

Classical and Quantum Data Interaction in Programming Languages: A Runtime Architecture

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Abstract

We propose a runtime architecture that can be used in the development of a quantum programming language and its programming environment. The proposed runtime architecture enables dynamic interaction between classical and quantum data following the restriction that a quantum computer is available in the cloud as a batch computer, with no interaction with the classical computer during its execution. It is done by leaving the quantum code generation for the runtime and introducing the concept of futures for quantum measurements. When implemented in a quantum programming language, those strategies aim to facilitate the development of quantum applications, especially for beginning programmers and students. Being suitable for the current Noisy Intermediate-Scale Quantum (NISQ) Computers, the runtime architecture is also appropriate for simulation and future Fault-Tolerance Quantum Computers.

Keywords: Quantum Computation, Programming Language, Quantum Programming, Runtime Architecture

1. Introduction

A quantum computer uses quantum mechanics phenomena, such as superposition and entanglement, to solve some problems faster than classical computers. Such a claim was first proposed by Feynman [1] motivated by the difficulty of simulating the evolution of quantum states. Later, confirmed by the pioneer works of Shor [2] and Grover [3]. And, recently demonstrated experimentally by Google [4].

A quantum programming language describes instructions for a quantum computer. It is a relatively new paradigm, but there are several implementations [5–16] from both industry and academy. The level of abstraction and quantum architecture targets vary from each language. For instance, Q# [6] is a high-level domain-specific language used to program quantum computers based on quantum logic gates, and Blackbird [8] is a low-level language used for continuous-variable quantum computation on photonic quantum computers.

Today, we are in the Noisy Intermediate-Scale Quantum (NISQ) era [17] marked by quantum computers

with a few dozen of noise qubits, where the commercial ones are accessible through the cloud, *e.g.*, the Amazon Braket service [18]. Due to the low-fidelity of the small number of qubits and the implemented gates, every quantum execution needs to be as much optimized as possible, forbidding the execution of a generic quantum code. For example, to activate the best performance, the quantum code that sums an arbitrary integer x into a quantum superposition should be specialized for every possible value of x .

In opposition to the NISQ computers, there are Fault-tolerant Quantum Computers [19] with enough qubits to run expensive quantum error correction (QEC) codes [19] on top of quantum applications. Nevertheless, we are still far from them. Although even there, we may have the same restrictions of accessibility (in the cloud, not locally) and the need to run highly optimize quantum applications due to the high cost of the QEC codes.

In this context, we propose a runtime architecture that can be used to both develop quantum programming languages, or embed quantum programming in general propose programming languages. The runtime architecture enables dynamic interaction between classical and quantum data stored in qubits despite the limitations that a quantum computer executes in batch, without interac-

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tion between classical and quantum computers during the quantum execution, and that the generated quantum code needs to be highly optimized for a specific execution. More precisely, this dynamic interaction allows the loop of classical information controlling quantum operations and quantum measurement operation with classical information, all regardless of whether that data is stored on the classic or quantum computer.

With the proposed runtime architecture, a quantum programming language can be developed as a general-purpose programming language that supports the quantum programming paradigm, and not a domain-specific programming language as most quantum programming languages [6, 13, 15, 16]. This abstraction permits the development of an application that takes advantage of quantum and classical computers with a single and consistent programming language, facilitating the development of quantum applications, especially for beginning programmers and students.

The proposed architecture has several components, where the main one is a shared library that manages the quantum code generation, optimization, and execution. Those components form a general framework for the construction of a quantum programming environment with a simulator and optimizing compilers.

The remainder of this paper is organized as follows. A brief introduction to quantum computation is given in Section 2. An overview of quantum programming and the constraints imposed on the proposed runtime architecture are shown in Section 3. The runtime architecture and its component are detailed in Section 4. The shared library features that enable the dynamic interaction between classical and quantum data are presented in Section 5. And, in Section 6, there are our conclusions and final remarks.

2. Quantum computation

This section introduces the concepts of quantum bit (qubit), quantum measurement, quantum entanglement, quantum circuit, and decoherence.

The basic unity of information used in quantum computation is the qubit. A qubit (or quantum bit), alike to a bit, can be at states 0 or 1, denoted by $|0\rangle$ and $|1\rangle$, but different from a bit, it can also be at both states at the same time, in what we call a superposition. In a superposition, a qubit is denoted by a convex sum, e.g., $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ where $\alpha, \beta \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 = 1$. It can be visualized geometrically in the Bloch sphere, e.g., the qubit $|\psi\rangle = \cos \frac{\theta}{2} |0\rangle + e^{i\phi} \sin \frac{\theta}{2} |1\rangle$ of Figure 1.

To extract information from a superposition, we need to perform a measurement that will randomly return 0

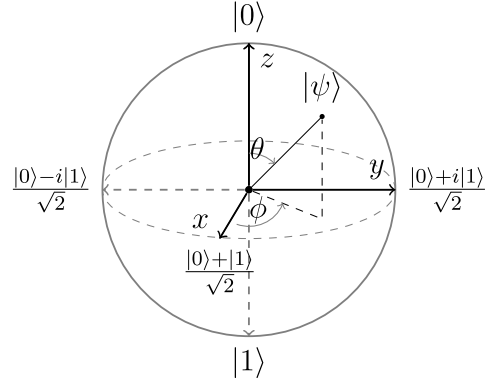


Figure 1: Bloch sphere used to visualize a single qubit.

or 1 according to the probability amplitude of the qubit state, e.g., $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ has the probability $|\alpha|^2$ of return 0 and $|\beta|^2$ of return 1. When a measurement is done, the qubit's superposition is destroyed, collapsing its state. For example, if the measurement of $|\psi\rangle$ returns 0 or 1, it collapses, respectively, to state $|0\rangle$ or $|1\rangle$.

Quantum entanglement is another important phenomenon for quantum computation. When a set of qubits is entangled, we cannot fully describe every qubit separately. It means that any operation on a single qubit will change the state of all qubits in the set. For example, if we measure one of two maximally entangled qubits, we know what will be the measurement result of the other qubit.

The evolution of a quantum state is described by a unitary operation. Consequently, any quantum operation, except measurement, is time-reversible, and we cannot copy the state of a qubit [20].

A quantum circuit [21] is a diagram that defines the evolution of a quantum state through time. An example of quantum circuit can be seen in Figure 2. A quantum circuit is executed from left to right by the application of quantum gates and measurements. The term quantum operation used in this paper refers to any process (not necessarily a quantum circuit) that changes the quantum state of a qubit.

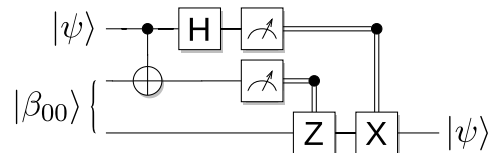


Figure 2: Quantum teleportation circuit, where $|\beta_{00}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$. The last two quantum gates Z and X are controlled by the measurement result of the top two qubits.

Decoherence is the process of loss of information that a quantum computer suffers due to its interaction with the environment, or the inaccurate execution of quantum operations. It is the primary barrier for quantum computation, limiting the time that a quantum computer can maintain the quantum information, and consequently, the circuit deep (number of quantum gates). To overcome this limitation, we can encode the quantum state in a quantum error correction (QEC) code [19]. However, this approach adds a costly overhead in the number of qubits and quantum gates used.

3. Quantum programming

In this section, a general overview of quantum programming languages is given along with the quantum programming restriction and characteristics imposed on the proposed runtime architecture.

Although it is acknowledged that an abstraction beyond the quantum circuit would benefit the development of new quantum applications [22], the abstraction of most quantum programming languages is equivalent to quantum circuit. It is particularly true for a set of quantum programming languages [5, 7–9, 12] called quantum instruction set or quantum assembly language. Those quantum programming languages aim to be an intermediary representation for higher-level programming languages and other quantum programming software [8, 12, 23].

Implement a quantum programming language as an embedded programming language is a usual strategy [8, 11, 13–15] that can reduce development cost, and provide vast libraries for the quantum programming language. However, the embedded programming language will also be limited by the additions of the base general-purpose programming language.

The most evident target for a quantum programming language is a quantum computer. Although, most quantum programming languages provide constructions that go beyond the NISQ computer processing power [14, 22]. This way, several targets are also provided. For example, classical simulators, usually with less than 30 qubits; resource estimators to calculate the cost of a particular quantum execution, usually, in numbers of qubits (circuit width) and gates (circuit deep); and, quantum circuit drawers, use to generate a graphic representation of a quantum execution, which is usually a quantum circuit.

The characteristics and constraints for a quantum programming language may diverge from each language. So, for this paper, we will consider the following ones.

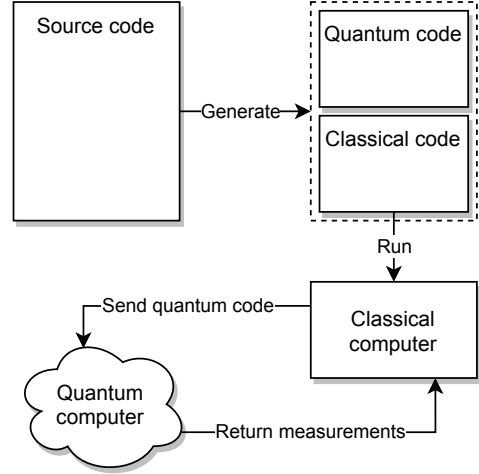


Figure 3: The general workflow of a quantum programming language.

The general workflow of a programming language is summarized in Figure 3. There, a single source code generates both the classical and quantum codes. This generation can be done by a compiler, interpreter (similar to Python), or a mixed approach. The classical code is then executed by a local classical computer, and the quantum code is sent to a remote quantum computer.

The quantum computer is a batch computer that takes a quantum code as input and outputs the measurement results. It is connected to a classical computer through a network infrastructure, likely the internet.

The classical computer coordinates what will be sent to the quantum computer, setting, *e.g.*, classical parameters of a quantum operation. Because of performance concerns, the majority of the classical code will be executed locally. However, for the quantum code supports the execution of loops (feedback) and classical controls (feedforward) statements, *e.g.*, if-then-else, the quantum computer needs to be able to execute simple classical expressions and branches.

4. The runtime architecture

We have designed the runtime architecture, summarized in Figure 4, following the constraints of Sections 2 and 3. The main limitation of the dynamic interaction of classical and quantum data is the batch execution of the quantum computer. This problem implies that the classical computer cannot interact with the quantum computer during its execution, *e.g.*, the classical computer cannot decide which operation will be executed by the quantum computer based on some measurement

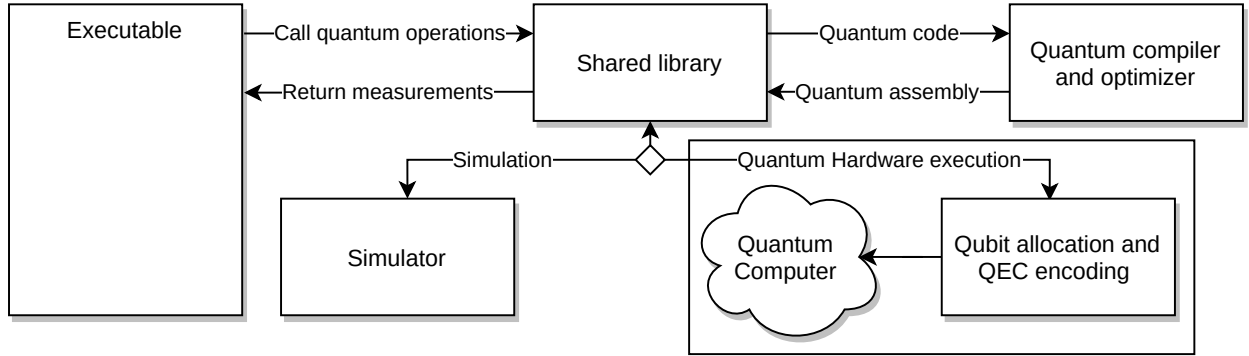


Figure 4: The proposed runtime architecture for dynamic interaction between classical and quantum data.

performed on the same execution. This lack of interaction forbids the execution of some quantum algorithms and protocols, *e.g.*, the quantum teleportation of Figure 2.

To overcome this limitation of interaction, the proposed runtime architecture relies on quantum computer’s ability to execute simple expressions and breaches, and the generation of the quantum code during the classical runtime. For further discussions on the implications of this strategy are given in Section 5.

The proposed architecture is composed of several components with the following workflow. First, an executable makes calls for a shared library that handle the quantum operations. This executable can be a binary file generated by a compilation process or an interpreter executing source code like Python. Then the shared library generates the quantum code during runtime and sends it to a compiler optimizer that returns a quantum assembly. After, the quantum assembly can be sent to a simulator or a quantum computer, where extra steps are needed to execute. Finally, the results of the quantum assembly execution, which are the measurement results, are returned to the shared library and then returned to the executable. The measurement results are classical data and can be used by the executable as such.

The following subsections detail every component of the runtime architecture as well as their interactions and intermediaries.

4.1. Shared library

The shared library works as an intermediary for other components of the runtime architecture. It handles calls to allocate and free qubits, applies quantum operations like quantum gates as well as its controlled and inverse versions, and measurements.

The calls performed by the executable are used to generate the quantum code, which is a quantum inter-

mediary representation that is not necessarily equivalent to a quantum circuit. The quantum code can have higher-level constructions, such as functions, loops, classical conditional statements, and arbitrary gates with an unlimited number of control qubits. As the library is independent of the quantum execution target, the quantum code is independent of the quantum architecture and has no preset limit of qubits.

To improve performance and coding dynamism, the library shall produce multiple unrelated quantum codes at the same time. For example, if the parameter of a quantum application is a random number, and we want to use a real random number generated by a quantum computer, then we need to initialize a second quantum code that is independent of the main one, to generate the random number. This approach reduces the number of qubits, and consequently, gates required to run the quantum application by splitting it into several quantum executions.

A shared library, in contrast to a static one, is loaded during the execution and not linked statically into the binary executable. It means that there is no need to recompile the code on every update, as soon as it maintains the same interface. Still, a static library can replace the shared library.

4.2. Quantum compiler and optimizer

The quantum compiler and optimizer translate the quantum code into a quantum assembly language and performs optimizations independent of quantum architecture [24, 25]. The quantum assembly, like the classical assembly, is a lower-level language, that is closer to the quantum hardware execution, but it remains independent of the quantum architecture.

For quantum hardware execution on today’s NISQ computers, the languages OpenQASM [5] and Quill [12] can be used for, respectively, IBM and Rigetti

quantum computers. For other executions targets, such as simulators or resource estimators, other languages [13, 14], and even classical programming languages using quantum programming libraries [12, 23, 26, 27] can be used. The quantum assembly can be a subset of the quantum code, using the same quantum programming language.

The quantum assembly must be expressive enough to represent every possible construction of the quantum code and simple enough to be efficiently executed by a quantum computer or simulator. It is important to notice that some quantum programming languages are more expressive than others. For example, the Quil can represent loops, using label and branch instructions, that is not possible with the OpenQASM.

4.3. Quantum simulator

While we are in the Noise Intermediate-Scale Quantum (NISQ) era, far from large scale fault-tolerant quantum computers, simulate a quantum computation may be the best option to test a quantum algorithm or application. However, even with the arrival of more powerful quantum computers and despite the exponential simulation time, simulators are yet useful for debugging quantum applications due to the impossibility of looking into a quantum superposition.

The simulator could execute the quantum code instead of the quantum assembly to improve performance. Complex operations that need to be decomposed in several quantum gates to be executed in a quantum computer can be executed in a single step by a simulator. For example, a controlled-NOT gate with multiple qubits of control, an oracle for Grover’s algorithm [3], and the modular exponentiation for Shor’s algorithm [2] can all be executed by a single quantum operation in a simulator.

4.4. Quantum hardware execution

The quantum assembly describes the execution of a quantum application in terms of logical qubits. Those are ideal qubits, free of noise and fully connected, where no error corrections are needed, and every qubit communicates with each other, *e.g.*, it is possible to apply a CNOT between any qubit. However, quantum computers work with physical qubits subject to noise (errors) and connectivity limitations. An example is the quantum computer IBMQ Melbourne of 15 qubits. Figure 5 shows its qubit connectivity and calibration.

The logical qubits of the quantum assembly need to be mapped into physical qubits to run on a quantum computer. This process is called qubit allocation [28]

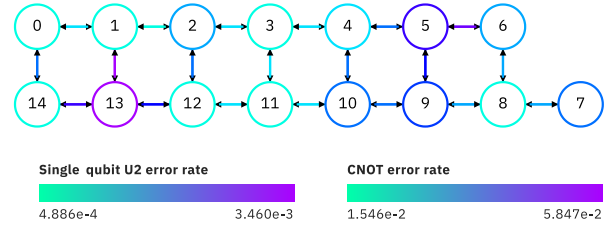


Figure 5: Quantum computer ibmq_16_melbourne v2.0.6 calibrated at April 16, 2020. Screenshot by author from <https://quantum-computing.ibm.com>.

or quantum circuit mapping [29]. Heuristics for optimization may vary from each quantum computer vendor since every explores different qubits layouts and construction technology.

Despite being too expensive for NISQ computers, quantum error correction is part fundamental of fault-tolerant quantum computers. So, the quantum assembly may pass throw a QEC encoder before been send to a quantum computer. As the qubit allocation, QEC encoding also depends on the quantum architecture and may be performed by proprietary software provided by the quantum computer vendor.

5. The shared library features

To provide the dynamic interaction between classical and quantum data, the shared library relies on two main features, the ability to generate the quantum code at runtime and that a measurement returns a future, in other words, the promise of a result. With the given restriction of Section 2 and 3, those two features are essential for the runtime architecture ability to execute generic quantum applications with the dynamic interaction between classical and quantum data, and even quantum circuits like the quantum teleportation of Figure 2 depends on it.

Due to decoherence, every quantum operation needs to be highly optimized. Therefore, it is discouraged to construct a sequence of gates that operates based on an undefined classical input. For example, Shor’s algorithm needs to perform modular exponentiation on a superposition taking a state $|x\rangle|0\rangle$ into $|x\rangle|a^x \bmod n\rangle$, where a and n are classical parameters. Thus, for the quantum code to be optimized for specific classical parameters, either they need to be statically defined (compile-time resolvable), or the quantum code generation needs to be delayed for the runtime where those parameters are available.

Besides enabling the description of parameterized quantum applications, as described above, the genera-

tion of quantum code at runtime also permits the description of responsive quantum applications, which can change its execution based on user input, sensor measurement, or quantum execution. For example, an application that for a given number returns its prime factors and a quantum code that uses a measurement result as input.

Some quantum application, like the quantum teleportation of Figure 2, uses the result of a measurement to control which gates are applied. However, as the quantum computer's decoherence time may be shorter than the response time between the classical and the quantum computer, a quantum computer executes in batch. So, such decisions of what needs to be done based on a quantum measurement demand to be made by the quantum computer. That is where measurement results as a future take place.

When a measurement is performed, the shared library returns a promise in the form of a future to the classical computer. That promise is just fulfilled when the measurement result is needed by the classical computer and the quantum code is executed. This way, classical control statements with quantum operations are possible in the runtime architecture, since they can be placed in the quantum code and executed by the quantum computer. A future can hold other information that is not necessarily a measurement result but is only available in the quantum computer, e.g., the result of expressions with measurement results and loop control variables. In addition to the if-then-else statement, higher-level construction, such as for and while, usually available on general purpose programming language, are also possible to be executed by a quantum computer.

For further programming dynamism, futures should be transparent for the programmer. For example, the following high-level pseudocode that implements quantum teleportation

```

1  qubit[] bell(aux0, aux1) {
2      qubit q0, q1;
3      if (aux0) x(q0);
4      if (aux1) x(q1);
5      h(q0);
6      cnot(q0, q1);
7      return q0, q1;
8  }
9
10 qubit teleport(a) {
11     b = bell(0, 0);
12     cnot(a, b[0]);
13     h(a);
14     m0 = measure(a);
15     m1 = measure(b[0]);
16     if (m1) z(b[1]);

```

```

17     if (m0) x(b[1]);
18     return b[1];
19 }
20
21 int main() {
22     qubit a;
23     h(a);
24     y = teleport(a);
25     print(measure(y));
26 }

```

generates the following quantum code:

```

1  qubit a;
2  h(a);
3  // teleport begin
4  // bell begin
5  qubit q0, q1;
6  h(q0);
7  cnot(q0, q1);
8  // bell end
9  cnot(a, q0);
10 h(a);
11 m0 = measure(a);
12 m1 = measure(q0);
13 if (m1) z(q1);
14 if (m0) x(q1);
15 // teleport end
16 return measure(q1)

```

Note that the if statements of the function bell are not present in the quantum code since the values aux0 and aux1 are known by the classical computer. However, the if statements of the function teleport operate with measures that are unknown by the classical computer, so they are placed in the quantum code. The quantum code is executed just when the measurement of the qubit y is needed for the print function in the main function.

Every future is a node of an abstract syntax tree (AST) that is generated at runtime. An AST is a data structure represented by a tree that stores the syntax of a program, in our case, the syntax of the quantum code. An operation between a future and some classical data also generates a new node (future), and the results are just placed into the futures (the promise is fulfilled) after the quantum code execution. **When the classical computer requests the result of a future, the AST is traversed, beginning at the node where the result was requested, generating the quantum code.** Every qubit also has its own AST holding the gates applied on it, which the future returned from the qubit measurement is connected as a parent node.

The generation of quantum code at runtime and the ability to return a future on a measurement allows that quantum and classical information interact regardless of

where they are stored. This interaction can be in terms of (i) classical data controlling the application of quantum operations, (ii) quantum measurement results used as input of a classical function, and the loop of those two, all transparent to the programmer.

6. Conclusion

We presented a runtime architecture for the constructions of quantum programming languages that enable dynamic interaction between classical and quantum data. Considering the restriction that a quantum computer processes in batch, making impossible the interaction between quantum and classical computer during the quantum execution, we propose the use of futures and the generation of quantum code at runtime to work around this limitation.

A future holds classical information that is generated in the quantum computer. It is used as a promise for a measurement result that is fulfilled after the quantum execution. Futures operates in both the classical and the quantum computer transparent for the programmer. With this strategy, classical constructions like if-then-else, for, and while are also possible to be executed in a quantum computer.

It is important to notice that full support for the classical constructions depends on the quantum target and quantum assembly language used. However, taking it into account, the loop of classical information controlling the execution of quantum operations and the result of quantum executions operating with classical data is possible on any quantum computer, including NISQ computes. The proposed runtime architecture also addresses both simulation and quantum computer execution considering its uniqueness.

Embed a quantum programming language on a general-purpose programming language is a widely used strategy, which is supported by the proposed runtime architecture. However, it is important to notice that semantic checks during compilation time can be difficult or impossible to implement depending on the host language and that some constructions can seem out of place with the host language.

Our runtime architecture presents a general framework for a quantum programming language and its programming environment. However, we do not properly address the problem of debugging quantum programs, and there is a lack of precision in the description of the quantum hardware execution. As future works, we intend to use this runtime architecture in the development of new quantum programming language, approaching

the dynamic interaction between classical and quantum data.

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