Qurry: A prototype quantum programming language

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Abstract

[Abstract commented out for now, will edit last]

1 Introduction

Innovation in near-term quantum programming requires the use of lightweight abstractions [Cite], which allow users to easily exploit the power of quantum computing while still understanding its fundamental mechanisms. In 1981, Richard Feynman noted that quantum physics appears to be impossible to simulate using a classical computer, but that quantum computers appeared to be perfectly capable of simulating quantum physics [Cite]. Effectively, quantum computation potentially allows new problems to be computed efficiently: in particular, this includes literal simulations of the physical world, but also abstract algorithms which may receive a superpolynomial change in time complexity. [Qurry allows quantum programmers to access the power of quantum computers, without sacrificing performance or understanding of the underlying mechanisms]

1.1 Motivation

Stephen Jordan, of Microsoft, keeps a nearly exhaustive list of quantum algorithms and the speedups that they offer: https://quantumalgorithmzoo.org/ [Cite]. According to this list at time of writing, there are thirty-five distinct algorithms which offer a potential superpolynomial speedup. This famously includes Peter Shor's factoring and discrete log algorithms, as well as, fundamentally, quantum simulation. Interestingly, many quantum algorithms such as the Deutsch-Jozsa algorithm are matched (at least practically, and sometimes theoretically) by probabilistic algorithms, and even some algorithms with superpolynomial speedups are based on older probabilistic versions. For instance, machine learning does not appear to have superpolynomial improvements at time of writing. The most promising application of quantum computing in the near term is in molecular simulation. At time of writing, quantum computers have been used to simulate di-Hydrogen, Be-H2, and [Other small molecules, Cite] [Qurry aims to assist in the development and implementation of each of these algorithms...]

1.2 Main

1.3 Background

The absolute basics of quantum computing are not nearly as intimidating as they are sometimes made out to be. The main requirement is linear algebra, but complex numbers and probability are also helpful. Conventionally, quantum data is represented on qubits. When measured, qubits will be in *either* of two states: 0 or 1. However, more generally, qubits are in a combination of these two states, which is known as a superposition. A particular active qubit's state is described by two complex numbers, α and β, which are collected in a vector. This is written in the simple equation $\psi = \alpha 0 + \beta 1$. However, the state vector α, β is not directly examinable. Instead, when a qubit is measured, one measures 0 with probability $|\alpha|^2$, and 1 with probability $|\beta|^2$, which must sum to 1. For single qubits, a state is evolved in the model simply by multiplying the state vector for a qubit by a $2x2$ unitary matrix, known as a one-qubit gate. This is written as Av. [Enumerate common one-qubit gates]

For n qubits, the state is simply a complex vector of length 2^n, and a n qubit gate is a $2^n by 2^n$ matrix. Importantly, though, past a single qubit, quantum states can be entangled. Two states are entangled when the measurement outcome of one qubit is correlated with the measurement outcome of other qubits. The simplest, most famous example of this is the Bell states, also known as EPR pairs. For instance, in one Bell state, two qubits are either measured both as 0, or both as 1, but there is no probability for them to differ. [Enumerate n qubit gates]

1.4 Parallels to C++ and its role in the classical software ecosystem

Lightweight abstractions, as defined by Bjarne Stroustrup [TODO: Cite], are abstractions that lower the cognitive load on the user, without sacrificing understanding of the underlying processes behind particular code.

In Bjarne's words: "The aim [of C++] is to allow a programmer to work at the highest feasible level of abstraction by providing A simple and direct mapping to hardware and Zero -overhead abstraction mechanisms"

Layers of abstraction are a fundamental idea in all of computer science, and quantum computing is no different. Currently, quantum computing operates on the abstraction that is the gate-level, where programs are defined by gates acting sequentially on particular qubits, instead of, for instance, specific microwave pulses (or another implementation-specific low-level mechanism [TODO: Expand on this]). The universal gate model of quantum computing generally allows a quantum programmer to ignore many details of the quantum computer they are running on: Sources of error aside, modeling the bond energy of molecular hydrogen is hypothetically the same on an ion-trap quantum computer as on a superconducting quantum computer. For instance, classical programmers using C++ generally need not worry about the specific [datatypes..]. However, some have argued for the importance of hardware, as in Google's phrase "hardware aware, not hardware agnostic". [TODO: Cite] Many aspects of hardware are particularly important, for instance, topology, which will potentially result in a programmer needing to modify a quantum algorithm for it to run on two separate computers. The goal of lightweight abstractions is to preserve these concerns, while still taking burden off of the programmer, and giving them a richer language with which to express themselves.

Quantum computing [motivations] [TODO: General motivations, cite Rigetti, cite Haskell/LISP/Rich Hickey, cite Probabilistic programming languages] [Cite Peter Selinger's papers]

1.5 Core

The matrix operator model of quantum computing actually lends itself to functional programming paradigms quite nicely, because quantum programs and quantum operators are functions in a sense. Additionally, since quantum states are fixed once measured, and are generally measured at the end of a program, in a sense memory is not truly mutated (even though it appears to be). [i.e. $result = Pv$, not $result = 0; Pv$]. A quantum program itself is simply a higher order function, which operates on an initial state vector. In turn, a particular quantum program is composed further of simpler matrix-functions, which operate on their own vectors, or are composed with other matrices. For instance, consider a bell state program. As a whole, we may call the bell state program which creates the + state B, and know that $B0$ [TODO: Dirac notation] is the application of the program B to a two-element zero vector. However, this program will further be composed as a Hadamard operator, H, and entanglement operator, $CNOT$, where H will operate on one qubit, and then $CNOT$ will operate on both qubits. [TODO: Math writeup]

In a traditional circuit language, these operators are composed by simply listing which qubits they operate on, and ordering them correctly in a circuit definition file. However, with higher-order functions, quantum operators can be composed in mariad helpful ways, as is common in function languages like Haskell or LISP (from which Qurry draws many influences).

1.6 Circuit Languages

At time of writing, Rigetti pyquil contains the following quantum gates and operations:

Single qubit gates and operations:

- RESET, I, X, Y, Z, H, S, T

Qubit gates taking an angle as the the parameter and qubit as the second:

- RX, RY, RZ, PHASE

Swap operators, where each takes two qubits, and PSWAP takes an additional angle as a first argument:

- SWAP, ISWAP, and PSWAP

Controlled operators:

- CZ, CNOT ['control', 'target']
- CSWAP ['control', 'target_1', 'target_2']
- CPHASE00, CPHASE01, CPHASE10, CPHASE ['angle', 'control', 'target']

And of course the hybrid measurement instruction, which takes a qubit as the first argument, and a classical register as the second:

- MEASURE

And also contains the following classical operations:

- TRUE, FALSE, NOT, NEG ['classical_reg']
- AND, OR, MOVE, EXCHANGE, IOR, XOR ['classical_reg1', 'classical_reg2']
- ADD, SUB, MUL, DIV ['classical_reg', 'right']
- EQ, GT, GE, LE, LT ['classical_reg1', 'classical_reg2', 'classical_reg3']
- LOAD ['target_reg', 'region_name', 'offset_reg']
- STORE ['region_name', 'offset_reg', 'source']
- CONVERT ['classical_reg1', 'classical_reg2']

1.7 Classical Probabilistic Languages

Classical probabilistic programming languages are a recent innovation from the MIT cognitive science community. Essentially, they create a way for non-expert programmers to access the power of Bayesian inference. Users can create simple probabilistic models in standard code, and then run them through an expert-created inference backend. Famously, this has resulted in dramatically reduced code complexity, with a famous case where a 50-line probabilistic program could compete with traditional approaches to face recognition [TODO: Cite].

2 Features

Qurry as a language is simply a circuit language with an overlay of higher-order functions. [Explain circuit languages and the functionality Qurry includes here, through pyquil]

2.1 Higher Order Functions

The simplest overlay is quite trivial. It is the *map* function, which allows an arbitrary quantum operator to be applied to several qubits. For instance, the operation ($mapHmyqubits$) does a hadamard state preparation, which is common in the beginning of some quantum algorithms. While simple, this example is important because *map* is a higher-order function. Namely, *map* takes two arguments: first, a linear operator on qubits, and second, a block of qubits where the linear operator is applied to each qubit in the block. Because this first argument is itself a linear operator (a function of sorts [TODO: Verify]), *map* is a higher-order function. Higher-order functions are already used implicitly when composing linear operators to create a quantum program, so it makes sense to expose them. [Discuss the *map* construct].

Additionally, many constructs are defined in terms of unitary gates. Any of these is also a higher-order function. A still simple but more useful example is a controlled unitary. First, consider a unitary that is controlled from one bit:

- cascade
- clear
- cond
- do
- macro

2.2 Higher Order Datatypes

[discuss define [TODO: memory model]]

Equally important is the ability to create higher-order datatypes. Instead of operating on the level of qubits, are able to arrange raw datatypes into more complex structures. The simplest, which is common in any quantum circuit language, is the ability to create arrays of qubits. [Discuss the *block* construct].

However, for full completeness, one must be able to arrange qubits into special structures, in the sense of C++ structs. Further, in object oriented programming, classes are essentially equivalent to structs, and then collections of functions that operate on a struct. For simplicity, elegance, and robustness, Qurry does not implement encapsulation or inheritance, but instead uses public access by default (in the spirit of Python, since after all, Qurry has a Python interface), and relies on composition instead of inheritance. [Discuss the *datatype* construct]. With the inclusion of composable data structures, users are able to create arbitrarily nested structures of qubits with semantically named fields.

Recursively composed higher-order datatypes, in combination with recursively composed higher-order functions are the foundation for creating a more abstract programming language.

[TODO: Elaborate on everything currently in lists]

3 Software Ecosystem

In addition to being a prototype quantum programming language, Qurry defines a software stack surrounding the language, which is intended to make development more pleasant. For instance, this software stack makes it exceptionally easy to add new language features and libraries to Qurry. This allows one to rapidly test new ideas in quantum programming and let the language evolve on its own as opposed to architecting a top-down "perfect" language.

4 Standard Library

Qurry contains mechanisms which enable easy inclusion of qurry code in the form of libraries. As an example, Qurry's standard library is implemented in this fashion.

Explain how the statistics library can be easily implemented.

At time of writing, Qurry contains the following constructs:

- gaussian
- bernoulli
- multinomial
- uniform

Similarly to in a classical probabilistic programming language, these enable the creation of classical probabilistic states, which can then be used in quantum programs. For instance, it is possible to create a multi-dimensional gaussian distribution, and then entangle an auxillary qubit with the state of the gaussian distribution.

5 Extension

Making additions to Qurry is particularly easy: For instance, the *map* feature is defined using the following python code:

```
from ..compiler.utils import named_uuid

def map(operator, blockname, kernel=None):
    '''
    Apply a single-qubit operator to every qubit in a block
    (map H blocka)
    '''
    try:
        block = kernel.definitions[blockname]
    except KeyError:
        raise ValueError('The block {} is not defined'.format(blockname))
```

```
return '\n'.join('{} {}'.format(operator, i)
        for i in range(block.start, block.end + 1))
```

6 Statistical Libraries

Since quantum computers are simply special probabilistic computers, Qurry also attempts to create a classical statistical library for high-level modeling. This is particularly useful in the same way that a classical probabilistic programming language is, namely for modeling anything statistical, and especially for bayesian machine learning. For instance, the R. Tucci and H. Dekant's group have shown uses for this through their software, Bayesforge [TODO: Cite]. Qurry includes simple statistical packages for creating states, but no inference engine. [However, Qurry might allow one to interface with Bayesforge]

7 Conclusion

In the creation of a Qurry and its corresponding framework, it is hoped that this will aid the development of quantum algorithms, as algorithm designers will have a new, richer, more abstract vocabulary with which to express themselves. To recap, this goal is approached in the following N ways. By introduction of lightweight abstractions from the C++ school of thought, efficient and transparent programming interfaces are created. Through specialized libraries, Qurry can claim to be a generalized library, while still offering powerful sub-frameworks for specific tasks. With functional programming paradigms, Qurry can move towards higher levels of abstraction as the semantics of quantum programming become better understood. Lastly, by creating a rapid prototyping framework, new language features can be developed in a bottom-up style, which will allow Qurry to be created naturally, instead of artificially.

8 Appendix one

Appendix content

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[1] [2] [3]

References

[1] Stephen Jordan. Quantum algorithm zoo.

[2] Bjarne Stroustrup. Foundations of c++.

[3] Richard Feynman. Simulating physics with computers, May 1981.