From Quantum Fuzzing to the Multiverse: Possible Effective Uses of Quantum Noise

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Abstract. Quantum noise is seen by many researchers as a problem to be resolved. Current solutions increase quantum computing system costs significantly by requiring numerous hardware qubits to represent a logical qubit to average the noise away. However, despite its deleterious effects on system performance and the increased costs it creates, it may have some potential uses. This paper evaluates those. Specifically, it considers how quantum noise could be used to support the fuzzing cybersecurity and testing technique and AI techniques such as certain swarm artificial intelligence algorithms. Fuzzing is used to identify vulnerabilities in software by generating massive amounts of input cases for a program. Quantum noise provides an effective built-in fuzzing capability that is centered around the actual answer to a computation. This same phenomena, of clustered and centered fuzz-noise around the answer of an operation, could be similarly useful to AI techniques that can make effective use of lots of point values for optimization. Effectively, by concurrently considering the 'multiverse' of possible results to an operation, created by compounding noise, more beneficial solutions that are proximal to the actual result of an operation can be identified via testing quantum noise points with an effectiveness algorithm. Both of these potential uses for quantum noise are considered herein.

Keywords: Quantum Computing, Quantum Fuzzing, Quantum Noise, cybersecurity and optimization.

1 Introduction

The development of a robust, commercially utilizable quantum computer has been slowed by the inherent noise of qubits. Quantum noise remains a significant problem for quantum system development and use; however, despite the impairment of system operations that it causes and the additional expense of duplicating physical qubits to create logical qubits that average out the noise, it may have some beneficial uses.

This noise is very problematic. In fact, the error caused by the decoherence of qubits makes many desirable quantum computing applications presently impractical [1]. However, this is expected to be a temporary and solvable issue [2]. At present, research is focusing on its mitigation [2].

However, while noise may cause a problem for some quantum computing uses, it may be beneficial for other ones. It can, prospectively, be used for fuzzing and some artificial intelligence (AI) techniques.

With fuzzing, the noise may provide an inherent testing capability. Fuzzing [3] is common technique which is an effective and popular approach to automated software defect identification (ASDI). ASDI identifies bugs that may have been missed or even intentionally discounted by a human analyst. It does this by trying lots of possible inputs to a program to see whether they work as expected – or cause a security issue of some kind. Using fuzzing, developers and analysts can identify areas within a program that pose security threats or have defects.

In addition to fuzzing, the quantum noise may be effective for systems that evaluate numerous possible solutions as part of AI optimization. Techniques like particle swarm, packet swarm and genetic algorithms intentionally make small changes to known solutions to see if these modified versions perform better (or more poorly) than their predecessor. Beneficial changes are retained (and, typically, an attempt to further refine them is made); harmful changes are discarded. Quantum noise produces these types of small changes and may 'stack' changes over time (compounding the error from the ideal answer), thus identifying additional prospective solutions to evaluate using the system's goodness metric.

In both cases, non-ideal qubit values from quantum noise could potentially be harnessed, transforming an unfortunate property of quantum computing into a usable capability for detecting software defects and expanding the search space (or, perhaps, even both concurrently). Noise utilization could be another immediate benefit of quantum computing capabilities. Even as solutions to mitigate or correct for noise are developed in the future – many of which involve using multiple qubits as one logical qubit to average noise impact away – these capabilities could still be utilized by polling physical qubit values directly (which will likely need to be done for the averaging function, anyway).

This paper reviews the potential for fuzzing and artificial intelligence to make use of this otherwise negative by-product of quantum computing. It continues with a review of relevant prior work. Following this, the use of quantum noise for fuzzing is reviewed. Next, the multiverse concept, which is integral to some potential AI techniques use of quantum fuzzing, is discussed. This is followed by a discussion of quantum noise enabling AI techniques, before concluding.

2 Background

This section presents prior work in several areas that provide a foundation for the work that is discussed herein. First, prior work on quantum computing is presented. Next, quantum noise is described. Then, fuzzing and vulnerability detection are discussed. Finally, the multiverse theory is reviewed.

2.1 Quantum Computing

Quantum computing is the application of quantum mechanics to computing. It utilizes qubits, which are the quantum counterpart to the binary bits used in classical systems. Qubits use the principle of superposition to assume a probabilistic state of both zero and one. Superposition and quantum entanglement are key properties of quantum computers which allow them to process a variety of tasks significantly faster than the fastest classical-style computing systems.

A selection of algorithms have been proposed to utilize the capabilities of quantum computing for applications such as identifying prime factors of large integers [4], searching for elements in large, unsorted list [5], and generating true random numbers [6]. At present, there is significant ongoing research which is focusing on the implementation of quantum computing for commercial applications [7], advancing classical computing fields such as artificial intelligence [8], and developing cryptography techniques for increased communications security [9].

A current byproduct and limitation of quantum computing is quantum noise. It is, at present, one of the largest obstacles to developing large-scale quantum computers that can be used for many targeted applications [10]. Quantum noise refers to the degree of uncertainty associated with a physical state during computation. Quantum noise affects the overall accuracy of qubits and consequently can potentially result in inaccurate computation results.

2.2 Quantum Noise

Quantum noise describes the decoherence of particles, which is a principle of quantum mechanics. This noise comes from fluctuations in the momentum of electrons at optical frequencies and from the inherently uncertain, dynamic nature of electric and magnetic fields [11]. Left unchecked, it will compound, moving some qubits further from their ideal (probabilistic) value over time. Figure 1 depicts the compounding decoherence of qubits, over time, starting from an arbitrary configuration and with an arbitrary amount of time between each depicted phase.

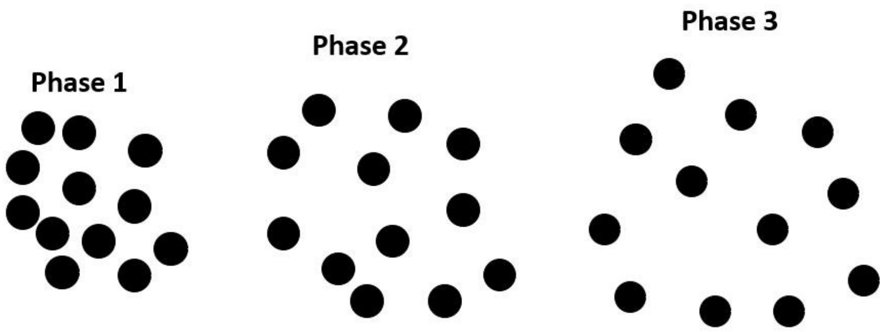

Figure 1. Qubit decoherence over time.

Quantum noise is recognized as one of the largest challenges in developing large-scale quantum computers. It is theorized that quantum systems with adequately low noise levels can be used to solve problems that are intractable by classical computers [10].

The noise-decoherence of qubits results in erroneous outputs for computations. The mitigation of quantum noise has been a key area of research focus. Numerous different methodologies have been proposed for resolving qubit decoherence to produce accurate computation. Duan & Guo [12], for example, proposed a noise-suppression scheme based on pulse control that mitigates noise using the application of a sequence of bit-flipping and phase-flipping methods.

Machine learning techniques have also been proposed as a solution for detecting and mitigating quantum decoherence. Cuozzo, et al. [13] discusses how machine learning algorithms can be used to suppress quantum noise using spatial masks applied to a pump beam. However, as described by Ball [14] and herein, the inherently random nature of noise in qubits has the potential to be harnessed for a variety of applications.

2.3 Fuzzing for vulnerability detection

Fuzzing is a common security assessment technique which has been used to identify weaknesses in a variety of different types of software. Vulnerability assessment and detection provides developers and IT staff with insight on how attackers could exploit weaknesses to access, corrupt, modify or delete sensitive data [15] or otherwise interfere with program operations.

Fuzzing begins with generating large amounts of random test cases of varying quality. These test cases are constructed to be accepted by the program but are designed to cause the program to fail when processing them. The performance of the application being tested is monitored when running the test cases, by the fuzzing software, to detect faulty behaviors [3]. Any abnormalities that are detected are then assessed to determine the location and source of the fault.

Through using this process, the principal benefit of fuzzing, that the detection of vulnerabilities becomes automated, is realized. This is critical, because large-scale software systems and deployed environments make it impractical for human analysts to effectively locate all vulnerabilities. Relying solely on human assessors runs the significant risk of missing a potentially harmful defect in a program. By implementing fuzzing, large-scale detection of vulnerabilities can be performed for a target program. Analysts are then freed to focus on testing areas of particular concern and complex logic that fuzzing may not fully test, as well as evaluating and implementing appropriate remedial actions for any defects that are detected [16].

2.4 The Multiverse Theory and the Many-Worlds Interpretation

Fuzzing is not the only conceptual use for quantum computing error data. One interesting property about the error produced by some quantum computers is the fact that it compounds over time, as additional error occurs for qubits that already have experienced error. In this regard, quantum error embodies principles of the many-worlds interpretation (MWI) of quantum mechanics. MWI proffers that there are many – if not infinite – worlds, which exist concurrently [17]: some are basically the same as this reality, while others are dramatically different. Figure 2 depicts both compounding quantum computing error and MWI.

MWI is similar to the multiverse theory, which asserts that there are an infinite number of universes operating in parallel to this one, which happen to be beyond the realm of observation [18]. The multiverse theory seeks to explain the nature of the universe – and potential universes – as observed, while MWI is based on a property of quantum mechanics. While physicists have studied the existence of billions of parallel universes, humanity currently lacks the resources to determine its accuracy [19].

MWI, on the other hand, is based on the collapse of a wavefunction being explained by quantum decoherence (a loss of information due to environmental interactions). The MWI suggests that all possibilities of a quantum measurement are present in at least one of many parallel worlds. This prevents various quantum paradoxes through the idea that every feasible outcome is realized in some different universe.

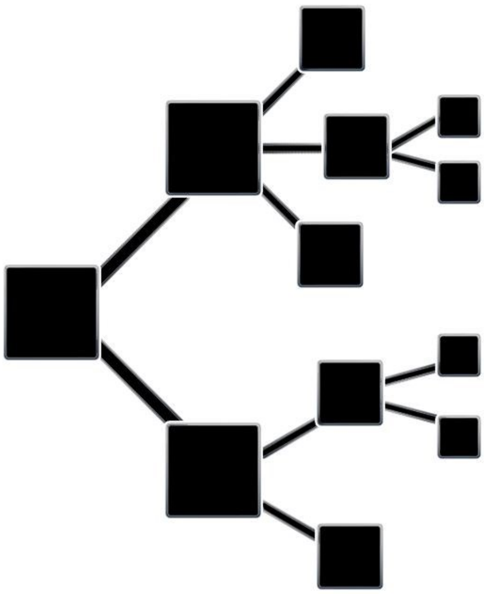

Figure 2. Depiction of compounding quantum computing error and the many-worlds interpretation.

Figure 2, thus, depicts the nature of both compounding error and the MWI / multiverse model. The left-most block represents the ideal, without any error present, in a compounding error depiction. In MWI / multiverse, it represents the present, where instantaneously a variety of different possibilities for outcomes exist. The sub-blocks, under the compounding error model, represent different degrees of compounded error (those that are directly connected to the left-most block have less error than those further to the right). For each case created by error compounding upon error, less qubits will be in that state. In MWI / multiverse, the blocks to the right of the left-most block represent alternate worlds where the various possibilities are realized.

The MWI / multiverse theory correlates with the large problem in quantum computing of quantum decoherence in qubits [20]. This decoherence causes erroneous outputs when performing quantum computation, as the environment surrounding qubits leads to a loss of information [21], rendering present quantum systems unreliable (i.e., the result of a single qubit may not be the ideal value). Techniques for quantum error correction have been studied. These include the use of multiple physical qubits for each logical one [22] as well as a variety of error correction protocols [23].

Continuously calculating certain tasks on an array of noisy, physical qubits is comparable to MWI / multiverse, in that inaccuracies produced by quantum decoherence result, over time, in a larger magnitude of error as more tasks are performed by the quantum computer.

3 Quantum Noise Fuzzing

As discussed in Section 2.3, fuzzing is performed by generating numerous input cases which are designed to test a target area within a piece of software. Fuzzing can be targeted at specific areas or functions or use a completely untargeted 'brute force' approach to the detection of software defects that could potentially result in security vulnerabilities or other issues with a program. The data of fuzzing input cases is intentionally faulty to test a variety of software characteristics [24] with a goal of detecting otherwise unknown vulnerabilities.

Coverage of the vulnerability search space is important to maximize the efficacy of fuzzing testing, thus, randomized input values are very well suited to use for fuzzing. Quantum computing inherently produces such random values, centered around an ideal value, as part of its operations, due to the endemic-to-system noise which results from the qubit's environmental interactions.

At present, noise must be handled at the application level, so getting access to noise values is quite straightforward. If a program desires to use averaging to mitigate noise, this will typically require the task to be performed several times. Thus, all values of the ideal result (the average that removes the impact of the noise) and the noise-present results are available for storage and use for fuzzing or other purposes. Figure 3 depicts how fuzzing might be conducted using a quantum computing system. Fuzzing could be conducted during special testing sessions. Alternately, all noise data that is a byproduct of operations could be stored to run for testing purposes when the system is not otherwise engaged in processing activities.

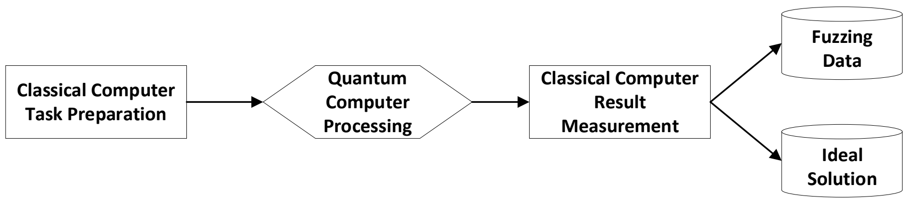

Figure 3. Process flow for quantum computing byproduct fuzzing.

At present, noise is a byproduct of quantum computing operations and is seen as a key obstacle in the development of large-scale quantum computing systems. Conventional fuzzing, which is needed for detecting unknown vulnerabilities in a given program, typically requires task generation capabilities that tend to be costly to operate and execute [25]. The potential to use quantum noise as either a generation mechanism for test data or a constant source of test data for software that uses quantum computing exploits a synergy between these two areas.

A noise implementation of fuzzing could potentially reduce fuzzing costs related to the generation of input tasks for a program. Prospectively, there may even be ways to use quantum noise from one process to facilitate fuzzing of another process. For example, the quantum noise could be recalculated as offset data that could be applied to another variable related to a different piece of software that was being subject to fuzzing testing.

Even as quantum computing systems evolve to mitigate the effect of noise (for example, by using lots of physical qubits as part of a single logical qubit for inherent averaging), as long as it is possible to obtain the raw data from the physical qubits, the underlying hardware noise can be used to facilitate testing, as described above. Notably, if a technology was developed that eliminated qubit noise at its source, this would render this secondary use of the noise data unworkable.

Effectively, this technique can be described mathematically as, in aggregate, identifying the numerical value of each qubit's decoherence and applying it to data that either is part of the same quantum computing job or to other software using an appropriate algorithm for the application of noise values to fuzzing test case generation.

A considerable advantage of harnessing noise for fuzzing techniques is that, unlike other fuzzing approaches, quantum noise fuzzing makes use of an otherwise non-ideal byproduct of quantum computations to perform the fuzzing at a lower computational cost, as compared to implementing fuzzing without this approach. In using quantum noise for fuzzing, the computational costs associated with the generation of a large magnitude of pseudorandom values for testing the integrity of software are reduced. Thus, quantum noise fuzzers would avoid fuzzing value generation costs, and may generate more effective random fuzz values, by virtue of the inherent random number generation capabilities [26] of quantum computing.

4 Quantum Noise and the Multiverse Theory / Many-Worlds Interpretation

The premise of the many-worlds interpretation and multiverse theory is that any one universe, where a given set of options from within the set of possible outcomes has occurred, is one of potentially nearly infinitely many parallel universes. This has a direct parallel to quantum computing: consider an individual, physical qubit that is probabilistically superposed in all states concurrently. There are theoretically infinite possibilities for the measurement of this qubit. A many-worlds interpretation of this suggests that, regardless of what is measured in a given universe, all possible measurements are existent in at least one universe.

Quantum theory posits that an isolated system (in this case, a qubit) can be represented by a state function. Here, the function representation of this system evolves, as projected by Schrodinger's equation. Upon measurement of this system, its state ultimately 'collapses' to a single measured value. This is a decoherence of state resulting in a loss of information [27]. The many-worlds interpretation mitigates concerns for collapsing wave functions, in that the measurement of a superposed state causes a collapse in the state's wave function, where MWI recognizes that the non-resultant measurement is assumed in a different world [28].

As more computations are performed using a collection of physical qubits, the level of decoherence compounds in a manner that is similar to MWI and the multiverse model. Just like successive choice opportunities result in numerous possible outcomes and that become 'worlds' under MWI, compounding noise results in numerous possible states based on different combinations of noise impact across operations.

As time progresses under MWI, the parallel worlds can change drastically, with respect to the 'original' world at a given starting time. Likewise, as time progresses for operating qubits, decoherence consequently results in increased magnitudes and distributions, across entangled and operation-associated qubit combinations, of error.

5 Quantum Noise and Artificial Intelligence

A key prospective area to leverage quantum noise is in artificial intelligence. Artificial intelligence techniques include a variety of optimization, classification and learning algorithms. Multiple artificial intelligence techniques, such as search, are used for single-agent pathfinding problems, two-player games, and constraint-satisfaction problems [29]. Alternatively, some supervised machine learning algorithms, such as Naive Bayes, can be implemented as a methodology for text classification [30].

The inherently random nature of quantum noise has the potential to be utilized for optimization and machine learning artificial intelligence techniques. Machine learning algorithms harness randomness for optimization and to solve deterministic problems, such as voting that results in a draw, where (when applicable) randomness can be used to determine the outcome. Some training-based machine learning applications require vast amounts of input values, many of which could potentially benefit from a random capability for optimization [31]. Figure 4 illustrates how quantum noise can be used as part of an artificial intelligence implementation. Quantum processing is included after classical artificial intelligence data preparation and prior to classical computing result measurement. This workflow demonstrates a potential approach to applying quantum noise value generation to expedite artificial intelligence processes. Models such as random forest (RF) are examples of effective classification algorithms for commonality identification and grouping of large datasets. Here, an enhanced degree of random in decision tree generation may result in increased efficacy of overall classification. The random nature of RF is found in both the random origin of a tree within the RF structure, and the tree node as a subset of features being randomly chosen to produce the best possible split. [32]

Harnessing the properties of noise in quantum computation for the generation of input values, optimizing machine learning algorithms, and classification of variables in large data sets are a few example applications of its effective use.

Swarm intelligence techniques could also potentially benefit from quantum noise. Swarm intelligence (SI) is a decentralized, collective collaboration of potentially self-managing systems inspired by biological examples of social insects and flocking behaviors of vertebrates. Here, algorithmic frameworks such as Ant Colony Optimization distribute, access, and utilize information [33], incentivized by the pursuit of a common goal. Comparable to how a large magnitude of individual ants operate in a collaborative manner to determine the shortest path between their nest and a food source, computational SI can be utilized to solve a variety of complex, large-scale tasks, such as optimization [34] and management of IoT operations, where the real-time, dynamic nature of an IoT environment requires large-scale process management, capabilities [35]. Examples of large-scale SI utilization are in electrical load forecasting, intrusion detection and machine learning optimization [36]. The random nature of quantum noise could be applied to the generation and distribution of artificial entities within a swarm, effectively making use of an otherwise detrimental factor of quantum computing. It could also be applied to particle property manipulation in particle swarm optimization. Particle swarm optimization [37] is a technique where particles are moved within an assessment matrix area to attempt to determine optimal solutions.

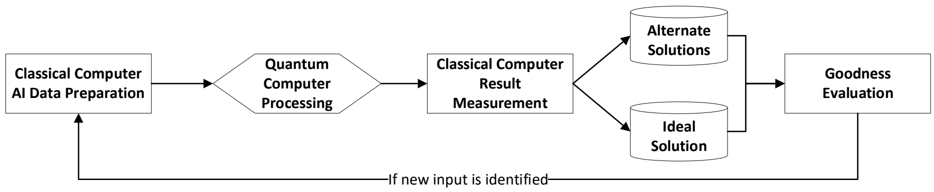

Figure 4. Use of quantum noise as part of an AI system.

6 Conclusions and Future Work

This paper has discussed how quantum computing noise can prospectively be used for fuzzing, for program testing and vulnerability identification, and as part of artificial intelligence techniques. Noise is a deleterious property of quantum computing which research has shied away from harnessing; however, Ball [14] correctly suggests that quantum noise can be utilized for numerous different applications.

Computational fuzzing is a potentially beneficial area of use due to the similarities between the input data expansion process and quantum computing noise. Fuzzing is a frequently used technique for identifying faults in software and its operating environments. This paper has discussed how quantum noise values could potentially be leveraged for generating the random input tasks necessary for fuzzing and the potential benefits of doing so.

Fuzzing was suggested as an immediately possible way of making beneficial use of quantum noise, however, it is one among a plethora of potential uses. Other possible uses were also discussed, such as optimization, artificial intelligence and swarm intelligence. Artificial intelligence, in particular, presents a number of options for leveraging quantum noise. Noise can prospectively be used as part of a modification to existing swarm intelligence-style techniques. As many AI and machine learning algorithms are dependent on processing large sets of possible data values to identify optimal ones, automatically generating, without significant associated computational cost, values that are proximal to a current value is inherently valuable. Techniques developed specifically for quantum computing implementation may also be designed to utilize this property, inherently; however, even classical optimization techniques which are interacting with quantum computing data or which are trying to optimize quantum computing processes, could prospectively make use of the noise.

The compounding nature of decoherence with respect to time was also discussed and it was compared to the principles of the multiverse model and multi-world interpretation of quantum mechanics. The utility of this expanding tree-like structure of noise-produced values was discussed as a prospective value to some artificial intelligence algorithms, as it would enhance search space coverage.

The proposed uses are examples of how different techniques could, ultimately, allow a passively produced and (at least with current technology) inevitable product of quantum computations to be used effectively. While this doesn't eliminate the noise issue for calculations, it does show that this property could be prospectively useful for some applications. Each of these prospective applications requires further review to gain an understanding of the benefits of their use of quantum computing noise capabilities. This, and the identification of other areas of quantum noise benefit, are key areas for future work.

Future work will be needed to consider the practicality of harnessing quantum noise for fuzzing implementations in terms characteristics such as efficacy and overall computational cost. Similarly, consideration should be given to the inherent quantum capability of generating random numbers and this value in the production of quantum fuzz. Quantum fuzzing should also be considered for use in the generation of fuzz values for software weakness detection. Quantum fuzzing may also find use in other areas such as machine learning optimization methodologies (such as particle swarm).

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