, namely, increasing the amplitude of the target state while suppressing the amplitude of the non-target state. Consequently, the target state becomes increasingly dominant and has a higher probability of appearing during measurement.

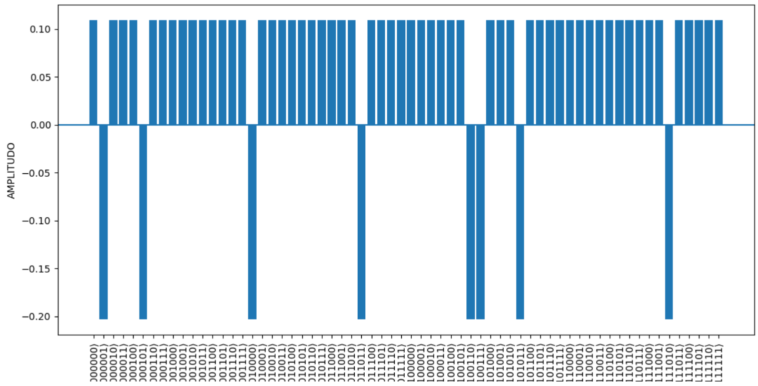

Figure 11. Third Iteration.

In the third iteration shown in Figure 11, the amplitude of the target state is $-0{,}20$, while that of the non-target state is $0{,}11$. Compared to the state amplitudes in the second iteration, the target state gas decreased while the non-target state increased. This is because the amplitude amplification process has passed its optimum point, as indicated by the decrease in the target state in the subsequent iteration.

In this research, 64 data points were randomly selected from 5,000 data points using the random sampling method. From these data, 8 target data points were obtained, with an optimal number of iterations of 2. These results are consistent with Equation 1, which is used to determine the optimal number of iterations in Grover's algorithm.

```
Jumlah data target ditemukan: 8
Membutuhkan 2 iterasi supaya optimal
```

Figure 12. The Optimal Number Iteration of Grover's Algorithm.

The Grover algorithm circuit is used in this research is shown in Figure 12. Each iteration of Grover's algorithm consists of two main components: the quantum oracle and the diffusion operator. The combination of these two components serves to amplify the amplitude of the target state, thereby increasing the probability of its appearance at the time of measurement.

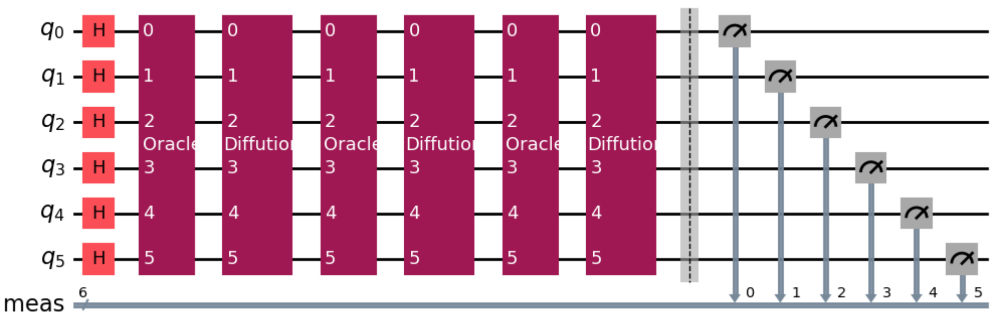

Figure 13. Grover's Circuit.

The visualization above demonstrates that Grover's algorithm is capable of effectively amplifying amplitudes to increase the probability of finding earthquake data that meet specific criteria in an unsorted seismic database. Although the amplitudes of some states are negative, this sign merely represents the phase shifts that occur during the execution of Grover's algorithm. In quantum mechanics, the probability of a state is determined by the square of the absolute value of its amplitude. Thus, an increase in the magnitude of the target state's amplitude still indicates an increased probability of finding that state at the time of measurement.

Following a series of steps in Grover's algorithm, the algorithm was applied to the entire seismic dataset consisting of 5,000 data points to identify target data based on the specified criteria, namely earthquakes with a magnitude of $\geq 5\ M_w$ and a depth ≤ 70 km.

```
=== HASIL PENCARIAN ALGORITMA GROVER===

Jumlah data target ditemukan: 353
Membutuhkan 3 iterasi supaya optimal
```

Figure 14. Search Result Identified by Grover's Algorithm.

The search results using Grover's algorithm are shown in Figure 14of the 5,000 data points analyzed, 353 target data points were found to meet the search criteria. Based on Equation 1, the optimal number of iterations required to maximize the probability of finding the target data is 3.

For comparison, a search using a classical algorithm was performed on the same dataset. The results in Figure 15 show that the classical algorithm also successfully found 353 target data points. However, the classical algorithm required 5,000 queries or iterations because each data point had to be checked one by one to determine whether it met the target criteria.

```
=== HASIL PENCARIAN KLASIK ===

Jumlah data target ditemukan: 353
Jumlah query (iterasi): 5000
```

Figure 15. Search Result Identified by Classical Algorithm.

The results in Figure 14 and Figure 15 show a significant reduction in the number of iterations for Grover's algorithm compared to the classical search algorithm. This is consistent with the theory behind Grover's algorithm, which offers a quadratic advantage in the search process. Based on the results of searches using classical and quantum solutions, the distribution of earthquakes identified by the search is not evenly spread across Indonesia. Earthquakes with a magnitude of $\geq 5\ M_w$ and a depth of $\leq 70\ km$ exhibit a distribution pattern concentrated in several regions. By using Q-Gis, the distribution of the earthquakes is shown in the Figure 16.

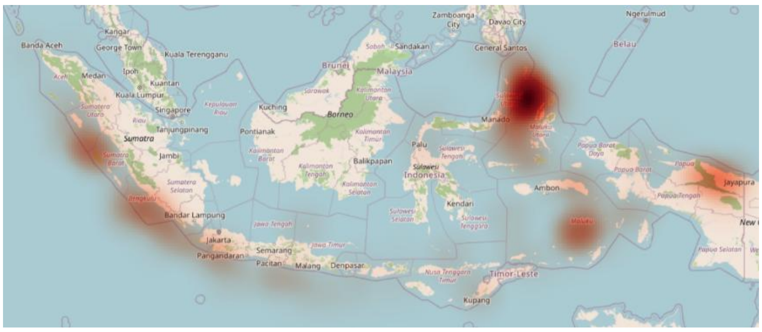

Figure 16. Earthquakes Distribution Map.

The highest concentration of earthquakes is observed in North Sulawesi and the waters north of North Maluku. Additionally, earthquake concentrations are also evident in the Maluku region, along the west coast of Sumatra, and in the Jayapura area. The southern part of Java, stretching from Pangandaran through Pacitan to Malang, also exhibits a relatively high frequency of earthquakes. However, the earthquake density in these regions remains lower than in North Sulawesi and North Maluku. The density of earthquake occurrences in each region is indicated by color gradients on the distribution map in Figure 8. Deeper shades of red indicate a higher frequency of earthquakes, while lighter shades indicate a lower frequency.

Conclusion

A comparison between Grover's algorithm and the classical search method shows that both methods yield the same number of target data points, namely 353. However, Grover's algorithm requires only 3 optimal iterations, whereas the classical search method requires 5,000 iterations to check all the data. These results indicate that Grover's algorithm has better search efficiency and supports the theory of quadratic speedup compared to the classical search algorithm. Grover's algorithm has a time complexity of $\boldsymbol{O}\,(\sqrt{\boldsymbol{N}})$, whereas the classical search algorithm has a time complexity of $\boldsymbol{O}(\boldsymbol{N})$. The search mechanism is carried out through an amplitude amplification process that increases the probability of the target state appearing compared to non-target states.

Visualization of the search results shows that the distribution of significant earthquakes in Indonesia is uneven with most occurring in certain regions. The highest concentration of earthquake events was found in North Sulawesi and the waters north of Maluku. In addition, relatively high earthquake activity was also observed in the Maluku region and along the west coast of Sumatra. The southern part of Java, stretching from Pengandaran and Pacitan to Malang, also exhibited a relatively high frequency of earthquakes. However, the density of earthquakes in these regions remains lower than in North Sulawesi and North Maluku. These results indicate that, based on the analyzed data, these regions have a significantly higher frequency of earthquakes compared to other regions.

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