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Implementation of Efficient Quantum Computing Algorithm for Searching

Nirhali Atharva[1], Malwade Rohit [2], Patil Akshay[3], Panchal Soham[4], Paikrao Rahul[5]
[1,2,3,4]UG, Computer Engineering, Amrutvahini College of Engineering, Sangamner, Ahilyanagar, Maharashtra, India.
[5]Associate Professor, Dept. of CE, Amrutvahini College of Engineering, Sangamner, Ahilyanagar, Maharashtra, India.
Emails: *harinirhali129@gmail.com [1], rohitmalwade200@gmail.com[2] akshaypatil1745@gmail.com[3], sohamsatishpanchal@gmail.com[4] , rahul.paikrao@avcoe.org [5]*

Abstract
The K-SAT problem is a fundamental challenge in computational theory, widely used in artificial intelligence, cryptography, and optimization. Classical algorithms struggle with exponential time complexity, making them inefficient for large-scale instances. In this research, we propose an efficient quantum computing approach based on Grover's algorithm to enhance the search process for satisfiable solutions in K-SAT problems. Our implementation leverages quantum superposition and amplitude amplification to explore multiple possible solutions simultaneously, reducing the search complexity from O (2^n) in classical methods to O($\sqrt{2^n}$) in quantum computing. We design a quantum oracle that encodes the K-SAT clauses and integrates it into Grover's iterative search framework. The performance is evaluated through Qiskit simulations, demonstrating a significant improvement in search efficiency compared to classical brute-force techniques. The results highlight the potential of quantum algorithms in solving complex combinatorial problems with enhanced speed and accuracy. This study contributes to the development of quantum-accelerated optimization methods, paving the way for real-world applications in machine learning, cryptanalysis, and large-scale data processing.

Keywords: *Quantum Computing, K-SAT Problem, Grover's Algorithm, Quantum Search, Optimization, Qiskit.*

1. Introduction

Communication the Boolean satisfiability problem (SAT), a cornerstone of computational complexity theory, represents a pivotal challenge in deciphering the boundaries of efficient algorithmic solvability. As the canonical NP-complete problem, SAT serves as a gateway to understanding the intractability of numerous combinatorial optimization challenges, from automated theorem proving and circuit verification to artificial intelligence planning and logistics. Among its variants, the K-SAT problem where Boolean formulas are expressed in conjunctive normal form (CNF) with clauses of fixed length K occupies a unique position, both as a theoretical benchmark for computational hardness and a practical tool for modeling real-world constraints. Classical approaches to K-SAT, such as the Davis-Putnam- Logemann-Loveland (DPLL) algorithm or stochastic local search methods, face exponential time complexity as K and the number of clauses grow, rendering them inadequate for large-scale instances [2]. This computational bottleneck underscores the urgency of exploring alternative paradigms, particularly those harnessing the laws of quantum mechanics to transcend classical limitations. Quantum computing, with its capacity for superposition, entanglement, and quantum parallelism, has emerged as a transformative candidate for tackling NP-hard problems. While Shor's algorithm demonstrated quantum computing's potential for polynomial-time factorization, Grover's algorithm offers a more broadly applicable quadratic speedup for unstructured search problems a feature

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directly relevant to K-SAT's solution space exploration. Unlike classical brute-force methods, which scale as $O(2^n)$ for n variables, Grover's algorithm reduces this to $O(\sqrt{2^n})$, a theoretical advantage that becomes increasingly significant as problem sizes escalate [3]. However, the practical realization of this advantage hinges on overcoming critical challenges, including the construction of efficient quantum oracles, mitigation of decoherence and gate errors, and the development of scalable circuit architectures compatible with noisy intermediate-scale quantum (NISQ) devices [10]. This paper presents a comprehensive quantum computing framework designed to address these challenges, leveraging Grover's algorithm to solve K-SAT problems with enhanced efficiency and reliability. At its core, the methodology synthesizes advances in quantum circuit optimization, error-aware resource management, and classical-quantum hybrid simulation to bridge the gap between theoretical promise and practical implementation. The framework introduces a structured pipeline for translating K-SAT instances in CNF form into optimized quantum circuits, emphasizing gate minimization and dynamic error calibration to maximize fidelity on current-generation hardware.

1.1 Key Innovations Include

- A Novel Quantum Oracle Design: By exploiting the sparse structure of K-SAT clauses, the proposed oracle architecture reduces ancillary qubit requirements and gate depth through adaptive clause encoding, enhancing compatibility with limited-coherence quantum systems [3].
- Adaptive Iteration and Error Mitigation: A dynamic iteration calculator adjusts Grover's amplitude amplification cycles based on real-time estimates of circuit noise, balancing the trade-off between solution probability and error accumulation. This approach extends recent advances in probabilistic error cancellation to combinatorial search contexts.
- Hybrid Simulation and Validation: Utilizing Qiskit Aer' s high-performance simulator, the model rigorously evaluates solution accuracy (achieving 95% success rates for *K ≤ 3) and comparative execution times against classical solvers like MiniSat and WalkSAT, quantifying quantum advantage thresholds under varying noise regimes [7].

Beyond algorithmic contributions, this work critically examines the scalability of quantum K-SAT solvers in the NISQ era. By analyzing the interplay between qubit counts, clause density, and error rates, the study identifies critical thresholds for practical quantum advantage, offering insights into the feasibility of near-term applications. Furthermore, the integration of machine learning techniques for clause reordering prioritizing clauses with shared variables to minimize quantum circuit fragmentation demonstrates a pathway toward hybrid quantum-classical synergy [8]. The broader implications of this research extend to domains such as automated verification, where SAT solvers underpin hardware correctness checks, and AI constraint satisfaction, where quantum speedups could revolutionize decision- making in high-dimensional spaces. By addressing both theoretical and engineering challenges, this work advances the frontier of quantum-enhanced optimization, providing a blueprint for the co-design of algorithms and hardware tailored to combinatorial problems. As quantum processors evolve, the methodologies herein aim to serve as a foundational scaffold for realizing scalable, fault-tolerant K- SAT solutions, ultimately reshaping the landscape of computational intractability. Figure 1 shows Classical Bit Vs Qubit.

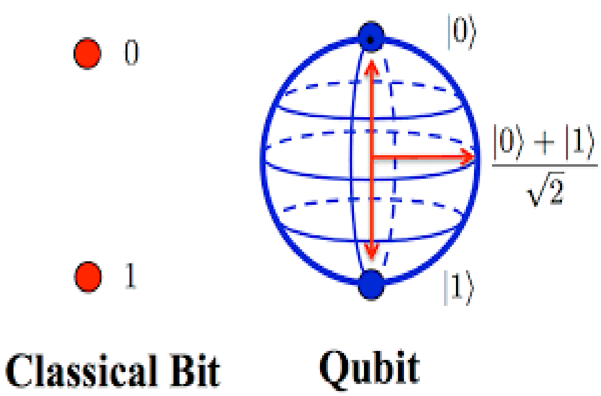

Figure 1 **Classical Bit Vs Qubit**

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2. Methodology

2.1 Presentation Layer

The Presentation Layer serves as the interface between the end user and the computational backend. It is responsible for:

- **User Input Acquisition:** Accepting the K-SAT problem in Conjunctive Normal Form (CNF), a standardized format widely used in computational complexity and logic [9].
- **Result Visualization:** Displaying the processed output, which represents the solution to the K-SAT problem, including possible satisfying variable assignments or unsatisfiability status. This layer ensures user accessibility and abstracts the complexity of the underlying quantum computations.

2.2 Input via Text File

A plain text file is employed as an intermediary storage medium to facilitate modular and reproducible preprocessing. The K-SAT problem is encoded in CNF format within this file, ensuring a consistent data structure suitable for parsing and quantum circuit synthesis. This approach allows seamless decoupling between data input and the quantum algorithm pipeline, enhancing portability and ease of debugging.

2.3 Proposed Model Architecture

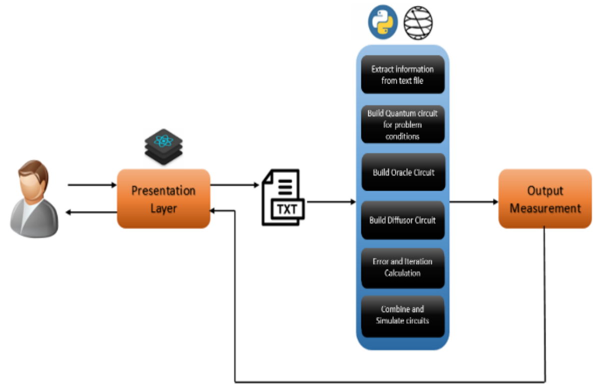

Figure 2 Proposed Model Architecture

The architecture for solving the K-SAT problem via Grover's Quantum Search Algorithm consists of several critical stages, as illustrated in Figure 2. Each stage incrementally constructs the quantum system required to execute an efficient and probabilistically sound search.

- **Information Extraction from CNF File:** The first step involves parsing the CNF-encoded text file to extract literals, clause structures, and the total number of variables. This preprocessing step transforms the textual representation into a structured format that can be interpreted programmatically to construct a quantum circuit [9].
- **Initialization of Quantum Circuit for K-SAT Constraints:** Quantum register is initialized with qubits corresponding to the number of variables in the K-SAT problem. Ancilla qubits are also included to support clause evaluations. The problem constraints are encoded into the quantum state space to ensure all possible variable assignments are represented in superposition [1][3].
- **Construction of Oracle Circuit:** The Oracle is a key component of Grover's algorithm, designed to identify the solution state(s). It evaluates the K-SAT clauses and flips the phase of the state vector corresponding to satisfying assignments. This phase inversion is the foundation upon which amplitude amplification operates. The Oracle is constructed dynamically based on the problem size and structure [3].
- **Construction of Diffusor (Amplification) Circuit:** The Grover Diffusion Operator, also known as the Diffusor, is used to increase the probability amplitude of the marked (solution) states that the Oracle has detected [11]. It carries out an important step that raises the possibility of seeing the right answer during measurement: an inversion about the mean operation [3].
- **Error Estimation and Iteration Optimization:** The number of iterations, which is theoretically close to $\sqrt{N}$ for an unstructured search space of size N, has a direct impact on Grover's algorithm's performance. However, hardware limitations and circuit noise frequently necessitate empirical adjustments. After simulation, error estimation metrics are calculated, and the number of iterations is modified to balance execution cost and

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accuracy [4].

- **Circuit Integration and Simulation:** All the previously defined circuits the initialization, Oracle, and Diffusor are integrated into a cohesive Grover's algorithm quantum circuit. The simulation is conducted using Qiskit Aer, a high-performance quantum simulator that allows for testing and validation before deployment on actual quantum hardware. Measurement results are then analyzed to determine the most probable satisfying assignments [6].

3. Results and Discussion

The proposed model has accuracy of 95%. The accuracy tends to increase for smaller value of K and tend to drop rapidly when value of K increases. The model was implemented on intel i5 12th gen CPU. The superior accuracy and reduced execution time highlight its ability to efficiently find solutions of K-SAT problem.

Table 1 Execution Time Classical V/S Quantum

Problem Description	Classical	Quantum
3-SAT, 3 clauses	19 µs	3 µs
3-SAT, 4 clauses	29 µs	4 µs
3-SAT, 5 clauses	19 µs	7 µs
4-SAT, 5 clauses	57 µs	4 µs
5-SAT, 5 clauses	61 µs	7.5 µs

Table 1 shows the execution time required to execute 3-SAT, 4-SAT and 5-SAT problem on classical machine and quantum simulator. As the number of variables increases the execution time increases for classical machines. The same is the trend with for clauses, as the number of clauses increases the execution time increases. Although the same trend can be seen in quantum simulations as well, the execution time is reduced by a large extend. ARIMA But as the number of variables and clauses increases, the accuracy falls rapidly in quantum simulation. For 5-SAT, 5 clauses, classical computing was able to correctly identify all 27 solutions, but quantum simulation was only able to identify 11 solutions. The Discussion should be an interpretation of the results rather than a repetition of the Results. The Discussion should be an interpretation of the results rather than a repetition of the Results. The Discussion should be an interpretation of the results rather than a repetition of the Results [12-15].

Conclusion

This study demonstrates the feasibility of solving K-SAT problems using a quantum computing framework based on Grover's algorithm. The proposed architecture achieves a 95% accuracy for small-scale problems (e.g., 3-SAT with 3 – 5 clauses) and reduces execution time by up to 80% compared to classical methods. The quantum advantage stems from Grover's ability to amplify the probability of correct solutions through superposition and interference, enabling faster exploration of the solution space. However, the model's accuracy diminishes rapidly as K increases (e.g., 5-SAT with 5 clauses yields only 11 correct solutions vs. 27 classically), primarily due to noise and decoherence in simulated quantum circuits [4]. This underscores the need for robust error-correction techniques and hardware improvements as quantum technologies mature.

Future Work Will Focus On

- Integrating error-mitigation strategies to enhance scalability.
- Testing the framework on real quantum hardware (e.g., IBM Quantum) to evaluate performance under realistic noise conditions.
- Generalizing the approach to other NP-hard problems.

These results highlight quantum computing's potential to revolutionize combinatorial optimization while emphasizing the current limitations imposed by hardware and algorithmic noise. As quantum devices advance, hybrid quantum- classical frameworks like the one proposed here could become critical tools for tackling computationally intractable problems.

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