Bugs4Q: A Benchmark of Real Bugs for Quantum Programs

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Abstract—Realistic benchmarks of reproducible bugs and fixes are vital to good experimental evaluation of debugging and testing approaches. However, there is no suitable benchmark suite that can systematically evaluate the debugging and testing methods of quantum programs until now. This paper proposes Bugs4Q, a benchmark of thirty-six real, manually validated Qiskit bugs from four popular Qiskit elements (Terra, Aer, Ignis, and Aqua), supplemented with the test cases for reproducing buggy behaviors. Bugs4Q also provides interfaces for accessing the buggy and fixed versions of the Qiskit programs and executing the corresponding test cases, facilitating the reproducible empirical studies and comparisons of Qiskit program debugging and testing tools. Bugs4Q is publicly available at https://github.com/2-928/Bugs4Q.

Index Terms—Quantum software testing, quantum program debugging, benchmark suite, Qiskit, Bugs4Q

I. INTRODUCTION

Software bugs have a significant impact on the economy, security, and quality of life. An appropriate method of bug finding can quickly help developers locate and fix bugs. Many software engineering tasks, such as program analysis, debugging, and software testing, are dedicated to developing techniques and tools to find and fix bugs. In general, these techniques and tools should be evaluated on real-world, up-to-date bug benchmark suites so that potential users can know how well they work. Such a benchmark suite should contain fail-pass pairs, consisting of a failed version, including a test set that exposes failures, and a passed version, which includes changes that fix failures. Based on this, researchers can evaluate the effectiveness of techniques and tools for performing bug detection, localization, or repair. As a result, research progress in this field is closely dependent on high-quality bug benchmark suites.

Quantum programming is the process of designing and constructing executable quantum programs to achieve a specific computational result. Several quantum programming approaches are available recently to write quantum programs, for instance, Qiskit [1], Q# [2], and Scaffold [3]. The current research in quantum programming focuses mainly on problem analysis, language design, and implementation. Despite their importance, program debugging and software testing have received little attention in the quantum programming paradigm. The specific features of superposition, entanglement, and no-cloning introduced in quantum programming, make it difficult to find bugs in quantum programs [4]. Several approaches have been proposed for debugging and testing quantum software [5]–[9] recently, but the debugging and testing remain challenging issues for quantum software [8], [10].

Researches on bug benchmark suites for classical software have been studied extensively [11]–[17], but few for quantum software. Recently, Campos and Souto [18] proposed some initial ideas on building a bug benchmark for quantum software debugging and testing experiments.

We may not know which debugging or testing methods are suitable for quantum software without a suitable bug benchmark suite for evaluating these tools, and this may pose some restrictions on the research and development of quantum software debugging and testing techniques. As the first step towards evaluating quantum software debugging and testing tools, this paper proposes Bugs4Q, a benchmark of thirty-six real, manually validated Qiskit bugs from four popular Qiskit elements (Terra, Aer, Ignis, and Aqua), supplemented with the test cases for reproducing buggy behaviors. Bugs4Q has made the following contributions:

• Bugs4Q collects reproducible bugs in Qiskit programs and supports downloading and running test cases for quantum software testing. Each actual bug and the corresponding fixes are publicly available for research.

• Bugs4Q collects almost all the existing bugs of Qiskit on GitHub and updates them in real-time, including the four elements of Terra, Aer, Ignis, and Aqua. Furthermore, these programs are sorted separately and filtered except for the bugs with originally available test cases and support for reproduction.

• Bugs4Q provides a database that includes an analysis of bug types to classify existing bugs for experimental evaluation of isolated bugs.

The rest of the paper is organized as follows. Section II briefly describes Bugs4Q, a bug benchmark suite for Qiskit. Section III introduces the process of manually reproducing bugs. Section IV describes the specific types of bugs in Qiskit with examples. Related work is discussed in Section V and concluding remarks are given in Section VI.

II. BUGS4Q BENCHMARK SUITE

To make sure that we can build a benchmark of real bugs, we have collected the existing bugs in the version control history and the real fixes provided by the developers.

Table I shows all programs and the numbers of corresponding real bugs that are available in the bug database of Bugs4Q.
In order to achieve benchmark rigor, each real bug must have its original bug version as well as a fixed version. This requires us to extract the relevant description of the bug and refer to its fixed commit. Moreover, the bugs we collect must comply with the following requirements:

- **Related to source code.** The reason for the bug is on the source files of the build system, but not the test files or the underlying files that build the Qiskit programs.

- **Related to quantum program.** The bug should have an impact on the operation or the outcome of the quantum program. Problems caused by configuration files required to run quantum programs or classical parts of quantum algorithms are not included in our database.

- **Reproducible.** More than one test case must be used to demonstrate the bug, and the bug must be reproducible under certain requirements. Depending on the nature of the quantum program, for example, the presence of probabilistic output causes the program not to be able to reproduce the results completely. It can lead to bugs that are difficult to reproduce in a controlled environment.

- **Isolated.** Fixes submitted by developers should also be related to the source files. Irrelevant changes need to be removed, and there is no code refactoring due to version changes. Excessive source file changes that are too complex will be incorporated into our database repository later after careful verification of isolation.

### Table I

| Program | Source | Bugs | KLOC | Test KLOC | Tests |
|---------|--------|------|------|----------|-------|
| Terra   | IBM Qiskit | 27   | 139  | 56       | 467   |
| Aer     | IBM Qiskit | 5    | 62   | 18       | 149   |
| Ignis   | IBM Qiskit | 1    | 14   | 3        | 29    |
| Aqua    | IBM Qiskit | 3    | 86   | 37       | 211   |

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**Fig. 1.** The building process of the benchmark database

Figure 1 depicts the main process of building our benchmark database. First, we look for programs on as criteria for our base database classification. After that, we collect the issues with bug tags and incorporate them into our first version of the database for manual validation. We then manually reproduce the bugs for further filtering and place those that meet the isolation criteria into our version-2.0 database for dynamic validation. Finally, extraneous patches will be cleaned up to complete the final version of the benchmark database.

**Fig. 2.** A simple quantum program in Qiskit

```python
@qiskit.circuit
def simple_qc():
    h(0)
    cx(0, 1)
    measure([0,1,2], [0,1,2])

job = execute(simple_qc, shots=1000)
result = job.result()
print(result.get_counts(simple_qc))
```

### A. Selecting Subject Programs

For project program selection, we only target Qiskit programs that are relatively well used on GitHub. We use the GitHub’s `issue` tab to find bugs in the program and collect both the buggy version and the fixed version. We have manually collected all the issues with bug tags. Our study is based on four elements of Terra, Aer, Ignis, and Aqua in Qiskit. A brief description of the four elements, which comes from the official description of Qiskit [1], are given as follows:

- **Terra** is the foundation on which the rest of Qiskit is built.
- **Aer** provides high-performance quantum computing simulators with realistic noise models.
- **Ignis** provides tools for quantum hardware verification, noise characterization, and error correction.
- **Aqua** provides algorithms for quantum computing applications.

In this process, we will choose quantum-related bugs and exclude pure classical program bugs. Quantum programs in general are operations on qubits, so bugs in quantum programs are defined as bugs that occur when operating on qubits. A complete quantum program includes initialization of qubits, gate operations, and measurement operations, as well as deallocations. As shown in Figure 2, a running example of a quantum program. For example, if a quantum gate (e.g. `circuit.cx(0, 1)` in a Qiskit program does not achieve a quantum state transition or a measurement result is wrong, it will be classified as a Qiskit bug.

### B. Collecting Bugs

Since there are not particularly many bugs in Qiskit, we collect them all manually. The bug collection process consists of two steps.

1) **Collecting and Filtering Bugs:** For each element in Qiskit, we focus on collecting issues from `closed` tags on GitHub. We also collect bugs with `open` status and mark them so that they can be put into our database as soon as they are submitted for fixing. For bugs in `open` status, we temporarily store them in a branch but leave them unprocessed. For bugs in `closed` status, we collect bugs and submitted fixes according
to their IDs (e.g., #1324). Of course, in our benchmark library, we use our own bug ID as the index.

In this work, we only consider bugs that have been fixed and are fully reproducible. So the bugs which have been reported but are in open status in GitHub issues and bugs that are not related to quantum programs will be filtered out. We also discard the case of having multiple fixes for bugs, i.e., having multiple fix links. Besides, bugs that disappear due to version changes are also not considered. After this work, we built the original bug database, which contains 206 quantum program-related bugs. As more and more bugs are raised, our database will be updated as we go forward.

2) Screening Test Cases: In order to reproduce the bugs more accurately, we choose the original program proposed by the developer in the bug report as our test case. The program proposed by the developer will be collected and tagged with the test in our library, accompanied by the second screening. There are 115 bugs with original test cases. For the bugs, without test cases, we will write the corresponding test cases of the bugs in our future work.

C. Manually Verifying and Reproducing Bugs

We manually check that our requirements are met for each bug that has a test case. All bugs that can be reproduced and meet the isolation criteria will be placed in our final benchmark suite. For incomplete test cases, we modify the recovery procedure as much as possible to achieve its proper operation. Nevertheless, in addition to errors in the original test cases, it is not uncommon to have too many and complex revision submissions that are not reproducible. As in Ignis, many files have the suffix .hpp and .cpp instead of .py. We chose to forgo collecting them into the current version of the benchmark suite. On the other hand, some of the submitted fixes have no impact on the bug recovery, so we only keep the fixes that impact the bug. Table II shows the number of bugs with test cases that can not be reproduced as well as the reasons. The results of the manual validation show that only thirty-six bugs have been successfully reproduced and isolated. The process of reproduction is still ongoing.

D. Sanity Checking through Dynamic Validation

In order to better reproduce the bug, we try to implement an automated approach. We first implement version control, calling the corresponding version of Qiskit for different bugs. After calling the bug indexed by ID, the file of the bug version will replace the corresponding file in Qiskit. Finally, the same

| Reasons of Non-reproducible Bugs | Number |
|---------------------------------|--------|
| One bug corresponds to multiple fixes | 6 |
| Fix too many files | 2 |
| Fixes not work | 9 |
| Actual error does not match the submitted bug | 2 |
| Program reports an error and cannot run | 35 |
| Other | 9 |

Final Bug Database

| Description | Number |
|-------------|--------|
| Bugs with original test cases | 36 |
code will be downloaded, fixed, and placed in our database as original test cases for verification. When we run the program in the configured environment, the result is consistent with the description of the bug submission message, which proves that the bug has been successfully reproduced. Next, the fixed file represented in Figure 5 replaces the file in the environment. If the bug disappears, the program runs successfully and is consistent with the description of the fix, the test passes.

C. Filter Information

Any commit fix has a Files changes section. We can sort through the modified files and code segments to locate the fixes that only affect the bug. When multiple buggy files exist in the process of reproducing bugs, we will recover them one by one because there are some files whose restoration does not affect the bug. Figure 7 shows the four files which have been used to fix the error #580 in Aer. The only two of these files, quantum_error.py and errorutils.py are the source files used to fix the bugs. Once sift out the other two files, we can reproduce the bug with the above two source files in turn. We find that only the file quantum_error.py affects the bug. Thus, the file errorutils.py is eliminated.

D. Representation in Benchmark Suite

The reproduced available bugs will be added to our database. As shown in Table IV, Buggy is the source file that caused the bug before the fix. Fixed is the file after the fix for the bug. Test is the original test case. In order to be able to document each bug in detail, we provide a detailed description of each bug and links to local files of our organization for them. Furthermore, Issue No and Modify are linked to bugs and fixes committed in GitHub, respectively.

IV. ANALYSIS

After reproducing each bug and populating the benchmark database, we also summarize some bug types as shown in Table V. To prove that the reproduced bug is consistent with the original description, we need to compare the results of the program run with the submitted bug information. For example, whether the error output we reproduced is consistent with the result in the description, or whether the program we reproduced reports errors are consistent with the submitted error messages. In this process we summarize the bugs we encountered.

A. Output Wrong

Output errors are the bugs we are most concerned about, which are not easily discovered but play a critical role in quantum programs. Erroneous output results can mislead program users. Here we reproduce a simple example in Aqua, with the issue number of #1324.

Considering the code snippet in Figure 8, the program that calls the CircuitSampler method and finds that v1 and v2 should have output the same result. But they are only the same when coeff=1, otherwise they often have different results. The file to fix this bug is vector_state_fn.py only, which is the source file in qiskit/aqua. Such bugs account for a large proportion of the bugs we reproduce.

1. https://github.com/Qiskit/qiskit-aer/issues/580
2. https://github.com/Qiskit/qiskit-aqua/issues/1324
TABLE IV
EXAMPLE OF A BENCHMARK DATABASE FOR BUGS4Q

| Bug ID | Issue No | Buggy | Fixed | Modify | Status | Version | Type | Test | Issue Registered | Issue Resolved |
|--------|----------|-------|-------|--------|--------|---------|------|------|------------------|----------------|
| 6      | #5914    | Buggy | Fixed | Mod    | Resolved | 0.16.4 | Bug  | Test | Feb 27, 2021     | Feb 28, 2021   |
| 7      | #5908    | Buggy | Fixed | Mod    | Resolved | 0.17.0 | Bug  | Test | Feb 26, 2021     | Mar 1, 2021    |

TABLE V
CLASSIFICATION OF BUGS

| Bug Type                        | Number |
|---------------------------------|--------|
| Output wrong                    | 15     |
| Noise simulation error          | 1      |
| Lost information                | 3      |
| Throwing exceptions             | 13     |
| Circuit diagram drawing error   | 4      |

Output before fixed:
QiskitError: "Type error handling
[(QuantumRegister(1, 'q1'), 0), 1]
<class 'list'>"

Output after fixed:
Qubit ordering:
|Qubit(QuantumRegister(1, 'q2'), 0),
Qubit(QuantumRegister(1, 'q1'), 0)|
Classical bit ordering:
|Clbit(ClassicalRegister(2, 'c'), 0),
Clbit(ClassicalRegister(2, 'c'), 1) |

Fig. 9. An example of noise simulation error

B. Noise Simulation Error

Due to the inherent nature of quantum computer hardware, the presence of noise makes programs that actually run in quantum computers not extraordinarily stable. So Qiskit provides Aer which can be implemented to simulate noise on a classical computer. This provides great convenience for us to study real quantum programs. Therefore it is particularly important to target the bugs of quantum noise simulators.

As shown in Figure 9 which is a program that imports the base gate from the quantum simulation backend from issue #1107. By default, the noise model contains in its usual base gate the id and U3. The purpose is that circuits could be executed even if the developer did not define noise on all gates. However, a bug in running the program due to a change in the default base gate of the IBM Q backend prevents it from working correctly. The bug here is that the u3 gate should not appear in the noise model, but rather the x gate. The fix for this commit is that the noise model will always have the same base gate as the backend base gate, regardless of whether the instruction has an error in the noise model. This type of error is only found in the Aer element and is not common.

C. Lost Information

Lost information, i.e., the program does not implement a specific function. Terra is the most used element and the one with the most bugs filed. There are many times the fix for bugs in other elements of the commit is to modify the files in the terra. The sample we cite is #5908, as shown in Figure 10.

Fig. 10. An example of throwing exceptions

D. Throwing Exceptions

Throwing an exception is as common and basic as an output error. Program errors and output errors account for almost all of the bugs in our Database. For example, Figure 10 which is from Qiskit Terra, #2369, is a simple program of using indexes and bits as parameters. Until it is fixed, this bug can be considered as a bug pattern. However, this issue is fixed as a bug here. So we collected it into our Database. In general, this kind of bug can be understood as the parameters of the called method do not support string types, or more precisely, only integer types. The problem here is that the gate parameter could not support a mix of indexes and bits. A commit fix made it possible for the gate parameter to support them.

In addition to the error types described above, we constantly summarize other bug types, such as quantum circuit diagram drawing errors. Qiskit programs generally generate circuit diagrams, which serve only to represent the process of changing quantum states and do not impact on the program’s execution. However, wrong circuit diagrams can also mislead users, and therefore we have collected them into one type. In our future work, we will add the types of bugs to our benchmark and propose a database with bug types as classification criteria for better use by researchers and developers.

4https://github.com/Qiskit/qiskit-aer/issues/1107
5https://github.com/Qiskit/qiskit-terra/issues/2369
Many benchmark suites have been proposed to evaluate debugging and testing methods for classical software. The Siemens test suite [16] is one of the first bug benchmark suites used in testing research. It consists of seven C programs, which contain manually seeded faults. The first widely used benchmark suite of real bugs and fixes is SIR (Software Artifact Infrastructure Repository) [11], which enables reproducibility in software testing research. SIR contains multiple versions of Java, C, C++, and C# programs which consist of test suites, bug data, and scripts. Other benchmark suites include Defects4J [13] and iBug [12] for Java, BenchBug [14], ManyBug (and InterClass) [17], and BUGSJS [15] for JavaScript projects.

However, all the benchmarks mentioned above focus on the classical software systems, and therefore cannot be used for evaluating and comparing quantum software debugging and testing methods.

Perhaps, the most related work with ours is QBugs proposed by Campos and Souto [18], which is a collection of reproducible bugs in quantum algorithms for supporting controlled experiments for quantum software debugging and testing. QBugs proposes some initial ideas on building a benchmark for an experimental infrastructure to support the evaluation and comparison of new research and the reproducibility of published research results on quantum software engineering. It also discusses some challenges and opportunities on the development of QBugs. However, at the time of writing this paper, the benchmark proposed by Campos and Souto [18] was not available to assess its details and usability. Our Bugs4Q, on the other hand, aims to construct a bug benchmark suite of real bugs derived from four real-world IBM Qiskit programs for quantum software debugging and testing, with real-world test cases for reproducing the buggy behaviors of identified bugs.

VI. CONCLUDING REMARKS

As quantum computers gradually come into the limelight, research into quantum programs has intensified, with analysis and testing techniques for quantum programs becoming an important part of the process. This paper proposes Bugs4Q, a benchmark of thirty-six real, manually validated Qiskit bugs from four popular Qiskit programs, supplemented with the test cases for reproducing buggy behaviors. Bugs4Q also provides interfaces for accessing the buggy and fixed versions of the Qiskit programs and executing the corresponding test cases, facilitating the reproducible empirical studies and comparisons of Qiskit analysis and testing tools.

In our future work, we would like to keep updating the Bugs4Q benchmark based on bug reports submitted on GitHub for Qiskit and continue to improve the tests to reproduce more bugs in Qiskit. Our benchmark will be continuously maintained on an ongoing basis. As Qiskit versions are updated, we will propose new extensions while keeping the previous version and subsequently develop new frameworks. Although quantum programs are now basically run with Qiskit simulators and the programs are small in size. However, we will try to replicate this on the QPU in a subsequent attempt to find out what kind of bugs occur in programs running on quantum computers. We would also like to summarize more bug types for the commonality of bugs to be more easily uncovered when Bugs4Q is extended to other quantum programming languages.

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