RWTH AACHEN UNIVERSITY
Chair of Computer Science 2
Software Modeling and Verification

Master Thesis Proposal

Compilation of Quantum Programs with Control Flow Primitives in Superposition

Sascha Thiemann
Matr.-No.: 406187
Study Program: Computer Science M.Sc.
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Supervisors: apl. Prof. Dr. Thomas Noll
Chair for Software Modeling and Verification
RWTH Aachen University

Prof. Dr. rer. nat. Dominique Unruh
Chair for Quantum Information Systems
RWTH Aachen University

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1 Introduction

Quantum algorithms like Shor's algorithm [Shor97] could provide a significant improvement to classical solutions given sufficient technology. Therefore, a lot of research is conducted in the area of Quantum Computing (QC). While there already exist detailed theoretical foundations [van20, Ying11, YYF12] and advanced algorithms for QC [ACR*10, BGB*18, LoCh19, Shor97], the technology of quantum computers is said to be on the level of classical computer in the 1950s [CFM17]. Currently, there are many architectures and ideas for the future of QC. In this proposal and the following thesis, we want to build upon the Quantum Control Machine proposed by Yuan et al. [YVC24] and discuss the idea of quantum control flow in general.

Quantum control flow can be divided into *quantum branching* and *iteration*. [YVC24] First defined by Ying et al. [YYF12], quantum branching is based on Dijkstra's guarded clauses [Dijk75]. Guarded clauses concern the nondeterministic executing of functions based on boolean expressions. In contrast, quantum branching allows for execution of functions based on a value in superposition such that the result may be a superposition of the results of the individual functions. Quantum branching is, e.g., used in simulation algorithms like [BGB*18], and [LoCh19]. Extending on the idea of branching, quantum iterations is the repetition of a function based on a value in superposition.

2 Motivation

With the emergence of quantum computing, many quantum languages were introduced. Most languages focus on a lower level representation of quantum circuits. An example is the popular Open Quantum Assembly Language (QASM)[CBSG17]. QASM consists mainly of quantum and classical gates that can be manipulated by predefined and composite gates as well as limited classical if-statements. In contrast, there are also languages with a focus on high level interactions, e.g. Tower[ChMi22] which contains data structures in superposition, and Silq [BBGV20] which allows for automatic uncomputing of registers. What all these languages have in common is the restriction to quantum data while using only classical control flow. Although quantum control flow was defined by Ying et al. [YYF12] over ten years ago, only very few languages have incorporated the principle. One example is the functional programming language proposed by Altenkirch et al. [AlGr05] where quantum branching is used to define, e.g., the Hadamard gate, as proposed by Ying et al. [YYF12]. Only

recently was the Quantum Control Machine (QCM) with quantum control flow at its core proposed by Yuan et al. [YVC24].

The QCMs syntax and logic are both heavily influenced by classical assembly languages. The language consists of quantum registers, gate, swap and get-bit operations[1], simple numeric operations on registers, and, finally, jump instructions. The jump instructions range from simple to conditional to indirect and are used to enable quantum control flow. Although the jump instructions are based on jumps in classical computers, they are limited by two concepts quantum computers based on unitary gates must adhere to, *reversibility* and *synchronization*. [YVC24]

When quantum computers are based on unitary gates, all their operations need to be unitary and, therefore, reversible as well. This also includes jump instructions which are not reversible in classical computers. To ensure reversibility of jumps, the QCM uses a *branch control register* whose value controls how much the instruction pointer of the machine advances after each instruction. The branch control register can then be manipulated reversibly by, e.g., adding or subtracting from it. The idea of a branch control register can also be found in reversible architectures for classical machines [AGY07, TAG12].

Although such a program counter addresses the issue of reversibility, it can become entangled with data registers when in superposition. This can lead to disruptive entanglement where the output of the program becomes invalid [YVC24]. To prevent any disruptive entanglement of the data and control registers, the QCM adheres to the principle of synchronization. It requires that the control flow is separated from the data at the end of execution. Examples where synchronization comes into play are given in Fig. 2.1 and Fig. 2.2 where x^y and $x^{\min\{y,max\}}$ are calculated respectively. While the first example is completely reversible, it does not adhere to the principle of synchronization. Given two different inputs, the loop will be executed a different number of times. This means that after the faster of the two programs completed the loop, the program counter of the slower one cannot catch up. To prevent this issue, the second program uses padding which is executed instead of the main loop.

Because of the reversibility of the QCM, any jump instruction in the code needs to have an opposing return jump instruction. Additionally, the synchronization principle requires any loop with n instructions to contain n padding instructions and any loops cannot depend on quantum data for their iterations. Together with the syntax based on classical assembly languages, the language of the QCM is hard to read and write.

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[1]The gate operations are limited to the Hadamard and NOT gates.

```
1      add    res $1
2      add    r1  y
3 l1: rjne   l3   r1   y
4 l2: jz     l4   r1
5      mul    res x
6      radd   r1   $1
7 l3: jmp    l1
8 l4: rjmp   l2
```

Figure 2.1: QCM exponentiation without synchronization

```
1      add    res $1
2      add    r1  max
3 l1: rjne   l3   r1   max
4 l2: jz     l4   r1
5 l5: jg     l7   r1   y
6      mul    res x
7 l6: jmp    l8
8 l7: rjmp   l5
9      nop          ; padding
10 l8: rjle   l6   r1   y
11     radd   r1   $1
12 l3: jmp    l1
13 l4: rjmp   l2
```

*

Figure 2.2: Synchronized QCM exponentiation

3 Concept

The concept for the master thesis is to take the idea of the QCM, specifically the core concept of quantum control flow, and reduce it to its most basic elements and make it realistic for and applicable to NISQ era quantum computers. Concretely, we want to go from jump instructions to basic if-else clause to reduce the complexity of the code and make it easier to read and write. These if-else clauses can easily be implemented as the application of controlled gates. Moreover, because of the synchronization principle and the fact that current quantum computer technology does not support loops depending on measurement, any other loop can be reduced to a for-loop that is unrolled at compile time.

To achieve this goal, we want to define a language "Luie" (short for loop-unrolled if-else) which is partially based on the quantum while language used by Ying [Ying11]. The language is extended by a quantum if clause which takes a quantum register and executes the statements in the clause based on the value of the register. Furthermore, the clause could even be extended to include the evaluation of boolean expression. While the language cannot include while statements based on measurements of registers, as it is the case in the language proposed by Ying, it can include bounded loops which are unrolled at compile time. The language will then be compiled to QASM. A basic grammar for the language can be seen in Appendix .1.

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.1 Grammar

```
1     grammar Luie;
2
3     parse
4      : block EOF
5      ;
6
7     block
8      : (definition | statement)*
9      ;
10
11    definition
12     : 'qubit' IDENTIFIER ';'
13     ;
14
15    statement
16     : GATE IDENTIFIER ';'
17     | qifStatement
18     ;
19
20    qifStatement
21     : ifStat elseStat? END
22     ;
23
24    ifStat
25     : IF IDENTIFIER DO block
26     ;
27
28    elseStat
29     : ELSE DO block
30     ;
31
32    GATE
33     : XGATE
34     | ZGATE
35     | HGATE
36     ;
37
38    XGATE : 'x';
39    ZGATE : 'z';
40    HGATE : 'h';
41
42    IF       : 'qif';
43    ELSE     : 'else';
44    DO       : 'do';
45    END       : 'end';
46
47    IDENTIFIER
48     : [a-zA-Z_] [a-zA-Z_0-9]*
49     ;
50
51    COMMENT
```

```
52        : ( '//' ~[\r\n]* | '/*' .*? '*/' ) ->
            skip
53        ;
54
55    SPACE
56        : [ \t\r\n\u000C] -> skip
57        ;
```