QRAFT: Reverse Your Quantum Circuit and Know the Correct Program Output

Extended Abstract

Tirthak Patel and Devesh Tiwari
Northeastern University

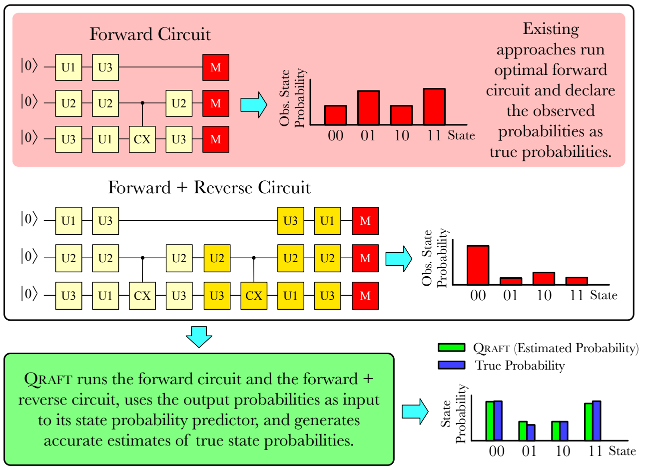
1. Motivation

Quantum computing has transitioned from a theoretical promise to a practical physical realization. However, one of the major bottlenecks toward a wide adoption of quantum computers is the high error rate in current Noisy Intermediate-Scale Quantum (NISQ) machines [13, 7]. Programs run on NISQ computers program complete successfully, but the the final outputs may be incorrect. Hence, the programmers do not know the correct program output (the output if the program was executed on an error-free quantum machine). While quantum computing promises orders of magnitude performance improvement for a class of algorithms, such improvements are not useful if the programmer cannot deduce the correct program output. Therefore, the goal of this paper is to *help quantum programmers automatically deduce the correct program output while running on error-prone NISQ machines*.

2. Limitations of the State of the Art

NISQ machines suffer from multiple types of errors such as qubit coherence errors, quantum gate operation errors, and state preparation and measurement errors. These can make the final program output erroneous. However, the error rates of different qubits on a given machine may differ significantly depending on the quantum operation type. Therefore, the impact of the errors experienced by a quantum program can be reduced by mapping a program's logical operations to the least erroneous physical components of a NISQ machine (e.g., avoid mapping the program on physical qubits that exhibit higher error rate for a certain type of quantum gate or operation).

Existing approaches attempt to reduce the impact of the errors experienced by a quantum program by intelligently performing a program's logical-to-physical mapping to the least erroneous qubits of a given quantum machine [16, 4, 23, 14, 20, 8, 15, 17, 2]. This approach is known as **"optimal circuit mapping"** – where the logical operations of a quantum program are intelligently *mapped* on a set of physical qubits considering multiple factors including the historical reliability characteristics of the physical qubits (their different error rates), the physical connection between qubits, and the sequence of operations in the quantum program. However, the current approaches have two major limitations:



Existing approaches run optimal forward circuit and declare the observed probabilities as true probabilities.

QRAFT runs the forward circuit and the forward + reverse circuit, uses the output probabilities as input to its state probability predictor, and generates accurate estimates of true state probabilities.

Figure 1: QRAFT leverages the forward + reverse circuit to generate accurate estimates of true state probabilities, as compared to existing optimal circuit mapping approaches.

I. Lack of knowledge about a program's true output: Current approaches aim to minimize the error occurrence probability and learn certain characteristics of the program under study (e.g., number of operations, type of operations, etc.) [21, 11, 1, 3, 23]. *However, these approaches do not (and cannot) know the "correct/true program output" of the program irrespective of how many times or on which qubits the program is executed. Hence, the observed output can only be used as the best guess of the correct program output.*

Prior studies assume that they know the correct program output apriori for small-scale quantum algorithms and report the difference between the observed output and the apriori-known correct program output as the "error in estimation of the program output" [17, 10, 18, 4, 22]. Unfortunately, this approach is not useful for programmers who may not always know the correct program output and may have multiple correct output states with probabilities of different magnitudes. Estimating the correct probability of these output states is critical, but current approaches are simply insufficient to tackle this.

II. Everyone has access to the "best" qubits and knows which qubits are the best: Existing approaches optimistically assume that all users have access to all the qubits and their historical error rates [12, 17, 4, 8, 15, 9, 20], especially the most reliable ones to run their programs. This assumption can be seriously challenged in future quantum computing systems shared among multiple users concurrently [2]. Moreover, historical error information may become business-sensitive, similar to classical computing systems.

3. Key Insights

The key insight behind QRAFT [1] is to *reverse the quantum circuit and repeatedly execute the full (forward + reverse) circuit* to deduce the correct program output of the original (or the forward) circuit. Quantum operations, unlike classical operations, are reversible; that is, the original input can be restored by applying an inverse operation. QRAFT leverages this property and extends it to the whole quantum circuit. Since quantum states cannot be cloned or checkpointed, QRAFT appends the reverse circuit at the end of the original (forward) circuit and executes the full (forward + reverse) circuit.

Reversing a circuit enables QRAFT to partially know the inherent correct output of the full circuit – all output states must get reduced to original input states – a piece of "ground truth" information that is not available to us irrespective of how many times the original circuit is executed, or on whichever qubit it is executed. This allows QRAFT to have a better estimation of how much error might have occurred in the original circuit execution. This is in contrast to existing approaches, which solely focus on optimizing the circuit map. As shown in Fig. 1, the reversibility property of quantum operations, which allows us to know the ground truth of states at the end of the execution of the full circuit, has previously not been leveraged to deduce the correct program output.

4. Main Artifacts

QRAFT is a new methodology for automatically deducing the correct program output. It is implemented as a software tool and evaluated on multiple IBM QX quantum machines. The workflow of QRAFT includes generating, reversing, and running quantum circuits to construct the training dataset, training a prediction model using the dataset, and using the prediction model for predicting true state probabilities of quantum algorithms. Artifacts of QRAFT include the over 1400 random quantum circuits and quantum algorithms run using the python-based Qiskit quantum programming framework on IBM QX cloud quantum computers and the model training tools of QRAFT implemented in MATLAB. QRAFT's framework is available open-source at: `https://doi.org/10.5281/zenodo.4527305`.

5. Key Results and Contributions

QRAFT is a novel, automated method to accurately estimate the true program output. QRAFT demonstrates that reversing the circuit can *reveal* how quantum computer errors affect the program. While this approach appears to be encouraging, a straight forward rule-based application of this approach does not yield the expected results due to the complex interactions of errors with the underlying original circuit. QRAFT designs and develops a learning-based prediction model that generates the true output state probabilities based on the observed state probabilities from the forward circuit and the observed errors from the forward + reverse circuit.

QRAFT, *while being simple in hindsight, is surprisingly effective* and improves upon the state-of-the-art approaches based on optimizing the circuit mappings to accurately estimate the magnitude of probabilities for programs with multiple states with non-zero output probabilities. This is a departure from existing works, which do not handle programs with multiple states with non-zero output probabilities states effectively and focus largely on dominant states [19, 15, 17, 1].

Our evaluation demonstrates that QRAFT reduces the median state error by up to 7%, dominant state error by up to 30%, and total program error by up to 20% across different algorithms. The state-of-the-art approach has only 20% of the circuit states with 0% error, while QRAFT ensures that over 70% of the states have 0% error when tested with 200 previously unseen and randomly generated circuits.

Furthermore, QRAFT demonstrates that it is possible to deduce the correct program output successfully, even in the absence of the optimal circuit map (relaxing a prerequisite of existing approaches, which assume unrestricted access to the "best" qubits and know which qubits are the best based on the historical error information). As expected, using the optimal circuit map makes QRAFT deliver near-perfect deduction of correct program output in many cases, but QRAFT remains fairly effective even when a non-optimized circuit map is used. Our evaluation confirms that QRAFT scales to larger number of qubits, and its effectiveness it not sensitive to the choice of the platform or specific circuit characteristics such as the circuit depth or the number of operations.

6. Why ASPLOS

QRAFT provides a novel solution in the quantum computing architecture and systems domain – a non-traditional but emerging area (one of the foci of ASPLOS conference). QRAFT attempts to bridge the gap between the traditional computer systems community and the quantum computing community. Recently, ASPLOS has published multiple quantum computing systems papers focusing on improving usability and resiliency of NISQ devices [9, 5, 8, 6, 19, 14, 4].

7. Citation for Most Influential Paper Award

QRAFT was the first work to leverage and demonstrate the reversibility property of quantum computing to deduce the correct output from the erroneous executions of quantum programs on the then error-prone near-term intermediate scale quantum computers. QRAFT's insights and open-source contributions enabled researchers to study and advance various other aspects of early quantum programs including resiliency, debugging, correctness, and effective resource management.

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[1] QRAFT, pronounced as craft, conveniently stands for quantum circuit reversal for attaining the full truth (about the program output).

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