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# Fault Detection Method Using Truth Table in Quantum Circuits

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**Abstract**
Quantum circuits are the foundation of quantum computers and quantum technologies. These circuits are created using quantum systems called quantum bits (qubits). Qubits are in a complex state that can take both a 0 and a 1 state at the same time, unlike the bits used by traditional computers. This provides features such as the ability of quantum circuits to perform parallel processing and solve some computational problems faster. There are many types of faults in quantum circuits. It is important to detect faults so that the quantum circuits to be developed can produce accurate results. In this study, a method using a truth table is proposed to detect possible faults that may occur in quantum circuits. The truth table is obtained from the '.tfc' files used in the creation of quantum circuits. The obtained truth table is compared with the output of the quantum circuit.

**Keywords:** Quantum Circuits, Fault Detection, Quantum Computing, Truth Table.

## 1. Introduction

Quantum computers are a revolutionary technology that has the potential to have computational speeds unmatched by conventional computers. The basis of this technology is the design and use of circuits called quantum circuits. Quantum circuits are created using complex quantum systems and are the basis of quantum computers and other quantum technologies. However, it is very important to ensure and test the accuracy of these circuits. The truth table of quantum circuits is a table that shows the results of all the input combinations of a quantum circuit. This table shows the correct output for each combination of inputs and is used to test the functionality of the quantum circuit and check its accuracy. To construct the truth table, first, all combinations of the input states of the quantum circuitry are listed Then the output is calculated for each combination of inputs, and the results are added to the table. The table is used to test the functionality of the quantum circuit. And it can be used to check accuracy. Creating a truth table in quantum circuits ensures the circuit works properly. This table can also detect faults within the quantum circuitry and for development purposes.

### Tools Used in Quantum Applications

• Qiskit: It is a library developed by IBM Quantum that enables quantum calculations with Python. Qiskit is a common tool used to build and simulate quantum circuits and generate truth tables. With Qiskit, the functionality of quantum circuits can be tested and the results analyzed.
• Cirq: It is a quantum programming framework developed by Google and a tool for the creation and analysis of quantum circuits with Python. Cirq can be used to generate truth tables when simulating quantum circuits.
• PyQuil: It is a library developed by Rigetti Computing that enables the creation and control of quantum circuits in Python language. PyQuil can be used as a tool to create and analyze truth tables of quantum circuits.

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• Q# Language: It is a quantum programming language developed by Microsoft. This language, which is integrated with Python, can be used for the creation and simulation of quantum circuits and the creation of truth tables.
• Quantum Inspire: It is a cloud-based quantum computing platform developed by QuTech. It comes with Python integration and can be used for the creation and simulation of quantum circuits and the creation of truth tables.
Widespread use of the Python programming language in the quantum computing community has led to the development of various tools for constructing truth tables in quantum circuits. Tools such as Qiskit, Cirq, PyQuil, Q# Language, and Quantum Inspire are common tools used for the creation and analysis of truth tables of quantum circuits. These devices have powerful capabilities for performing quantum computations and modeling quantum circuits.

**Related Studies**

Quantum computing is a very exciting field with the potential to exceed the limitations of traditional computers. Quantum circuits form the basic building blocks of quantum computers and are circuits where quantum gates perform various calculations by manipulating the states of qubits. Truth tables are important for analyzing the functionality and performance of quantum circuits.

Detection and isolation of faults is an extremely critical step in the physical realization of quantum circuits. The field of quantum computing, another interesting topic, is also developing rapidly. Today, there is a shortage of professionals with deep computer and physics knowledge who can meet the needs of companies developing and researching quantum technologies.

This article focuses on extensive studies of faults in quantum circuits. The studies in the literature on truth tables used to evaluate the functionality of quantum circuits are examined. The literature review includes some of the theoretical information and studies from past years to the present on quantum fault tolerance and quantum computing.

Rahaman et al.[1] focused on fault diagnosis in reversible circuits under the missing gate fault model. Under this model, they presented a new fault detection technique in a combination circuit with missing gate faults [1].

Barends et al.[2] present a quantum-related study by showing a set of universal logic gates in superconducting multiqubit processors. They stated that the average one-qubit gate accuracy reached 99.92% and the two-qubit gate accuracy reached 99.4% [2]. Lin et al.[3] By introducing a tool called physical design sensitive fault-tolerant quantum circuit synthesis (PAQCS), they offer a 30.1% reduced overhead in converting logic circuits to physical circuits compared to previous work [3]. Bera [4] showed that the behavior of faulty quantum circuits under the single fault assumption can be fully characterized by faulty gates and corresponding fault patterns [4]. Orts et al.[5] analyzed state-of-the-art reversible adders for quantum computing and classified them using metrics comparing their strengths and weaknesses [5]. Bocharov et al.[6] showed that they developed a simpler and more general method for reversibly synthesizing probabilistic quantum circuits [6]. Cai et al.[7] examined the recent development of bosonic codes and discussed the opportunities of bosonic codes in fault-tolerant quantum computation and other quantum applications [7]. Chen et al.[8] investigated the previously uncontrollable quantum circuits by proving the conditions for the two circuits to be partially equivalent, and developing algorithms based on this condition [8]. Gurl et al.[9]stated that decision diagrams are a promising data structure in quantum circuit simulation and they have found a successful application [9]. Wang et al.[10] focused on a new image encryption algorithm and showed that the truth table is based on the new chaos and spread values [10]. Mirizadeh et al.[11] used the FHAS algorithm by designing fault-tolerant reversible half and full adders/subtractors [11]. Singh et al.[12]implemented quantum circuits in Python in different test scenarios faster using Qiskit [12]. Swathi et al.[13] made applications focusing on various reversible logic Gates [13]. Yetis et al.[14] developed a new algorithm for optimal circuit generation and focused on image data [14]. Karmakar et al.[15] proposed a fault-tolerant logic gate-based RO PUF [15]. Golestan et al.[16] discussed the use of quantum computing in power systems and summarized recent developments [16]. Sharma et al.[17] continued their studies by focusing on various issues [17]. Kissinger et al. [18] proposed a method that aims to reduce the number of non-Clifford gates in fault-tolerant quantum computations [18]. Bar et al. [19] aimed to overcome the limited qubit number barrier by using a variational quantum circuit (VQC) [19].

## Motivation

Quantum circuits serve as the fundamental components of quantum computers, and quantum gates and circuits are designed to achieve specific quantum operations. The truth table is a tabular representation that maps input evaluations to corresponding output states, commonly used in classical computers to depict logical operations.
In the literature concerning reversible quantum circuits, it becomes evident that understanding the count of inputs, outputs, and gates is crucial for optimizing quantum circuits. An identified gap in the literature pertains to the automatic determination of inputs, outputs, and gate quantities within quantum circuits. This existing gap within the literature constitutes the principal motivation for our study. The motivation to detect the truth table in quantum circuits is important for quantum computers to become more complex and scalable. Under this motivation, determining truth tables of quantum circuits can help evaluate factors such as fault tolerance, side effects, and efficiency of quantum gates and circuits. Thus, it can guide the development process to enable quantum computers to produce more reliable and accurate results.

## 2. Types of Faults in Quantum Circuits

Quantum circuits are constructed using single-qubit and multi-qubit quantum gates. Circuit failures can arise during the creation of quantum circuits. There are various reasons for circuit faults, including issues within the system, faults in system components, and disruptions from the external environment. There are types of faults that permanently or temporarily affect the capabilities of a circuit for a long or limited time. Failure models that may occur in quantum circuits have been examined in five types in the literature. These fault types are shown in Figure 1.

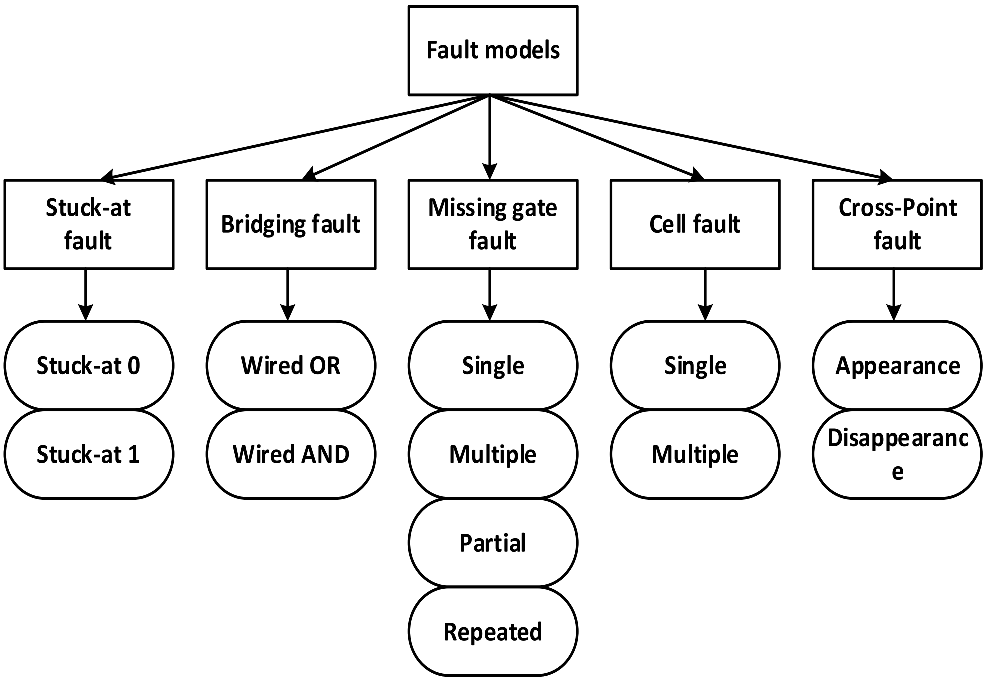



**Figure 1.** Failure models in quantum circuits[20]

As depicted in Figure 1, quantum circuits can experience failures such as Stuck-at, Bridging, Missing gate, Cell, and Cross-Point faults. These failures can have an impact on the results of quantum circuits. Figure 2 illustrates the instances of Stuck-at, Bridging, Missing gate, Cell, and Cross-Point failures.

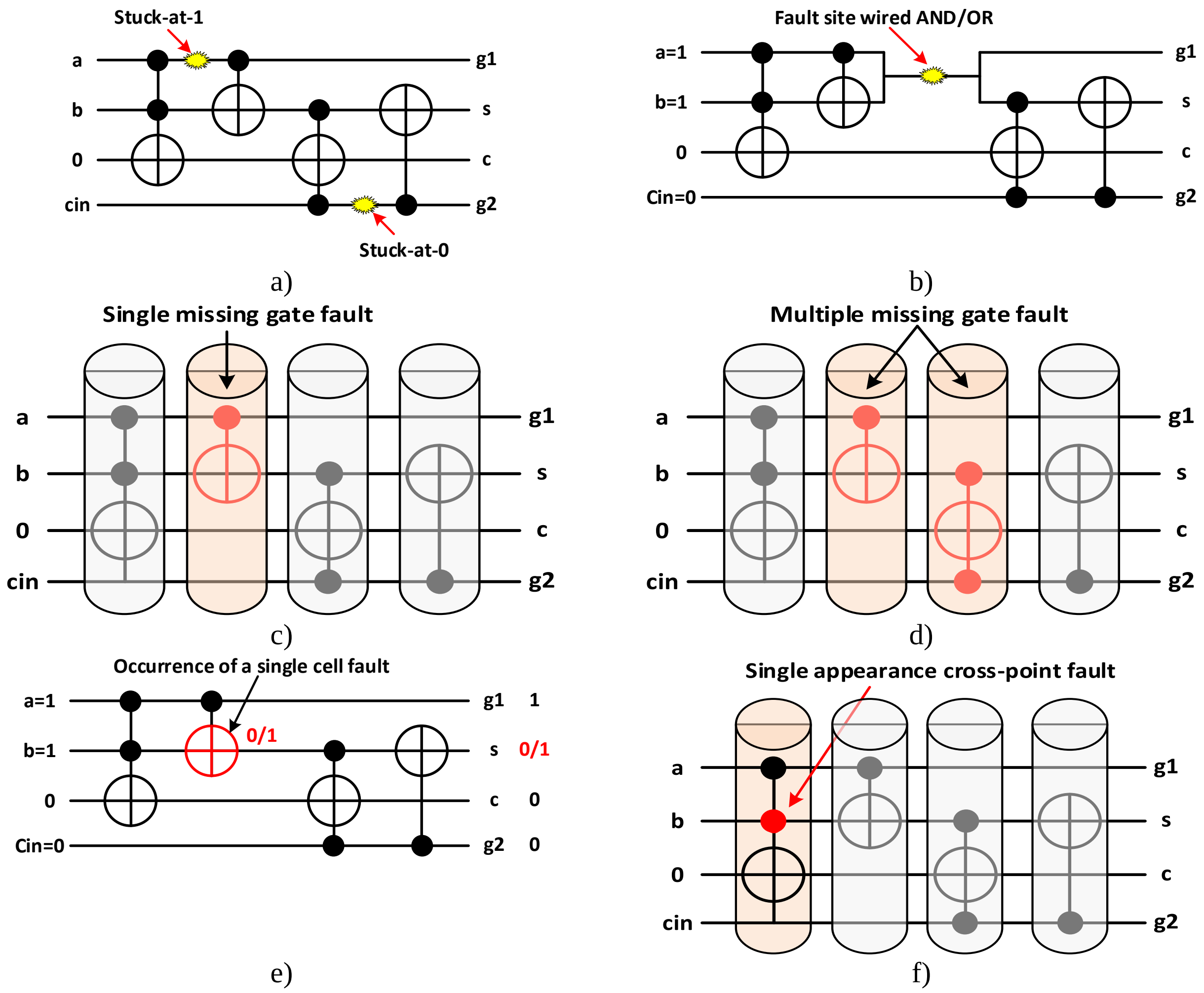



**Figure 2.** Fault types of quantum circuits[20] a) The stuck-at fault model b) The bridging fault model c) The single missing gate fault model d) The multiple missing gate fault model e) The single-cell fault model f ) The single appearance cross-point fault model

## 3. Material Method

The initial phase involves the generation of sample quantum circuits. During the construction of these circuits, a MATLAB program was employed, leading to the development of a specialized software package. Within this software package, ".tfc" files are generated. Subsequently, the necessary modifications were made to these ".tfc" files, resulting in the transformation of these files into quantum circuits. This transformation was accomplished utilizing the "RCViewer+" quantum simulation tool. The purpose of creating these data sets is to extract the state table of these circuits and to compare the state table we want with the state table of the faulty circuit to determine whether there is an fault in this circuit. The truth table was obtained after the quantum circuit converted from the “.tfc” file was passed through matrix multiplication. Next, the truth table was extracted using the "RCViewer+" quantum simulator from the previously generated ".tfc" file. The acquired truth tables will be subjected to a comparative analysis. An illustrative representation of the approach introduced in this research is provided in Figure 3.

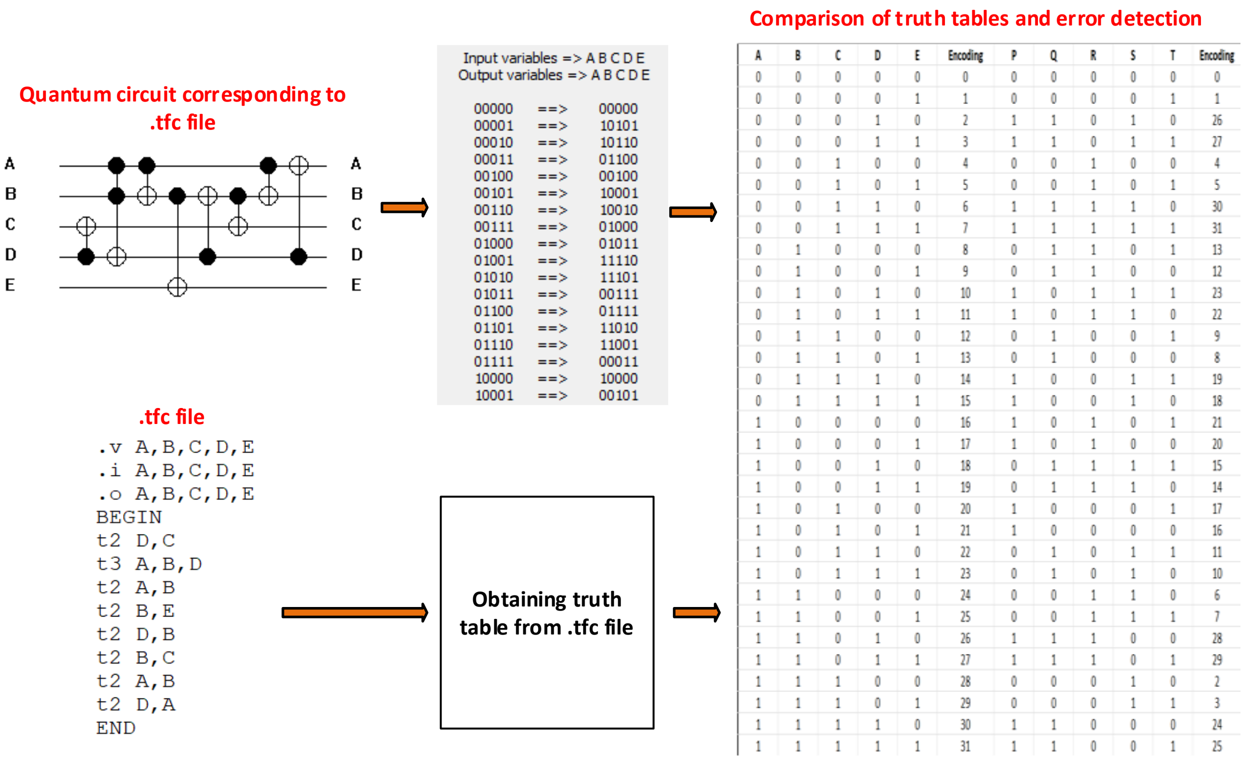



**Figure 3.** Graphical summary of the proposed method for the detection of the quantum circuit and input number

## Data Set

In this study, the primary objective is to assemble a dataset using quantum simulators that are implemented on conventional computers. The dataset will then be subjected to image processing techniques and harnessed by deep learning models to identify various elements within the circuits, including inputs, outputs, gates, and circuit components. By acquiring the state tables of the scrutinized quantum circuits, it becomes feasible to detect any faults present within these circuits. The approach employed to determine the output of a provided input in the quantum circuit is elucidated in Figure 4.

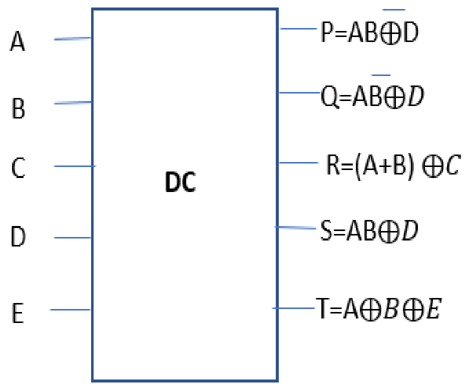



**Figure 4.** The equation used to construct the truth table of the quantum circuit

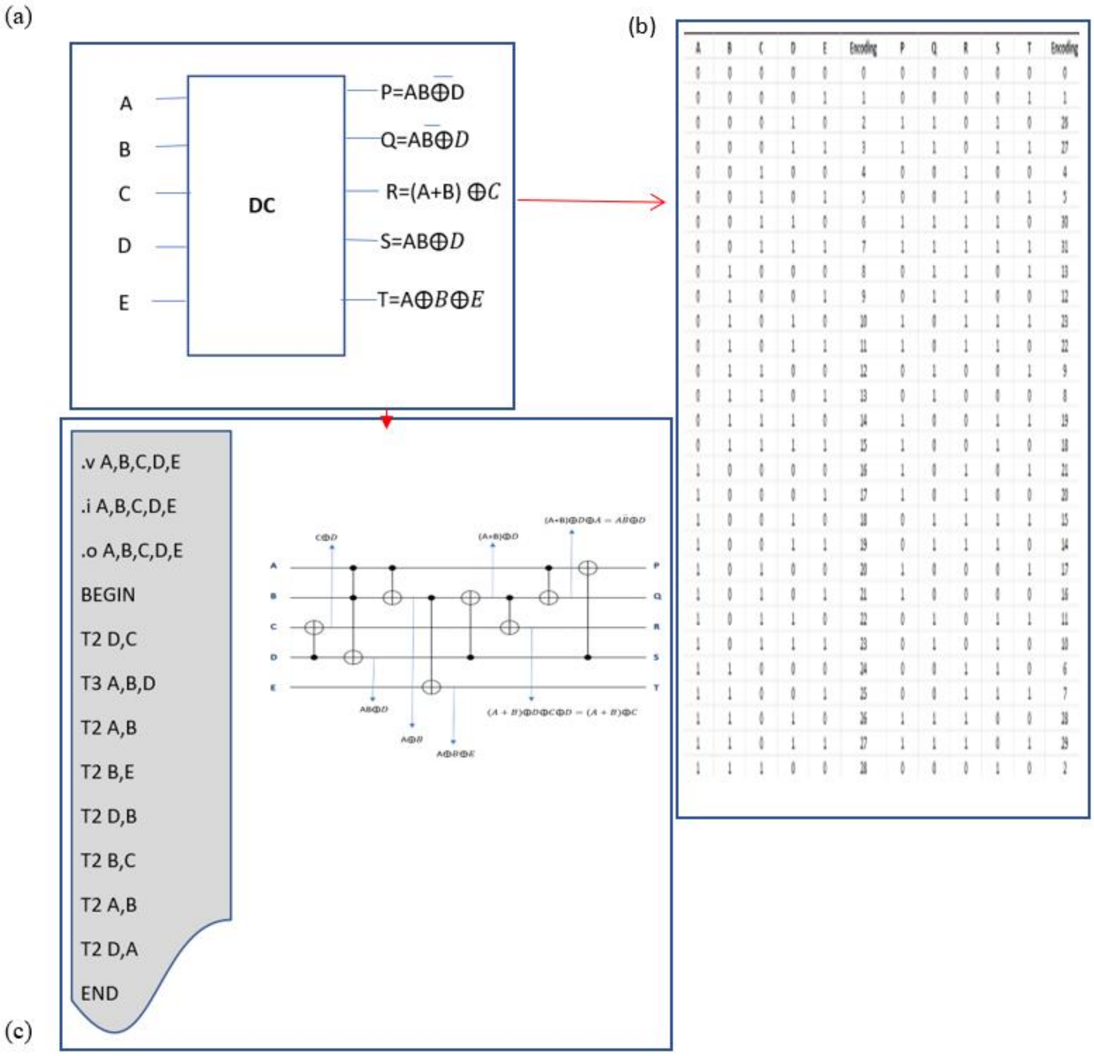
The process of generating the truth table then involves calculating all combinations of the inputs of the quantum circuit and determining the output for each combination. These results can then be collected in a table.
It presents the complete array of input state combinations alongside the associated circuit outputs for each state. These outputs have been pre-determined for every possible input combination. This computation is achieved by performing matrix multiplications of gates that are deployed within the qubits of the circuit, corresponding to each distinct input state. The truth table that emerges from this process is depicted in Figure 5.

| A | B | C | D | E | Encoding | P | Q | R | S | T | Encoding |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 0 | 26 |
| 0 | 0 | 0 | 1 | 1 | 3 | 1 | 1 | 0 | 1 | 1 | 27 |
| 0 | 0 | 1 | 0 | 0 | 4 | 0 | 0 | 1 | 0 | 0 | 4 |
| 0 | 0 | 1 | 0 | 1 | 5 | 0 | 0 | 1 | 0 | 1 | 5 |
| 0 | 0 | 1 | 1 | 0 | 6 | 1 | 1 | 1 | 1 | 0 | 30 |
| 0 | 0 | 1 | 1 | 1 | 7 | 1 | 1 | 1 | 1 | 1 | 31 |
| 0 | 1 | 0 | 0 | 0 | 8 | 0 | 1 | 1 | 0 | 1 | 13 |
| 0 | 1 | 0 | 0 | 1 | 9 | 0 | 1 | 1 | 0 | 0 | 12 |
| 0 | 1 | 0 | 1 | 0 | 10 | 1 | 0 | 1 | 1 | 1 | 23 |
| 0 | 1 | 0 | 1 | 1 | 11 | 1 | 0 | 1 | 1 | 0 | 22 |
| 0 | 1 | 1 | 0 | 0 | 12 | 0 | 1 | 0 | 0 | 1 | 9 |
| 0 | 1 | 1 | 0 | 1 | 13 | 0 | 1 | 0 | 0 | 0 | 8 |
| 0 | 1 | 1 | 1 | 0 | 14 | 1 | 0 | 0 | 1 | 1 | 19 |
| 0 | 1 | 1 | 1 | 1 | 15 | 1 | 0 | 0 | 1 | 0 | 18 |
| 1 | 0 | 0 | 0 | 0 | 16 | 1 | 0 | 1 | 0 | 1 | 21 |
| 1 | 0 | 0 | 0 | 1 | 17 | 1 | 0 | 1 | 0 | 0 | 20 |
| 1 | 0 | 0 | 1 | 0 | 18 | 0 | 1 | 1 | 1 | 1 | 15 |
| 1 | 0 | 0 | 1 | 1 | 19 | 0 | 1 | 1 | 1 | 0 | 14 |
| 1 | 0 | 1 | 0 | 0 | 20 | 1 | 0 | 0 | 0 | 1 | 17 |
| 1 | 0 | 1 | 0 | 1 | 21 | 1 | 0 | 0 | 0 | 0 | 16 |
| 1 | 0 | 1 | 1 | 0 | 22 | 0 | 1 | 0 | 1 | 1 | 11 |
| 1 | 0 | 1 | 1 | 1 | 23 | 0 | 1 | 0 | 1 | 0 | 10 |
| 1 | 1 | 0 | 0 | 0 | 24 | 0 | 0 | 1 | 1 | 0 | 6 |
| 1 | 1 | 0 | 0 | 1 | 25 | 0 | 0 | 1 | 1 | 1 | 7 |
| 1 | 1 | 0 | 1 | 0 | 26 | 1 | 1 | 1 | 0 | 0 | 28 |
| 1 | 1 | 0 | 1 | 1 | 27 | 1 | 1 | 1 | 0 | 1 | 29 |
| 1 | 1 | 1 | 0 | 0 | 28 | 0 | 0 | 0 | 1 | 0 | 2 |
| 1 | 1 | 1 | 0 | 1 | 29 | 0 | 0 | 0 | 1 | 1 | 3 |
| 1 | 1 | 1 | 1 | 0 | 30 | 1 | 1 | 0 | 0 | 0 | 24 |
| 1 | 1 | 1 | 1 | 1 | 31 | 1 | 1 | 0 | 0 | 1 | 25 |

**Figure 5.** The truth table obtained as a result of matrix multiplication

## 4. Experimental Results

In this research, the creation of the dataset involved the generation of ".tfc" files through the MATLAB program. These generated ".tfc" files were subsequently imported into the "RCViewer+" program, and the resulting quantum circuits were saved in ".bmp" format. The truth tables of the recorded quantum circuits were created by the “RCViewer+” generation and compared with the truth tables we created with the “.tfc” code. These two states recorded the same result for life in the table. The fact that the two-state tables are the same shows that there is no fault in the circuit.




| A | B | C | D | E | Encoding | P | Q | R | S | T | Encoding |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 0 | 26 |
| 0 | 0 | 0 | 1 | 1 | 3 | 1 | 1 | 0 | 1 | 1 | 27 |
| 0 | 0 | 1 | 0 | 0 | 4 | 0 | 0 | 1 | 0 | 0 | 4 |
| 0 | 0 | 1 | 0 | 1 | 5 | 0 | 0 | 1 | 0 | 1 | 5 |
| 0 | 0 | 1 | 1 | 0 | 6 | 1 | 1 | 1 | 1 | 0 | 30 |
| 0 | 0 | 1 | 1 | 1 | 7 | 1 | 1 | 1 | 1 | 1 | 31 |
| 0 | 1 | 0 | 0 | 0 | 8 | 0 | 1 | 1 | 0 | 1 | 13 |
| 0 | 1 | 0 | 0 | 1 | 9 | 0 | 1 | 1 | 0 | 0 | 12 |
| 0 | 1 | 0 | 1 | 0 | 10 | 1 | 0 | 1 | 1 | 1 | 23 |
| 0 | 1 | 0 | 1 | 1 | 11 | 1 | 0 | 1 | 1 | 0 | 22 |
| 0 | 1 | 1 | 0 | 0 | 12 | 0 | 1 | 0 | 0 | 1 | 9 |
| 0 | 1 | 1 | 0 | 1 | 13 | 0 | 1 | 0 | 0 | 0 | 8 |
| 0 | 1 | 1 | 1 | 0 | 14 | 1 | 0 | 0 | 1 | 1 | 19 |
| 0 | 1 | 1 | 1 | 1 | 15 | 1 | 0 | 0 | 1 | 0 | 18 |
| 1 | 0 | 0 | 0 | 0 | 16 | 1 | 0 | 1 | 0 | 1 | 21 |
| 1 | 0 | 0 | 0 | 1 | 17 | 1 | 0 | 1 | 0 | 0 | 20 |
| 1 | 0 | 0 | 1 | 0 | 18 | 0 | 1 | 1 | 1 | 1 | 15 |
| 1 | 0 | 0 | 1 | 1 | 19 | 0 | 1 | 1 | 1 | 0 | 14 |
| 1 | 0 | 1 | 0 | 0 | 20 | 1 | 0 | 0 | 0 | 1 | 17 |
| 1 | 0 | 1 | 0 | 1 | 21 | 1 | 0 | 0 | 0 | 0 | 16 |
| 1 | 0 | 1 | 1 | 0 | 22 | 0 | 1 | 0 | 1 | 1 | 11 |
| 1 | 0 | 1 | 1 | 1 | 23 | 0 | 1 | 0 | 1 | 0 | 10 |
| 1 | 1 | 0 | 0 | 0 | 24 | 0 | 0 | 1 | 1 | 0 | 6 |
| 1 | 1 | 0 | 0 | 1 | 25 | 0 | 0 | 1 | 1 | 1 | 7 |
| 1 | 1 | 0 | 1 | 0 | 26 | 1 | 1 | 1 | 0 | 0 | 28 |
| 1 | 1 | 0 | 1 | 1 | 27 | 1 | 1 | 1 | 0 | 1 | 29 |
| 1 | 1 | 1 | 0 | 0 | 28 | 0 | 0 | 0 | 1 | 0 | 2 |

**Figure 6.** Comparison of truth tables created by two different methods

The accuracy of quantum circuits holds paramount importance in the success of quantum computing, as faults can rapidly accumulate and undermine the integrity of computation results. To evaluate the performance of quantum circuits, truth tables are employed. These truth tables facilitate the assessment of quantum circuits by juxtaposing their outputs against the anticipated outputs. Such tables offer insights into the precision of individual quantum gates as well as the overall accuracy of the entire circuit. Accurate truth tables play a pivotal role in the design of efficient quantum circuits, enabling researchers to pinpoint and rectify faults within the circuitry. Consequently, the generation of precise truth tables stands as a crucial and indispensable phase in the advancement of quantum computing technology.

Experimental results obtained in the process of constructing the truth table of quantum circuits are used to test the functionality of quantum circuits and check their accuracy. These results show that the output is calculated correctly for all combinations of the input states of the quantum circuit.

Experimental results are constantly studied and improved to improve the accuracy of quantum circuits and to be able to solve more complex problems. These studies will help quantum computers and quantum technologies become more widespread.

## 5. Conclusions

In this study, the complete array of input states for the quantum circuit is generated through the utilization of the TFC library. Subsequently, by computing the output value for each distinct combination, a comprehensive truth table is

formulated. This procedure aids in comprehensively documenting the behavior of the quantum circuit across all potential input scenarios.
Truth tables have a wide variety of potential applications in quantum computing. It can be used to optimize the design of quantum circuits, identify and correct faults in quantum hardware, and evaluate the performance of quantum algorithms. Additionally, accurate truth tables can be used to compare the performance of different quantum computers and simulators, allowing researchers to compare their results and identify areas for improvement.
Experimental results have shown that the generated truth table accurately reflects the functionality of the quantum circuit. This method could be valuable for testing quantum circuits and checking their accuracy.
This endeavor establishes an initial foundation for constructing truth tables for quantum circuits. Subsequent efforts could potentially enhance and fine-tune this methodology, or even explore alternative approaches tailored for more extensive and more intricate quantum circuits. The realm of truth table creation within quantum computing holds numerous uncharted avenues for future investigation and innovation. These opportunities extend to research and development, offering prospects for devising novel techniques to generate comprehensive truth tables.

## 6. Acknowledgements

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