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

Master Thesis Proposal

Title tbd

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1 Introduction

- Quantum Computer ability to solve (certain) algorithms faster than classical computers
- e.g. Factorization
- Therefore, a lot of research into quantum computers
- While detailed theoretical foundation
- (Technology of) Quantum Computer on level with classical computer 1950s [CFM17].
- Different architectures and ideas for future of QC
- Want to build on recent proposal

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 would be 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. 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 10 years ago, only very few languages have incorporated the principle. One example is the functional programming language proposed by Altenkirch et al. [AlGr05] where `if`$^\circ$ is used to define the Hadamar gate. 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 basic on jumps in classical computers, they are heavily limited by two concepts quantum computers based on unitary gates must adhere to, *reversibility* and *synchronization*. [YVC24]

Because quantum computers are based on unitary gates, all there 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* which values controls how much the instruction pointer of the machine advances after an execution. The branch control register can then be manipulated reversibly. The idea of a branch control register can also be found in reversible architectures for classical machines[AGY07, TAG12].

Example for non-reversibility?

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 $x^{\texttt{min}\{y,max\}}$ are calculated respectively. While the first example is completely reversible, it does not adhere to the principle of synchronization. Given the inputs two different inputs, the loop will be executed a different amount of times. This means that after the faster input completed the loop, the program counter of the slower input 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 its iterations. Together with the syntax based on classical assembly languages, the language of the QCM is hard to read and write.

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 NISQ era quantum computers. Concretely, we want to from jump instructions to basic if-else clause to reduce the complexity of the code and make it

[1] The gate operations are limited to the Hadamar 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

easier to read and write. Moreover, because of the synchronization principle, 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. This could even be extended to include 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

```
grammar Luie;

parse
 : block EOF
 ;

block
 : (definition | statement)*
 ;

definition
 : 'qubit' IDENTIFIER ';'
 ;

statement
 : GATE IDENTIFIER ';'
 | qifStatement
 ;

qifStatement
 : ifStat elseStat? END
 ;

ifStat
 : IF IDENTIFIER DO block
 ;

elseStat
 : ELSE DO block
 ;

GATE
 : XGATE
 | ZGATE
 | HGATE
 ;

XGATE : 'x';
ZGATE : 'z';
HGATE : 'h';

IF       : 'qif';
ELSE     : 'else';
DO       : 'do';
END       : 'end';

IDENTIFIER
 : [a-zA-Z_] [a-zA-Z_0-9]*
 ;

COMMENT
```

```
      : ( '//' ~[\r\n]* | '/*' .*? '*/' ) ->
          skip
      ;

    SPACE
      : [ \t\r\n\u000C] -> skip
      ;
```