

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

Master Thesis Proposal

Title tbd

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1 Introduction

- Short intro into QC
 - What is QC
 - Why is it important
 - What can it be used for

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 pre-defined 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 un-computing 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 `ifo` 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 operations¹, 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

¹The gate operations are limited to the Hadamar and NOT gates.

Example for non-reversibility?

```

1      add    res $1
2      add    r1 y
3 11:  rjne   13 r1 y
4 12:  jz     14 r1
5      mul    res x
6      radd   r1 $1
7 13:  jmp    11
8 14:  rjmp   12

```

Figure 2.1: QCM exponentiation without synchronization

```

1      add    res $1
2      add    r1 max
3 11:  rjne   13 r1 max
4 12:  jz     14 r1
5 15:  jg     17 r1 y
6      mul    res x
7 16:  jmp    18
8 17:  rjmp   15
9      nop                                ; padding
10 18:  rjle   16 r1 y
11      radd   r1 $1
12 13:  jmp    11
13 14:  rjmp   12

```

Figure 2.2: Synchronized QCM exponentiation

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].

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 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 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.

Language specification ...

- Idea
 - reduce QCM to basics
 - lead to concept section
- Language features: qif-else, bounded loops, (boolean eval)
- Translation to quasm
- overall (more) realistic for NISQ
- Further (compiler optimizations)
- Example grammar

Explain in concept

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```

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      ;
```