QLang: Qubit Language
(Final Report)

Christopher Campbell Clément Canonne Sankalpa Khadka Winnie Narang
Jonathan Wong

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Chapter 1

An Introduction to the Language

The QLang language is a scientific tool that enables easy and simple simulation of quantum computing on classical computers. Featuring a clear and intuitive syntax, QLang makes it possible to take any quantum algorithm and implement it seamlessly, while conserving both the overall structure and syntactical features of the original pseudocode. The QLang code is then compiled to C++, allowing for an eventual high-performance execution – a process made simple and transparent to the user, who can focus on the algorithmic aspects of the quantum simulation.

1.1 Background: Quantum Computing

In classical computing, data are stored in the form of binary digits or bits. A *bit* is the basic unit of information stored and manipulated in a computer, which in one of two possible distinct states (for instance: two distinct voltages, on and off state of electric switch, two directions of magnetization, etc.). The two possible values/states of a system are represented as binary digits, 0 and 1. In a quantum computer, however, data are stored in the form of *qubits*, or quantum bits. A quantum system of n qubits is a Hilbert space of dimension 2^n; fixing any orthonormal basis, any *quantum state* can thus be uniquely written as a linear combination of 2^n orthogonal vectors $\{|i\rangle\}_i$ where i is an n-bit binary number.

Example 1.1.1. A 3 qubit system has a canonical basis of 8 orthonormal states denoted $|000\rangle$, $|001\rangle$, $|010\rangle$, $|011\rangle$, $|100\rangle$, $|101\rangle$, $|110\rangle$, $|111\rangle$.

To put it briefly, while a classical bit has only two states (either 0 or 1), a qubit can have states $|0\rangle$ and $|1\rangle$, or any linear combination of states also known as a *superposition*:

$$|\phi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where $\alpha, \beta \in \mathbb{C}$ are any complex numbers such that $|\alpha|^2 + |\beta|^2 = 1$.

Similarly, one may recall that logical operations, also known as *logical gates*, are the basis of computation in classical computers. Computers are built with circuit that is made up of logical gates. The examples of logical gates are AND, OR, NOT, NOR, XOR, etc. The analogue for quantum computers, *quantum gates*, are operations which are a *unitary transformation* on qubits. The quantum gates are represented by matrices, and a gate acts on n qubits is represented by $2^n \times 2^n$ unitary matrix[1]. Analogous to the classical computer which is built from an electrical circuit

[1] That is, a matrix $U \in \mathbb{C}^{2^n \times 2^n}$ such that $U^\dagger U = I_{2^n}$, where $\cdot^\dagger$ denotes the Hermitian conjugate.

containing wires and logic gates, quantum computers are built from quantum circuits containing "wires" and quantum gates to carry out the computation.

More on this, as well as the definition of the usual quantum gates, can be found in Appendix A.

1.1.1 Dirac notation for quantum computation

In quantum computing, *Dirac notation* is generally used to represent qubits. This notation provides concise and intuitive representation of complex matrix operations.

More precisely, a column vector $\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix}$ is represented as $|\psi\rangle$, also read as "ket psi". In particular, the computational basis states, also know as *pure states* are represented as $|i\rangle$ where i is a n-bit binary number. For example,

$$|000\rangle = \begin{bmatrix} 1\\0\\0\\0\\0\\0\\0\\0 \end{bmatrix}, |001\rangle = \begin{bmatrix} 0\\1\\0\\0\\0\\0\\0\\0 \end{bmatrix}, |010\rangle = \begin{bmatrix} 0\\0\\1\\0\\0\\0\\0\\0 \end{bmatrix}, \ldots, |101\rangle = \begin{bmatrix} 0\\0\\0\\0\\0\\1\\0\\0 \end{bmatrix}, |110\rangle = \begin{bmatrix} 0\\0\\0\\0\\0\\0\\1\\0 \end{bmatrix}, |111\rangle = \begin{bmatrix} 0\\0\\0\\0\\0\\0\\0\\1 \end{bmatrix}$$

Similarly, the row vector $\begin{bmatrix} c_1^* & c_2^* & \ldots & c_n^* \end{bmatrix}$, which is also complex conjugate transpose of $|\psi\rangle$, is represented as $\langle\psi|$, also read as "bra psi".

The inner product of vectors $|\varphi\rangle$ and $|\psi\rangle$ is written $\langle\varphi, \psi\rangle$. The tensor product of vectors $|\varphi\rangle$ and $|\psi\rangle$ is written $|\varphi\rangle \otimes |\psi\rangle$ and more commonly $|\varphi\rangle|\psi\rangle$. We list below a few other mathematical notions that are relevant in quantum computing:

- z^* (complex conjugate of elements)
  if $z = a + ib$, then $z^* = a - ib$.
- A^* (complex conjugate of matrices)
  if $A = \begin{bmatrix} 1 & 6i \\ 3i & 2+4i \end{bmatrix}$ then $A^* = \begin{bmatrix} 1 & -6i \\ -3i & 2-4i \end{bmatrix}$.
- A^{T} (transpose of matrix A)
  if $A = \begin{bmatrix} 1 & 6i \\ 3i & 2+4i \end{bmatrix}$ then $A^{\mathrm{T}} = \begin{bmatrix} 1 & 3i \\ 6i & 2+4i \end{bmatrix}$.
- $A^\dagger$ (Hermitian conjugate (adjoint) of matrix A)
  Defined as $A^\dagger = \left(A^{\mathrm{T}}\right)^*$; if $A = \begin{bmatrix} 1 & 6i \\ 3i & 2+4i \end{bmatrix}$ then $A^\dagger = \begin{bmatrix} 1 & -3i \\ -6i & 2-4i \end{bmatrix}$
- $\||\psi\rangle\|$ (ℓ_2 norm of vector $|\psi\rangle$)
  $\||\psi\rangle\| = \sqrt{\langle\psi|\psi\rangle}$. (This is often used to normalize $|\psi\rangle$ into a unit vector $\frac{|\psi\rangle}{\||\psi\rangle\|}$.)

- $\langle\varphi|A|\psi\rangle$ (inner product of $|\varphi\rangle$ and $A|\psi\rangle$).
  Equivalently[2], inner product of $A^\dagger|\varphi\rangle$ and $|\psi\rangle$

1.1.2 Quantum Algorithms

A quantum algorithm is an algorithm that, in addition to operations on bits, can apply quantum gates to qubits and measure the outcome, in order to perform a computation or solve a search problem. Inherently, the outcome of such algorithms will be probabilistic: for instance, a quantum algorithm is said to *compute a function f on input x* if, for all x, the value $f(x)$ it outputs is correct with high probability. The representation of a quantum computation process requires an input register, output register and unitary transformation that takes a computational basis states into linear combination of computational basis states. If x represents an n qubit input register and y represents an m qubit output register, then the effect of a unitary transformation U_f on the computational basis $|x\rangle_n|y\rangle_m$ is represented as follows:

$$U_f(|x\rangle_n|y\rangle_m) = |x\rangle_n|y \oplus f(x)\rangle_m, \tag{1.1}$$

where f is a function that takes an n qubit input register and returns an m qubit output and $\oplus$ represents mod-2 bitwise addition.

1.2 Goal and objectives

QLang has been designed with a handful of key characteristics in mind:

Intuitive. Any student or researcher familiar with quantum computing should be able to transpose and implement their algorithms easily and quickly, without wasting time struggling to understand idiosyncrasies of the language.

Specific. The language has one purpose – implementing quantum algorithms. Though, the language supports many linear algebraic computation, it is mainly aims for quantum computation. Anything that is not related to nor useful for this purpose should not be – and is not – part of QLang (e.g., the language does not support strings).

Simple. Matrices, vector operations are pervasive in quantum computing – thus, they must be easy to use and understand. All predefined structures and functions are straightforward to use, and have no puzzling nor counter-intuitive behavior.

In a nutshell, QLang is simple, includes everything it should – and nothing it should not.

[2] Recall that we work in a complex Hilbert space: the inner product is a sesquilinear form.

Chapter 2

QLang in practice: a Tutorial

2.1 Basics and syntax

A QLang file (extension `.ql` by convention) comprises several functions, each of them having its own variables. Once compiled, a program will start by calling the compute() function that must appear in the `.ql` file, and whose prototype is as follows:

```
def compute(): int trial {
  trial =10;
}
```

In particular, the main entry point compute() receives no argument and, automatically prints the return variable defined in the function declaration. The execution of above program prints 10. Note also that QLang is case-sensitive: compute and Compute would be two different functions (however, indentation is completely unrestricted).

Comments in the language are single-line, and start with a #: everything following this symbol, until the next line return, will be ignored by the compiler. Furthermore, a function is defined (and declared – there is no forward declaration) by the keyword def followed by the details of the function:

```
def function_name(type1 param1, type2 param2, ..., typek paramk): type returnvar {
  # variable declarations
  # body of the function
}
```

The valid types in QLang for parameters, return variables and variables are `int`, `float`, `comp`, `mat`: respectively integers, real numbers, complex numbers and matrices (the latter including, as we shall see, qubits). In the above, the return variable returnvar is available in the body of the function, and its value will be returned at the end of the function call. All other local variables must be declared, at the beginning of the function body: in particular, it is not possible to mix variable declaration and assignment:

```
def foo( mat bar ): mat blah {
  int bleh;                        # OK
  int bluh = 0;                    # Not OK: parsing error
  comp blih, bloh;                 # Not OK: one variable at a time
  comp blih; comp bloh;    #OK
```

```
  bleh = 5;                          # OK
  bleh = bleh+1                      # Not OK: missing semicolon
  bleh = bleh * 4 +
         2^bleh;                     # OK: statements can span several lines
  bleh = bleh-1; bleh = 2*bleh;     # OK: several statements per line
  blah = bleh * bar;                 # OK: blah is the returned variable
}
```

As examplified above, each statement (declaration, assignment, operation) can span any number of lines, and end with a semicolon.

Qubits, matrices and vectors. Before turning to the flow control structures, recall that QLang is designed specifically for the sake of implementing quantum algorithms; as such, it supports the usual quantum notations for bra and kets (although it stores and recognize then as of type mat):

```
mat idt;
mat vct;
mat qub;
qub = |11>;                      # this is a ket of dirac notation
qub = <01|;                      # this is a bra of dirac notation
idt = [(1,0)(0,1)];              # this is a matrix
vct = [(1,2,C(3.2 + 1.I))];      # this is a vector (with complex entries)
vct = qub;                       # this is OK
```

In the above, the 3 variables have the same type – the difference is only syntatical, in order to provide the user with an intuitive way to program the quantum operations.

2.2 Control structures, built-in functions and conversions

Now that the basic syntax of the language has been described, it is time to have a look at the fundamental blocks of any algorithm: the control structures, such as loops and conditional statements.

Loops. QLang supports two sorts of loop, the for and while statements. While their behaviors are illustrated below, it is important to remember two features of the for loop: namely, that (a) the loop index must be a variable declared beforehand; and (b) that the (optional) keyword by allows to set the increment size by any integer, even negative.

```
int i; # Will be used as 'for' loop index
int a;

for( i from 0 to 2 by 1 ) # OK
  a=a+5;

for( i from 2 to 0 by -1 ) # OK
{
    a=a*10;
    continue; # going to next iteration: the next instruction will never be executed.
    print(a);
}

for( i from 1 to 10 ) # OK: missing "by 1" is implicit
```

```
{
    a=a-3;
    break; # leaves the loop.
}

while( a leq 10 ) # OK
a=a+1;

while( a neq 0 )  # OK
{
    a = (a+1) ;
    continue;
    print(0); # never reached
}
```

As shown above, braces are optional when the body of the loop comprises only one line.

Conditional constructs. As in many languages, QLang supports a C-like if…else construct:

```
        if( predicate )
        {
           # Do something
        }
        else
        {
           # Do something else
        }
```

The predicate can be any expression evaluating to an integer: if non-zero, the if statement is entered; otherwise, the (optional) else statement is entered, if it exists. Note that QLang does not provide a builtin construct elseif, but instead relies on a nested combination of if and else:

```
if(z eq 5) a = 0;

a = a - 2;
if( z leq 5 )
{
   a = 0;
}
else
{
   a = 10;
   b = 24;
}

if( a gt 100 )
{
   print(b); # a > 100
}
else if( a eq 10 )
{
   print(a);
}
```

Builtin functions and operators. As shown in the previous two examples, QLang provides builtin constructs to perform basic or fundamental tasks:

Comparison operators: gt, lt, geq, leq, eq, neq take two operands a, b, and return 0 (resp. 1) if respectively $a > b$, $a < b$, $a \geq b$, $a \leq b$, $a \leq b$ and $a = b$ and $a \neq b$;

Builtin functions: these are convenient functions such as print, printq (for qubit syntax), or mathematical ones applying to matrices such as norm, adj, to complex values (sin, im, ...) or to 0/1 integers ("Booleans") such as and, xor.

Operators: the language supports the usual unary (negation $-$, logical negation not), binary (addition $+$, substraction $-$, exponentiation ˆ ...) operators, as well as some more specific ones (tensor product @).

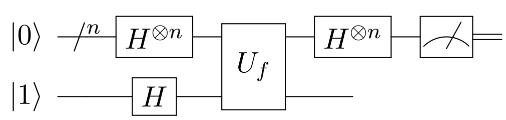
The complete list of these functions, operators and builtin constants can be found in Chapter 3.

Implicit conversions. Implicit conversions for some operators such as eq is possible, according to the following rule: `int`⇝`float`⇝`comp`⇝`mat`. However, the language is otherwise strongly typed: it is not possible to assign a complex number to a variable of type `mat`, for instance.

2.3 Diving in: Deutsch–Jozsa Algorithm

To illustrate and describe the process of writing in QLang, this section will walk the reader through the implementation of one of the most emblematic quantum examples, namely *Deutsch-Jozsa Algorithm*. The goal of this algorithm is to answer the following question: given query access to an unknown fucntion $f\colon \{0,1\}^n \to \{0,1\}$, promised to be either constant or balanced[1], which of the two holds? Classically, it is easy to see that this requires (in the worst case) querying just over half the solution space, that is $2^{n-1}+1$ queries. Quantumly, the Deutsch-Jozsa algorithm enables us to answer this question with just *one* query!

The circuit performing the algorithm is given below:



To implement it in QLang, we first have to implement the n-fold Hadamard gate $H^{\otimes n}$; recalling that the Hadamard gate H is a built-in operator of the language, this can be done as follows:

```
  def hadamard(int n): mat gate{
        #returns Hadamard gate of 2^n dimensions
        int i;
        gate = H;
        for(i from 1 to n-1 by 1){
                gate = gate @ H;
        }
}
```

[1] f is said to be balanced if $f(x) = 0$ for exactly half of the inputs $x \in \{0,1\}^n$; or, equivalently, if $\mathbb{E}_x[f(x)] = \frac{1}{2}$.

Now, to implement the measurement gate (or, more precisely, to return the measurement matrix), we write the following code that takes a ket $|x\rangle$ and returns the matrix $|x\rangle\langle x|$:

```
def measure(mat top): mat result{
        # returns the measurement matrix
        mat ad;
        mat ad = Adj(top);
        result = top * ad;
}
```

(Note that $|x\rangle\langle x|$ was written as $|x\rangle\,\text{adjoint}(|x\rangle)$, which is performed above using the transparent conversion between vectors and matrices provided by the language.)

Since the qubit in the top register is n-bit, we can write a function that allows us to create such a qubit for any n.

```
def topqubit(int n): mat input{
        # n-bit qubit
        int i;
        input = |0>;
        for(i from 1 to n-1 by 1){
                input = input @ |0>;
        }
}
```

Once all the "building blocks" (gates) of the algorithm have been implemented, we can write down the algorithm *as it appears from the circuit above*: the function takes as argument the parameter size n, as well as the unitary matrix implementing the quantum gate U_f (the access to the unknown function f), and returning either 0 or 1, depending one wether the function is constant or balanced.

```
def deutsch(int n, qubk top, mat U): float outcomeZero{
        mat bottom; mat top; mat input;
        mat hadtop; mat meas;

        bottom = |1>;
        top = topqubit(n);
        input = top @ bottom;

        hadtop = hadamard(n);
        input = (hadtop @ H)*input;
        input = U * input;
        input = (hadtop @ IDT)*input;
        meas = measure(top);

        input = (meas @ IDT)* input;
        outcomeZero = norm(input);

        }
```

Finally, we can call (and test) our algorithm by defining two unitary transformations (here U_b and U_c) and testing our function on them – and print the output. This is done by writing the entry point function, compute:

```
def compute (): float outcome{
        int n; mat Ub; mat Uc;

        n = 1;
        Ub = [(1,0,0,0)(0,1,0,0)(0,0,0,1)(0,0,1,0)];
        Uc = [(1,0,0,0)(0,1,0,0)(0,0,1,0)(0,0,0,1)];

        outcome = deutsch(n, Ub);
        print(outcome);

        outcome = deutsch(n, Uc);
        print(outcome);

        n = 2;
        Ub = [(1,0,0,0,0,0,0,0)
              (0,1,0,0,0,0,0,0)
              (0,0,1,0,0,0,0,0)
              (0,0,0,1,0,0,0,0)
              (0,0,0,0,0,1,0,0)
              (0,0,0,0,1,0,0,0)
              (0,0,0,0,0,0,0,1)
              (0,0,0,0,0,0,1,0)];

        outcome = deutsch(n, Ub);
}
```

The above program will print 0, 1, 0 for balanced function, constant function and balanced function respectively.

Chapter 3

Reference Manual

3.1 Lexical conventions

There are five kinds of tokens in the language, namely (1) literals, (2) constants, (3) identifiers, (4) keywords, (5) expression operators, and (6) other separators. At a given point in the parsing, the next token is chosen as to include the longest possible string of characters forming a token.

3.1.1 Character set

QLang supports a subset of ASCII; that is, allowed characters are `a-zA-Z0-9@#,-_;:()[]{}<>=+/|*`, as well as tabulations `\t`, spaces, and line returns `\n` and `\r`.

3.1.2 Literals

There are three sorts of literals in the language, namely *integer*, *float*, and *complex*. All three can be negative or positive (negation is achieved by applying the unary negative operator to them). Integers are given by the regular expression `['0'-'9']+`, floats are given by `['0'-'9']+ '.' ['0'-'9']*`, and complex are given by `C(F)|C(F+FI)|C(FI)`, where F is any floating point number.

3.1.3 Constants

There are several built-in numerical constants that can be treated as literals, they include:

`e` the base of natural logarithm $e = \sum_{k=0}^{\infty} \frac{1}{k!}$. Equivalent to `exp(1)`; has type comp.

`pi` the constant π. Has type float.

3.1.4 Identifier (names)

An identifier is an arbitrarily long sequence of alphabetic and numeric characters, where `_` is included as "alphabetic". It must start with a lowercase or uppercase letter, i.e. one of `a-zA-Z`. The language is case-sensitive: `hullabaloo` and `hullABaLoo` are considered as different.

3.1.5 Keywords

The following identifiers are reserved for keywords, using them as function of variable name will result in an error at compilation time.

```
int float comp mat C I def return eq neq lt gt leq geq
true false not and or xor norm trans det adj conj unit @
im re sin cos tan if else for from to by while break continue
```

3.1.6 Expression Operators

Expression operators are discussed in detail in section 3.4, Expressions.

3.1.7 Seperators

Commas are used to separator lists of actual and formal parameters, colons are used to separate the rows of matrices, semi-colons are used to terminate statements, and the hash-symbol (#) is used to begin a comment. Comments extends until the next carriage return. Multi-line comments are not supported.

3.1.8 Elementary operations and spacing

An operation, or language elementary unit, starts from the end of the previous one, and ends whenever a semicolon is encountered. Whitespace does not play any role, except as separators between tokens; in particular, indentation is arbitrary.

3.2 Objects and types

3.2.1 Objects and lvalues

As in C, "an object is a manipulatable region of storage; an lvalue is an expression referring to an object."

3.2.2 Valid types

The language features 4 elementary types, namely `int`, `float`, `comp`, `mat`. Is also valid, any type that inductively can be built from a valid type as follows:

- elementary types are valid;
- an *matrix* of a valid type is valid. Matrices have fixed size (that must be declared at compilation time), and are comprised of any elements of any type (that is, a matrix can have elements of non-necessarily identical types);
- a *function* taking as input a fixed number of elements from (non-necessarily identical) valid types, and returning a valid type.

3.3 Conversions

Applying unary or binary operators to some values may cause an implicit conversion of their operands. In this section, we list the possible conversions, and their expected result – any conversion not listed here is impossible, and attempting to force it would generate a compilation error.

- int → float
- float → comp
- int → comp

The equality and comparison operators (eq, leq, geq, lt, gt) will perform the implicit conversions above, when they make sense. For instance, 0 eq $C(0.0 + 0.0I)$ is valid, and the comparison will be between two complex numbers (after the first operand is converted into a comp). Similarly, 1 lt 2.5 is valid, the integer left-hand side being cast into a float (note that leq, geq, lt, gt are not defined for complex numbers, but only int and float).

3.4 Expressions

3.4.1 Operator Precedence

Unary operators have the highest precedence, followed by binary operators, and then assignment. The precedence and associativity within each type of operator is given in the table below. The lists of operators are read left to right in order of descending precedence. Also, the | symbol is used to group operators of the same precedence.

<table>
<tr><th>Operator Type</th><th>Operator</th><th>Associativity</th></tr>
<tr><td>Primary Expressions</td><td>() [] <| |></td><td>Left</td></tr>
<tr><td>Unary</td><td>re im norm unit trans det adj conj sin cos tan - | not</td><td>Right</td></tr>
<tr><td>Binary</td><td>^ | * / % | + - | lt gt leq geq | eq neq | and | or xor</td><td>Left (except ^ which is Right)</td></tr>
<tr><td>Assignment</td><td>=</td><td>Right</td></tr>
</table>

3.4.2 Literals

Literals are integers, floats, complex numbers, and matrices, as well as the built-in constants of the language (e.g. pi). Integers are of type int, floats are of type float, complex numbers are of type comp, qubits and matrices are of type mat. The built-in constants have pre-determined types described above (e.g. pi is of type float).

The remaining major subsections of this section describe the groups of *expression* operators, while the minor subsections describe the individual operators within a group.

3.4.3 Primary Expressions

identifier

Identifiers are primary expression. All identifiers have an associated type that is given to them upon declaration (e.g. float *ident* declares an identifier named ident that is of type float).

literals

Literals are primary expression. They are described above.

(*expression*)

Parenthesized expressions are primary expressions. The type and value of a parenthesized expression is the same as the type and value of the expression without parenthesis. Parentheses allow expressions to be evaluated in a desired precedence. Parenthesized expressions are evaluated relative to each other starting with the expression that is nested the most deeply and ending with the expression that is nested the least deeply (i.e. the shallowest).

primary-expression(*expression-list*)

Primary expressions followed by a parenthesized expression list are primary expressions. Such primary expressions can be used in the declaration of functions or function calls. The expression list must consist of one or more expressions separated by commas. If being used in function declarations, they must be preceded by the correct function declaration syntax and each *expression* in the expression list must evaluate to a type followed by an identifier. If being used in function calls each *expression* in the expression list must evaluate to an identifier.

[*expression*-elementlist]

Expression element lists in brackets are primary expressions. Such primary expressions are used to define matrices and therefore are of type `mat`. The expression element list must consist of one or more expressions separated by commas or parenthsized. Commas separate expressions into matrix columns and parentheses group expressions into matrix rows. The expressions can be of type `int`, `float`, and `comp` and need not be identical. Additionally, the number of expressions in each row of the matrix must be the same. An example matrix is shown below.

```
int a = 3;
int b = 12;
mat my_matrix = [ (0+1, 2, a)( 5-1, 2*3-1, 12/2)];
```

<*expression*|

Expressions with a less than sign on the left and a bar on the right are primary expression. Such expressions are used to define qubits and therefore are of type `mat`. The notation is meant to mimic the "bra-" of "bra-ket" notation and can therefore be thought of as a row vector representation of the given qubit. Following "bra-ket" notation, the expression must evaluate to an integer literal of only 0's and 1's, which represents the state of the qubit. An example "bra-" qubit is shown below.

```
mat b_qubit = <0100|;
```

|*expression*>

Expressions with a bar on the left and a greater than sign on the right are primary expression. All of the considerations are the same as for <*expression*|, except that this notation mimics the "ket" of "bra-ket" notation and can therefore be though of as a column vector representation of the given qubit. An example "ket-" qubit is shown below.

```
int a = 001;
mat k_qubit = |a>;
```

3.4.4 Unary Operators

not *expression*

The result is a 1 or 0 indicating the logical not of the *expression*. The type of the expression must be int or float. In the *expressions*, 0 is considered false and all other values are considered true.

re *expression*

The result is the real component of the *expression*. The type of the expression must be comp. The result has the same type as the expression (it is a complex number with 0 imaginary component).

im *expression*

The result is the imaginary component of the *expression*. The type of the expression must be comp. The result has the same type as the expression (it is a complex number with 0 real component).

norm *expression*

The result is the norm of the *expression*. The type of the expression must be mat. The result has type float, and corresponds to the 2-norm; in the case of comp or float.

unit *expression*

The result is a 1 or 0 indicating whether the expression is a unit matrix. The type of the expression must be mat.

trans *expression*

The result is the transpose of the *expression*. The type of the expression must be mat. The result has the same type as the *expression*.

det *expression*

The result is the determinant of the *expression*. The type of the expression must be mat. The result has type comp.

adj *expression*

The result is the adjoint of the *expression*. The type of the expression must be mat. The result has the same type as the *expression*.

conj *expression*

The result is the complex conjugate of the *expression*. The type of the expression must be comp or mat. The result has the same type as the *expression*.

sin *expression*

The result is the evaluation of the trigonometric function sine on the *expression*. The type of the expression must be int, float, or comp. The result has type float if the expression is of type int or float and type comp if the expression is of type comp.

cos *expression*

The result is the evaluation of the trigonometric function cosine on the *expression*. The type of the expression must be int, float, or comp. The result has type float if the expression is of type int or float and type comp if the expression is of type comp.

tan *expression*

The result is the evaluation of the trigonometric function tangent on the *expression*. The type of the expression must be int, float, or comp. The result has type float if the expression is of type int or float and type comp if the expression is of type comp. (If an error occured because of a division by zero, a runtime exception is raised.)

3.4.5 Binary Operators

expression* ^ *expression

The result is the exponentiation of the first *expression* by the second *expression*. The types of the expression must be of type int, float, or comp. If the expressions are of the same type, the result has the same type as the *expressions*. Otherwise, if at least one *expression* is a comp, the result is of type comp; if neither expressions are comp, but at least one is float, the result is of type float.

expression* * *expression

The result is the product of the *expressions*. The type considerations are the same as they are for *expression* ^ *expression* except that it also allows for matrices.

expression* / *expression

The result is the quotient of the *expressions*, where the first *expression* is the dividend and the second is the divisor. The type considerations are the same as they are for *expression* ^ *expression*. Integer division is rounded towards 0 and truncated. (If an error occured because of a division by zero, a runtime exception is raised.)

expression* % *expression

The result is the remainder of the division of the *expressions*, where the first *expression* is the dividend and the second is the divisor. The sign of the dividend and the divisor are ignored, so the result returned is always the remainder of the absolute value (or module) of the dividend divided by the absolute value of the divisor. The type considerations are the same as they are for *expression*ˆ *expression*.

expression* + *expression

The result is the sum of the *expressions*. The types of the expressions must be of type int, float, comp, or mat. If at least one *expression* is a comp, the result is of type comp; if neither expressions are comp, but at least one is float, the result is of type float. Qubits and matrices are special and can only be summed with within operands of the same type (and, in the case of matrices, dimensions).

expression* - *expression

The result is the difference of the first and second *expression*. The type considerations are the same as they are for *expression* + *expression*.

expression* @ *expression

The result is the tensor product of the first and second *expressions*. The expressions must be of type of mat. The result has the same type as the *expression*.

expression* eq *expression

The result is a 1 or 0 indicating if it is true or false that the two *expression* are equivalent. The type of the expressions must either be the same, or one of the two should be implicitly convertible to the other type (e.g., 0.2 eq 1, where the right-hand side is an int that can be cast into a float).

expression* lt *expression

The result is a 1 or 0 indicating if it is true or false that the first *expression* is less than the second. The type of the expressions must be int or float.

expression* gt *expression

The result is a 1 or 0 indicating if it is true or false that the first *expression* is greater than the second. The type of the expressions must be int or float.

expression* leq *expression

The result is a 1 or 0 indicating if it is true or false that the first *expression* is less than or equal to the second. The type of the expressions must be int or float.

expression* geq *expression

The result is a 1 or 0 indicating if it is true or false that the first *expression* is greater than or equal to the second. The type of the expressions must be `int` or `float`.

expression* or *expression

The result is a 1 or 0 indicating the logical *or* of the *expressions*. The type of the expressions must be `int` or `float` and must be the same. In the *expressions*, 0 is considered `false` and all other values are considered `true`.

expression* and *expression

The result is a 1 or 0 indicating the logical *and* of the *expressions*. The type considerations are the same as they are for *expression* or *expression*.

expression* xor *expression

The result is a 1 or 0 indicating the logical *xor* of the *expressions*. The type considerations are the same as they are for *expression* or *expression*.

3.4.6 Assignment Operators

Assignment operators have left associativity

lvalue = *expression*

The result is the assignment of the expression to the lvalue. The lvalue must have been previously declared. The type of the expression must be of the same that the lvalue was declared as. Recall, lvalues can be declared as `int`, `float`, `comp`, and `mat`.

3.5 Declarations

Declarations are used within functions to specify how to interpret each identifier. Declarations have the form

declaration:
  type-specifier declarator-list

3.5.1 Type Specifiers

There are five main type specifiers:
type-specifier:

```
int
float
comp
mat
```

3.5.2 Declarator List

The declarator-list consist of either a single declarator, or a series of declarators separated by commas.

declarator-list:
    declarator
    declarator , declarator-list

A declarator refers to an object with a type determined by the type-specifier in the overall declaration. Declarators can have the following form

declarator:
    identifier
    declarator ( )
    (declarator)

3.5.3 Meaning of Declarators

Each declarator that appears in an expression is a call to create an object of the specified type. Each declarator has one identifier, and it is this identifier that is now associated with the created object.

If declarator D has the form

D ( )

then the contained identifier has the type "function" that is returning an object. This object has the type which the identifier would have had if the declarator had just been D.

Parentheses in declarators do not change the the type of contained identifier, but can affect the relations between the individual components of the declarator.

Not all possible combinations of the above syntax are permitted. There are certain restrictions such as how array of functions cannot be declared.

3.6 Statements

3.6.1 Expression statements

Expression statements are the building blocks of an executable program. As the name suggests, expression statements are nothing but expressions, delimited by semicolons. Expressions can actually be declarations, assignments, operations or even function calls. For example,

```
x = a + 3;
```

is a valid expression statement, and so is

```
print(a);
```

3.6.2 The if-else statement

The `if-else` statement is used for selectively executing statements based on some condition.Essentially, if the condition following the `if` keyword is satisfied, the specified statements get executed.To specify what happens if the condition does not evaluate to true, we have the `else` keyword. In case we want to evaluate more than one condition at a time, `if-else` can be nested.

```

  if( condition ){
  }
  else{
  }


Example:
 if ( x eq 5) {
    print(5);
 } else if (x eq 3) {
    print(3);
 } else {
    print(0);
 }
```

3.6.3 The for loop

The for statement is used for executing a set of statements a specified number of times. The statements within the for loop are executed as long as the value of the variable is within the specified range. As soon as the value goes out of range, control comes out of the for loop. To ensure termination, each iteration of the for loop increments/decrements the value of the variable, bringing it one step closer to the final value that is to be achieved.

By default, increment or decrement is by 1. However, if the desired increment is something other than one, the optional keyword by lets you specify that explicitly.

An example of for loop, increment by 2 is as follows:

```
  int k;
  for(  k from 1 to 10 by 2 ) {
  }
```

The two keywords break and continue can be used inside the body of the loop to respectively exit it prematurely, or skip to the next iteration.

3.6.4 The while loop

The while statement is used for executing a set of statements as long as a predicate (condition) is true. As soon as the predicate is no longer satisfied, control comes out of the while loop. An example of while loop is given below:

```
while(  k leq 100 ) {
  k = k^2;
}
```

The two keywords break and continue can be used inside the body of the loop to respectively exit it prematurely, or skip to the next iteration.

3.7 Scope rules

Name bindings have a block scope. That is to say, the scope of a name binding is limited to a section of code that is grouped together. That name can only be used to refer to associated entity in that block of code. Blocks of code in QLang are deliminated by the opening curly brace ('{') at the start of the block, and the closing curly brace ('}') at the end of the block.

Within a program, variables may be declared and/or defined in various places. The scope of each variable is different, depending on where it is declared.There are three primary scope rules.

If a variable is defined at the outset/outer block of a program, it is visible everywhere in the program.

If a variable is defined as a parameter to a function, or inside a function/block of code, it is visible only within that function.

Declarations made after a specific declaration are not visible to it, or to any declarations before it.

For instance, consider the following snippet.

```

int x = 5;

int y = x + 10;  # this works

int z = a + 100;  # this does not

int a = 200;
```

3.8 Constant expressions

In order to facilitate efficiency in writing expression, the language introduces various mathematical constants such as π , e and matrices such *Pauli* matrices and *Hadamard* matrices which are frequently used in quantum computation. The keywords *I, X, Y, Z, and H* are reserved for this expressions.

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \qquad Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}.$$

The *Hadamard gate* is defined by the matrix:

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.$$

3.9 Examples

We present some examples that illustrates the use of Qlang in solving quantum computing problems.

3.9.1 Solving Quantum Computation Problem

Problem1

Evaluate the following expressions: a. $(H \otimes X)|00\rangle$ b. $\langle 101|000\rangle$ c. $\langle 01|H \otimes H|01\rangle$

```
def compute() : mat evaluate (){
  mat a;
  a = |00>;
  evaluate = (H @ X) * a;
  printq(evaluate);

}
```

Problem 2

Consider the circuit and show the probabilities of outcome 0 where $|\Psi_{in}\rangle = |1\rangle$

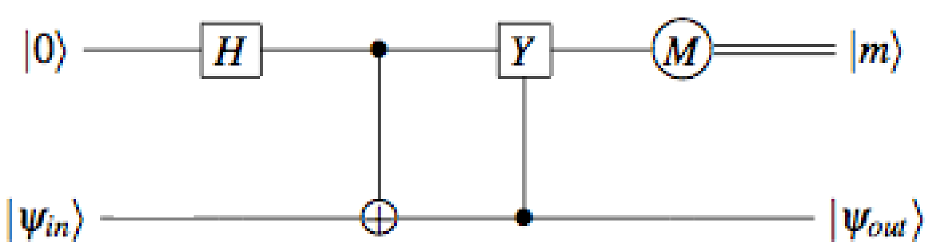


Figure 3.1: Quantum Circuit

```
def measure(mat top): mat outcome{
        mat ad;

        ad = adj(top);
        outcome = top*ad;
}

def outcomezero(mat bottom) : float probability{

        mat top; mat input;
        mat had; mat cnot; mat ynot;
```

```
        mat output;  mat meas;

        top = |0>;
        input = top @ bottom;

        had = H @ IDT;
        cnot = [(1,0,0,0)
                (0,1,0,0)
                (0,0,0,1)
                (0,0,1,0)];


        ynot = [(1,0,0,0)
                (0,0,0,-1)
                (0,0,1,0)
                (0,-1,0,0)];

        output = (ynot*(cnot*(had*input)));

        printq(output);

        probability = norm(output);

}

def compute() : float outcome{

        mat bottom;

        bottom = |1>;
        outcome = outcomezero(bottom);
        print(outcome);

}
```

Output

```
(0.707107)|10> + (-0.707107)|11>
1
```

3.9.2 Simulation of Quantum Algorithm

Deutsch Jozsa Algorithm

```
def measure (mat top) : mat outcome{
        # returns the measurement matrix for top qubit
        mat ad;

        ad = adj(top);
        outcome = top * ad;
}

def hadamard (int n) : mat gate{
        # returns Hadamard gate for n qubit system
        int i;
        gate = H;

        for (i from 0 to n-1 by 1){
```

```
            gate = gate @ H;
        }
}

def topqubit (int n) : mat input{
        #returns zero qubit for n qubit system
        int i;
        input = |0>;

        for (i from 0 to n-1 by 1){
                input = input @ |0>;
        }
}

def deutsch (int n, mat U) : float outcomeZero{
        # series of unitary transformation followed by measurement
        mat bottom; mat top; mat input;
        mat hadtop; mat meas;

        bottom = |1>;
        top = topqubit(n);
        input = top @ bottom;

        hadtop = hadamard(n);
        input = (hadtop @ H)*input;
        input = U * input;
        input = (hadtop @ IDT)*input;
        meas = measure(top);

        input = (meas @ IDT)* input;
        outcomeZero = norm(input);
}


def compute () : float outcome{

        int n; mat Ub; mat Uc;
        #test for n equals 1
        n = 1;
        # Ub is balanced, Uc is constant
        Ub = [(1,0,0,0)(0,1,0,0)(0,0,0,1)(0,0,1,0)];
        Uc = [(1,0,0,0)(0,1,0,0)(0,0,1,0)(0,0,0,1)];

        outcome = deutsch(n, Ub);
        print(outcome);

        outcome = deutsch(n, Uc);
        print(outcome);

        # test for n equals 2
        n = 2;
        Ub = [(1,0,0,0,0,0,0,0)
              (0,1,0,0,0,0,0,0)
              (0,0,1,0,0,0,0,0)
              (0,0,0,1,0,0,0,0)
              (0,0,0,0,0,1,0,0)
              (0,0,0,0,1,0,0,0)
              (0,0,0,0,0,0,0,1)
              (0,0,0,0,0,0,1,0)];

        outcome = deutsch(n, Ub);
}
```

Output

```
0
1
0
```

Grover's Search Algorithm

The following program implements special case of Grover's Search Algorithm for f(0) =1.

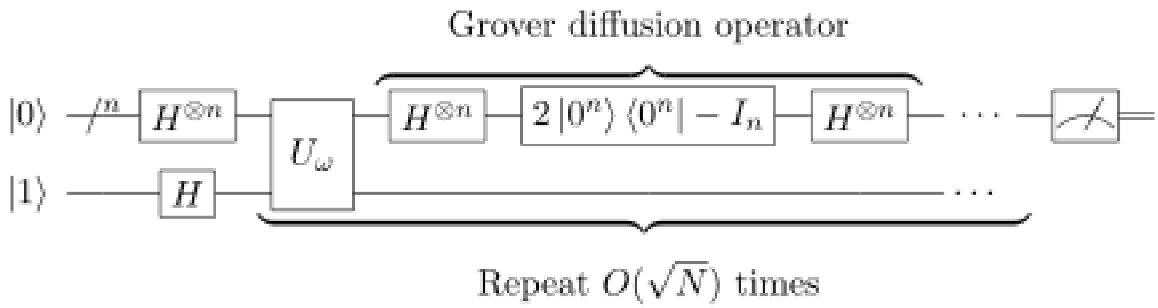


Figure 3.2: Grover Algorithm Circuit

```
def measure (mat top) : mat outcome{
        # measurement matrix for top qubit
        mat ad;

        ad = adj(top);
        outcome = top * ad;
}

def ntensor (int n, mat k) : mat gate{
        # return n qubit k
        int i;
        gate = k;

        for (i from 0 to n-1 by 1){
            gate = gate @ k;
        }
}

def prepareU (int n) : mat gate {
        # prepare the Uw or grover oracle
        mat i;
        mat u;

        i = [(1,0)
             (0,0)];

        u = ntensor(n+1, i);
        gate = ntensor(n+1,IDT)-2*u;
}

def prepareG (int n) : mat gate{
        # prepare grover defusive operator
```

```
        mat s; mat sa; mat i; mat h;

        s = ntensor(n,|0>);
        sa = adj(s);
        i = ntensor(n,IDT);
        gate = 2*s*sa - i;
        h = ntensor(n, H);
        gate = h*gate*h;
        gate = gate @ IDT;
}

def grover (int n) : float outcomeZero{

        mat bottom; mat top; mat input;
        mat hadtop; mat u; mat g; mat go; mat meas;
        int i;

        bottom = |1>;
        top = ntensor(n, |0>);
        input = top @ bottom;

        hadtop = ntensor(n, H);
        input = (hadtop @ H)*input;
        u = prepareU(n);
        g = prepareG(n);

        # grover operator
        go = g*u;

        # apply grover operator over iteration
        for (i from 0 to n by 1){
                input = go*input;
        }

        # measure on top qubit
        meas = measure(top);
        input = (meas @ IDT)* input;
        # likelihood to get 0 on top register
        outcomeZero = norm(input);
}


def compute () : float outcome{
        #simulate the grover for f(0)=1

        int n; mat Ub; mat Uc;
        n = 1;

        outcome = grover(n);
        print(outcome);

        n = 2;
        outcome = grover(n);
}
```

Output

```
0.707107
0.5
```

Chapter 4

Project Plan and Organization

The majority of our initial meetings consisted of creating a rough outline of how we envisioned our language. Much of the concept for the language was decided upon by Sankalpa, who was originally the one who suggested designing a quantum computing language. This strong foundation is what allowed us to create qlang.

4.1 Project Management

4.1.1 Planning

Throughout the semester we met regularly to keep everyone up to date on the overall progress of the project. Initially, it was twice a week after class for short meetings, but as the semester went on, we began to meet nearly everyday. At the end of every week, there was a short session reviewing what was accomplished that week, as well as our goals for the upcoming week.

4.1.2 Specification

Upon creation, the LRM was the manifestation of our vision. However, it was almost immediately upon submitting the LRM that we realized that there were some changes that had to be made. This was a common theme throughout the development process. Even though we had a set ideal of what we wanted, the specification of the implementation varied during the course of our work. However, constantly thinking about how certain things would affect, or be influenced by, the LRM caused us to think more critically about our code. Though our LRM changed during the project lifetime, QLang evolved as well.

4.1.3 Development

To ensure the group as a whole was able to coordinate their independent work, we used Git as a distributed version control system. Each team member worked on an individual feature. When they were satisfied that their section was working and had passed unit tests, it was pushed into the master branch. Once it was pushed, the other team members looked over the feature and made suggestions as well as pointed out any bugs that were missed. This iterative process was repeated the entire project.

4.1.4 Testing

We continuously performed unit tests throughout the development process. However, it was not until the end that we completed more rigorous acceptance testing. This was due to the continued evolution of our language as well as features. One constant throughout the project was a configurable test script that allowed us to complete the compilation process to a certain point. This allowed us to isolate tests for the individual parts of the compiler such as the AST or code generator.

4.2 Style Guide

The following coding guidelines were generally followed while coding:

- One statement per a line
- Each block of code following a "let" statement is indented
- Helper functions are written for commonly reused code

4.3 Project Timeline

Commits to master, excluding merge commits

The above graph shows the project timeline for the QLang compiler. It represents the number of commits over the course of the project, with a total of 397 commits. Work was generally centered around large project deadlines but slowing down near the end of the project as we were wrapping up.

4.4 Roles and Responsibilities

Christopher Campbell - System Architect (coded the greater part of the semantics)
Sankalpa Khadka - Language Guru (designed the majority of the features of our language)
Winnie Narang – Testing Verification and Validation (created the bulk of the test suite)
Jonathan Wong – Manager (built the QLang C++ library)
Cément Canonne - LaTex

4.5 Software Development Environment

The QLang project was built on a combination of OS X and Arch Linux platforms. As stated above, Git was used as a distributed version control system. The compiler itself was written using both vim and sublime. The project was done mostly in OCaml, but a QLang C++ library was created to augment the C++ Matrix library Eigen that is used for much of the linear algebra. Since our code was compiled to C++, g++ was used to compile the code into an executable. Lastly, Bash/shell scripts and makefiles were used to automate compilation and testing.

4.6 Project Log

Below is an excerpt from our git log in the format of "<YYYY-MM-DD>: <Author> - <Commit Message>".

```
2014-12-17: khadka - main
2014-12-17: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: Christopher Campbell - removed vestigial tokens
2014-12-17: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: khadka - main
2014-12-17: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: Winnie Narang - tex
2014-12-17: Christopher Campbell - lessons learned
2014-12-17: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: khadka - lessons learned
2014-12-17: Jonathan Wong - script to compile to execution file for single .ql file
2014-12-17: Jonathan Wong - cleaned up directory and minor change to Makefile
2014-12-17: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: Winnie Narang - main.tex
2014-12-17: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: khadka - demo2
2014-12-17: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: Winnie Narang - PPT
2014-12-17: khadka - grover
2014-12-17: Winnie Narang - merge
2014-12-17: khadka - grover
2014-12-17: khadka - lessions, examples
2014-12-17: khadka - revised tutorial and introduction
2014-12-17: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: khadka - demo 2 for probability
2014-12-17: khadka - demo 3 Deutsch
2014-12-17: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: Winnie Narang - tex files
2014-12-17: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-17: Christopher Campbell - negative numbers in floats and funcitons with no params working
2014-12-17: khadka - demo 1 added
2014-12-16: Jonathan Wong - fixed up rows/cols
2014-12-16: Jonathan Wong - added cpp compilation to Makefile in Compiler directory
2014-12-16: Jonathan Wong - just kidding didn't get rid of them all
2014-12-16: Jonathan Wong - got rid of extraneous ; in generator print
2014-12-16: Jonathan Wong - added compile cpp to runTest script
2014-12-16: Jonathan Wong - cleaned directory
2014-12-16: Jonathan Wong - fixed vectorToBraket
2014-12-16: Jonathan Wong - Added double endl to print
2014-12-16: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-16: Christopher Campbell - fixed qlang.hpp
2014-12-16: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-16: Christopher Campbell - should be fixed
2014-12-16: Winnie Narang - Removed conflict
2014-12-16: Winnie Narang - Merge
2014-12-16: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-16: Christopher Campbell - added break and continue
2014-12-16: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
```

```
2014-12-16: khadka - introduciton
2014-12-16: Winnie Narang - Formatted result in exec_output a little
2014-12-16: Winnie Narang - Comp n float matrix binop tests
2014-12-16: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-16: Christopher Campbell - more updates
2014-12-16: Christopher Campbell - more updates to presentation
2014-12-16: Christopher Campbell - more updates to presentation
2014-12-16: Christopher Campbell - more updates2
2014-12-16: Christopher Campbell - more updates
2014-12-16: Christopher Campbell - working on powerpoint2
2014-12-16: Christopher Campbell - working on powerpoint2
2014-12-16: Christopher Campbell - working on powerpoint
2014-12-16: Christopher Campbell - working on powerpoint
2014-12-16: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-15: Jonathan Wong - duplicate Eigen, fixed cpp makefile
2014-12-15: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - fixed tensor product
2014-12-14: khadka - merge
2014-12-14: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Winnie Narang - Better test for im,not and neg
2014-12-14: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - for some reason Eigen was deleted. Fixed vectorToBraket to
                                  handle float coefficients
2014-12-14: Winnie Narang - Fixup for assertion failed issue for determinant
2014-12-14: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Winnie Narang - Fixed adjoint
2014-12-14: Jonathan Wong - minor changes to norm test
2014-12-14: Jonathan Wong - minor change
2014-12-14: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Winnie Narang - Merge
2014-12-14: Jonathan Wong - added constants test
2014-12-14: Winnie Narang - All tests passing execution except for those with printq
2014-12-14: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Christopher Campbell - added rows, cols, and elem builtin funcs
2014-12-14: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - added some mat operators and qubit printing
2014-12-14: Winnie Narang - Fixed else if keyword bug in generator.ml
2014-12-14: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Christopher Campbell - updated test suite
2014-12-14: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - accidently removed if_stmt.ql
2014-12-14: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Christopher Campbell - updated test suite
2014-12-14: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - moved includes directory into Compiler dir, since that is
                                  the directory we are going to submit
2014-12-14: Christopher Campbell - analzyer
2014-12-14: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: khadka - chaning deutsch
2014-12-14: Jonathan Wong - minor changes to merge
2014-12-14: Christopher Campbell - updated test suite again
2014-12-14: Christopher Campbell - updated test suite
2014-12-14: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - fixed tests for norm and det to reflect them returning comp
2014-12-14: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-14: Christopher Campbell - fixed det
2014-12-14: Jonathan Wong - reorganized cpp directory and eigen lib. Added compilation to
                                  runTests.sh.
2014-12-14: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-14: Jonathan Wong - some modifications to qlang.cpp
```

```
2014-12-13: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-13: Winnie Narang - Refined failures folder and added powerpoint
2014-12-13: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-13: khadka - row and column
2014-12-13: Clement Canonne - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-13: Clement Canonne - LRM, changes to get it consistent with the language.
2014-12-13: Clement Canonne - LRM, changes to get it consistent with the language.
2014-12-13: Christopher Campbell - really fixed it this time
2014-12-13: Christopher Campbell - fixed comp comparisons
2014-12-12: Christopher Campbell - script updates
2014-12-12: Christopher Campbell - updated test script
2014-12-12: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-12: Christopher Campbell - updated test script to take folder param
2014-12-12: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-12: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-12: Christopher Campbell - syntax changes to analyzer
2014-12-12: Jonathan Wong - changed const I to IDT
2014-12-12: Winnie Narang - Refined failure test cases
2014-12-12: Christopher Campbell - run tests update
2014-12-12: Christopher Campbell - updated run tests
2014-12-12: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-12: Winnie Narang - Failure test cases refined
2014-12-12: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-12: Christopher Campbell - updated run tests script
2014-12-12: Jonathan Wong - fix to if else
2014-12-12: Jonathan Wong - Removed merge tokens from generator
2014-12-12: Clement Canonne - Including the previous LRM, roughly (un)modified for now.
2014-12-12: Clement Canonne - Tutorial: finished for now (i.e., not finished: DS algo and some
                                  others (?) still to add. Turning to the refence manual.
2015-12-12: Christopher Campbell - fixed by x in for loop'
2014-12-12: Clement Canonne - Added tests for while, for and if
2014-12-12: Clement Canonne - Tutorial: if, loops, etc
2014-12-12: Clement Canonne - Going through the tutorial: added basics
2014-12-12: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-12: khadka - parts by parts
2014-12-12: Clement Canonne - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-12: Clement Canonne - Fixing parsing errors.
2014-12-12: Christopher Campbell - changed norm, det, and equality/inequality analysis
2014-12-12: khadka - generator
2014-12-11: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-11: Winnie Narang - Added some meaningful failures
2014-12-11: Christopher Campbell - makefile for compiling our test output cpp
2014-12-11: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-11: Christopher Campbell - fixed mod
2014-12-11: Winnie Narang - generating outputs for qland programs complete
2014-12-11: Winnie Narang - Got cpp code compilation working in general
2014-12-11: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-11: Jonathan Wong - added multiple qubit functionality to qubitToString -> vectorToBraket
2014-12-11: khadka - small change in function call
2014-12-11: Winnie Narang - runTests.sh working
2014-12-11: Clement Canonne - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-11: Winnie Narang - Resolving merge issues
2014-12-11: Clement Canonne - Updated code for the tutotial, improved syntax for the code
                                  highlighting.
2014-12-11: Clement Canonne - Started fixing deutsch.ql, not valid yet (parsing errors)
2014-12-11: Winnie Narang - Updated runTests.sh
2014-12-11: Clement Canonne - Adding stuff to the tutorial. TODO: check the Deutsch algo .ql
                                  file in the tests, it seems to be buggy.
2014-12-11: Christopher Campbell - small updates
2014-12-11: Christopher Campbell - print working
2014-12-10: Christopher Campbell - working
```

```
2014-12-10: Christopher Campbell - updated
2014-12-10: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-10: Christopher Campbell - updated
2014-12-10: Winnie Narang - Cleaning up temp cpp and ql files
2014-12-10: Winnie Narang - Merge
2014-12-10: Winnie Narang - Updated testing
2014-12-10: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-10: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-10: Christopher Campbell - adding support for polymorphing print function
2014-12-10: khadka - print stuff
2014-12-10: Christopher Campbell - commit
2014-12-10: Christopher Campbell - removed qub
2014-12-10: khadka - print qubit
2014-12-10: Jonathan Wong - enforced 1 dimensionality of qubitToString
2014-12-10: khadka - test cases
2014-12-10: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-10: khadka - generator to handle print and equals
2014-12-10: Jonathan Wong - removed main from qlang.cpp
2014-12-10: Jonathan Wong - moved eigen lib into directory
2014-12-10: Jonathan Wong - added qubitToString to generate string representation (|> & <|) of
                            a qubit
2014-12-10: Clement Canonne - Tutorial
2014-12-10: Clement Canonne - Tutorial
2014-12-10: Clement Canonne - iAdd tutorial file.
2014-12-10: Clement Canonne - Add package for quantum circuits in Latex.
2014-12-10: Clement Canonne - Starting to add final report, first attempt (wip)
2014-12-10: Clement Canonne - Starting the first commit for the final report.
2014-12-10: Jonathan Wong - Fixed qlang.cpp so test1.cpp and test2.cpp compiles
2014-12-09: Christopher Campbell - trying to get test algorithms to work
2014-12-06: khadka - algorithms to test for
2014-12-06: Christopher Campbell - if else working
2014-12-06: Christopher Campbell - implemented if else
2014-12-06: Christopher Campbell - matricies and complex working
2014-12-05: Christopher Campbell - fixed matricies
2014-12-05: Christopher Campbell - blah
2014-12-05: khadka - gen
2014-12-05: khadka - function call defined
2014-12-05: khadka - mat defination changed
2014-12-05: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-05: khadka - print statement and qlc file output
2014-12-05: Christopher Campbell - reading this?
2014-12-05: khadka - additional test cases
2014-12-05: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-05: Christopher Campbell - still no one reading this
2014-12-05: Christopher Campbell - no one is reading this
2014-12-05: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-05: Christopher Campbell - you suck more
2014-12-05: Christopher Campbell - you suck
2014-12-05: khadka - damn
2014-12-05: khadka - qubit def
2014-12-05: Christopher Campbell - fixed qubits
2014-12-05: Christopher Campbell - fixed qubits
2014-12-05: khadka - new qub
2014-12-05: Christopher Campbell - updated
2014-12-04: Jonathan Wong - changed all matrix gen to matrixXcf
2014-12-03: Jonathan Wong - midfix of cpp qubit
2014-12-03: Jonathan Wong - code gen qubit bra ket functionality
2014-12-03: Jonathan Wong - attempt to add qubit func
2014-12-03: Christopher Campbell - started final report document
2014-12-03: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-03: Christopher Campbell - fixed qubit and return variable issue with analyzer
```

```
2014-12-03: khadka - working generator
2014-12-03: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-03: khadka - merge conflict resolution
2014-12-03: Winnie Narang - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-03: Winnie Narang - Semantic checks error output formatted
2014-12-03: Jonathan Wong - Fixed semicolons and added initializer for return
2014-12-03: Winnie Narang - Test Script and few cases
2014-12-03: Christopher Campbell - remove test.sh
2014-12-03: Christopher Campbell - fixed weird matrix output issue
2014-12-03: khadka - test2
2014-12-03: khadka - example test1
2014-12-03: khadka - working qlc.ml
2014-12-03: khadka - almost complete code generator; works
2014-12-03: khadka - working qlc
2014-12-03: khadka - working code generator with fixes
2014-12-03: khadka - changes in test1.ql
2014-12-03: khadka - working qlc with entire pipeline
2014-12-03: khadka - Working makefile with all the requirements
2014-12-02: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-02: Christopher Campbell - implemented matrix checking with the analyzer and printing
                                  with the ast and sast pretty printer
2014-12-02: Winnie Narang - semantic testing; not working yet
2014-12-02: Jonathan Wong - updated generator
2014-12-02: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-02: Christopher Campbell - analyzer is working. also made changes to qubits across all
                                  files that may affect your work. please review them and we
                                  can talk about it
2014-12-01: Jonathan Wong - removed extraneous headers
2014-12-01: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-01: Jonathan Wong - Some minor fixes
2014-12-01: khadka - vardecl
2014-12-01: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-01: khadka - vardecl
2014-12-01: Jonathan Wong - Added return variable initializer
2014-12-01: khadka - vardecl
2014-12-01: Winnie Narang - Merged
2014-12-01: Winnie Narang - Call
2014-12-01: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-12-01: Jonathan Wong - writeQubit and changes to header
2014-12-01: Jonathan Wong - Consolidated qlang.h and constants.h into one file
2014-12-01: khadka - merging
2014-12-01: khadka - writeMatrix included
2014-12-01: Winnie Narang - Lit_comp
2014-12-01: Winnie Narang - cppExpr
2014-12-01: Jonathan Wong - Finished writeUnop
2014-12-01: Christopher Campbell - removing uncessary comments now that we have a better
                                  understanding of how everything works
2014-12-01: Christopher Campbell - analyzer compiles, but not complete and not tested
2014-12-01: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-12-01: Christopher Campbell - big progress on analyzer, but still not compiling
2014-11-30: khadka - more generator
2014-11-30: Jonathan Wong - Added cpp directory with qubit gen
2014-11-30: Winnie Narang - Working on Unop
2014-11-30: Winnie Narang - Worked on cppExpr
2014-11-30: Winnie Narang - Fixed cppStmt
2014-11-30: Jonathan Wong - Merged conflicts, includes most of the controlflow
2014-11-30: Jonathan Wong - Initial merge
2014-11-30: Winnie Narang - Merged While and For
2014-11-30: Winnie Narang - generator - added codegen skeleton for while
2014-11-30: khadka - conflict solved
2014-11-30: khadka - sast with updated statements
```

```
2014-11-30: khadka - changes with generator
2014-11-30: khadka - qlc with generator
2014-11-30: khadka - additional generator.ml
2014-11-30: Jonathan Wong - start writeIfStmt in code gen
2014-11-30: Jonathan Wong - Fixed minor typing mistakes
2014-11-30: khadka - code generator starting point
2014-11-30: Christopher Campbell - more updates...
2014-11-29: Christopher Campbell - more updates to analyzer
2014-11-29: Christopher Campbell - cleaned up analyzer
2014-11-29: Christopher Campbell - sast is back
2014-11-29: Christopher Campbell - updates to analyzer
2014-11-26: Christopher Campbell - successfully able to parse full programs
2014-11-26: Christopher Campbell - got statement lists working, program will be next
2014-11-26: Christopher Campbell - getting further along withe testing
2014-11-26: Christopher Campbell - compile script
2014-11-26: Christopher Campbell - basic testing
2014-11-26: Christopher Campbell - small changes
2014-11-26: Christopher Campbell - merged
2014-11-26: Christopher Campbell - updates to analyzer
2014-11-23: Winnie Narang - Merge with exampleCPP
2014-11-23: Winnie Narang - Pretty printing working...
2014-11-23: Jonathan Wong - Made initial fixes to grover search
2014-11-23: Jonathan Wong - Added control, updated problems, more examples
2014-11-23: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-11-23: Jonathan Wong - Updated examples. Created constants and tensorProd
2014-11-23: khadka - test1 program
2014-11-23: Jonathan Wong - Fixed example 3
2014-11-23: Jonathan Wong - Possible fix to example 3
2014-11-23: Jonathan Wong - Made initial changes to LRM based on TA feedback
2014-11-22: Christopher Campbell - small change
2014-11-22: Christopher Campbell - added more to ananalyzer, but I know it's not compiling
                                  right now so don't even try
2014-11-20: Christopher Campbell - updated analyzer
2014-11-20: Christopher Campbell - completed unop and binop checks for analyzer nad made
                                  small changes to the other files
2014-11-19: Christopher Campbell - still working on analyzer
2014-11-19: Christopher Campbell - merging
2014-11-19: Christopher Campbell - working analyzer - far from done
2014-11-19: khadka - a first working sast
2014-11-19: khadka - included sast.mli in make
2014-11-19: Jonathan Wong - Added C++ code for examples in LRM. Prob 3 broken
2014-11-17: Winnie Narang - Pretty printer for AST added, not compete yet
2014-11-16: Christopher Campbell - added files for sast, analyzer, and compiler
2014-11-16: Christopher Campbell - fixed shift/reduce conflicts for our 'for' statements
                                  and complex numbers ; '
2014-11-12: Christopher Campbell - added project examples
2014-11-10: Christopher Campbell - finished ast, parse, and scanner for the most part, but
                                  need to be carefully reviewed and tested
2014-11-09: Christopher Campbell - updated ast, parser, and scanner
2014-11-09: Christopher Campbell - updated ast and parser
2014-11-09: Christopher Campbell - updated ast and parser
2014-11-09: Christopher Campbell - updated scanner
2014-11-09: Christopher Campbell - updated ast and parser
2014-11-04: Christopher Campbell - Updated Ast and scanner
2014-11-04: khadka - new tokens added
2014-11-04: khadka - fix merge conflicts
2014-11-04: khadka - updated with all the token from the scanner
2014-11-04: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-11-04: Christopher Campbell - Finished AST, although it will almost certainly need
                                  revision
2014-11-04: Jonathan Wong - Added some tokens to parser
```

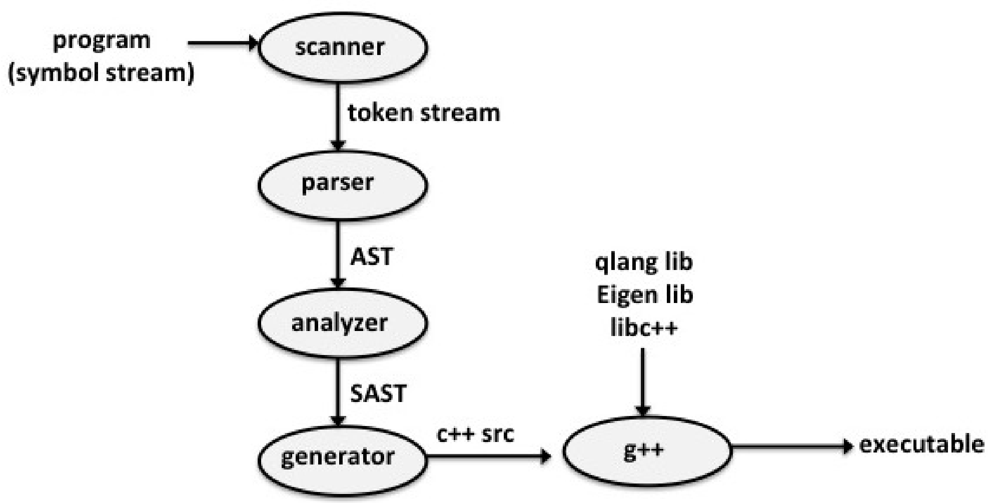
```
2014-10-27: khadka - build main.pdf
2014-10-27: Jonathan Wong - turned off colour and notes in main.tex
2014-10-27: Jonathan Wong - redo scope commit
2014-10-27: khadka - examples
2014-10-27: Winnie Narang - Refined Statements and Scope
2014-10-27: Winnie Narang - Added statements and scope rules
2014-10-27: Jonathan Wong - Fixed rolled back changes in sec-declarations
2014-10-27: Clement Canonne - Added matrix and array access [i] and [i,j]
2014-10-27: Clement Canonne - Changes (fixed inconsistencies and types; added valid types and
                              conversions).
2014-10-27: Clement Canonne - Added files for new sections.
2014-10-27: Clement Canonne - Second round of change: fixed some inconsistencies.
2014-10-27: Clement Canonne - First round of changes: (lexical conventions updated soon).
2014-10-26: khadka - main
2014-10-26: khadka - grover circuit
2014-10-26: khadka - new examples
2014-10-26: Christopher Campbell - Finished sec-expressions.text
2014-10-26: Jonathan Wong - Merge https://github.com/thejonathanwong/PLT
2014-10-26: khadka - main
2014-10-26: Jonathan Wong - Fixed sec-declarations.tex
2014-10-26: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-26: khadka - main
2014-10-26: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-26: Christopher Campbell - Updating sec-expressions.tex
2014-10-26: khadka - troubleshooting
2014-10-26: khadka - updated examples
2014-10-26: khadka -  section on constant expressions
2014-10-26: khadka -  main with updated sections
2014-10-26: Christopher Campbell - Added sec-expressions-table.tex
2014-10-26: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-26: Christopher Campbell - Fixed formatting and compile issues with sec-declarations.tex
2014-10-26: khadka - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-26: khadka - section for examples
2014-10-26: khadka - just the main
2014-10-26: thejonathanwong - Added declarations section
2014-10-26: khadka - new section for constant expressions
2014-10-26: khadka - new package for graphics
2014-10-26: khadka - new section examples
2014-10-26: khadka - images
2014-10-26: khadka - updated packages with listling for code formatting
2014-10-26: khadka - example section
2014-10-24: Christopher Campbell - Completed a large part of 'expressions' section and small
                              changes other places
2014-10-20: Christopher Campbell - Made small changes to the scanner and added package and
                              preamble files
2014-10-15: Clement Canonne - Filled section 2.
2014-10-15: Clement Canonne - Filled lexical conventions, added packages and preamble files.
2014-10-15: Clement Canonne - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-15: Clement Canonne - (latest changes)
2014-10-14: Christopher Campbell - Completed most of the scanner
2014-10-13: Christopher Campbell - added . to symbols
2014-10-13: Christopher Campbell - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-13: Christopher Campbell - Started scanner
2014-10-13: Clement Canonne - It goes on: started filling the reference manual, added a file for
                              the keywords.
2014-10-13: Clement Canonne - Merge branch 'master' of https://github.com/thejonathanwong/PLT
2014-10-13: Clement Canonne - First push: baby reference manual, take #1.
2014-10-13: Christopher Campbell - Added folder and documents for our compiler
2014-10-13: Christopher Campbell - Adding microc to resources
2014-10-13: khadka - starter for langauge referece manual
2014-10-13: Sankalpa Khadka - starter ast
```

```
2014-10-12: khadka - Project proposal
2014-09-30: Christopher Campbell - Adding a Resources folder. It already contains two quantum
                                   computing resources that are pretty helpful.
2014-09-29: thejonathanwong - Initial commit
```

Chapter 5

Architectural Design

5.0.1 Block Diagram



5.0.2 Components

1. Scanner

   The scanner was implemented using ocamellex - the associated file is scanner.mll. It was chiefly implemented by Christopher Campbell and Winnie Narang.

   The scanner takes a program (symbol stream) as input and tokenizes it to produce a token stream. The tokenization process provides basic syntax checking, rejecting programs that contain illegal symbols and illegal combinations of symbols (e.g. the $ symbol). Additionally, it discards information that is unnecessary for the remainder of the compilation process such as white space and comments.

2. Parser & Abstract Syntax Tree

The parser was implemented using ocamlyacc - the associated files are ast.ml and parser.mly. It was chiefly implemented by Christopher Campbell and Sankalpa Khadka.

The parser takes the token stream produced by the scanner as input and parses it to produce an abstract syntax tree (AST), which describes the overall structure of the program. ast.ml provides parser.mly with the acceptable structure of the AST. The parsing process provides further syntax checking, rejecting programs that do not strictly meet the syntactic requirements of the AST (e.g. a malformed for statement).

3. Analyzer & Semantically Analyzed Syntax Tree

   The analzyer was implemented in OCaml - the associated files are analyzer.ml and sast.ml. Additionally, analyzer.ml utilizes ast.ml in order to be able to analyze its input. It was chiefly implemented by Christopher Campbell.

   The analyzer takes the ast produced by the parser and analyzes it to produce a semantically analyzed abstract syntax tree (SAST). Like the AST, the SAST describes the overall structure of the program, but it also includes type information that was attached during the analysis process. sast.ml provides analyzer.ml with the acceptable structure of the SAST. The analysis process provides rigorous semantic checking, rejecting programs that violate type requirements (e.g. assigning a complex number to a variable declared as an integer), declaration requirements (e.g. using a variable that was not declared or attempting to declare a variable more than once), scope requirements (e.g. using a variable declared in another function), order requirements (e.g. calling a function before it is declared), and other language-specific requirements (e.g. not declaring a compute function). Additionally, the analyzer adds built-in information (i.e. built-in variables and functions) to the sast.

4. Generator

   The generator was implemented in OCaml - the associated file is generator.ml. Additionally, generator.ml utilizes sast.ml in order to be able to process its input. It was chiefly implemented by Sankalpa Khadka, Jonathan Wong, and Winnie Narang.

   The generator takes the sast produced by the analyzer and generates c++ code from it. Most of the code it generates is hard coded into generator.ml, but but it also draws on code from our standard library - qlanglib, libc++, and Eigen (a third-party library).

5. QLang Library

   The QLang Library was implemented in c++ - the associated files are qlang.hpp and qlang.cpp. It was chiefly implemented by Jonathan Wong. The QLang library contains c++ code for carrying out some of the more complex conversions from qlang code to c++ code in the generator (e.g. generating qubits and carrying out the tensor product).

Chapter 6

Test Plan

6.1 Testing Phases

6.1.1 Unit Testing

Unit testing was done at very point essentially, as we were in the coding phase. Every building block was tested rigorously using multiple cases. We tested for recognition of dataypes, variables , expression statements and functions initially, and then moved on to AST generation.

6.1.2 Integration Testing

In this phase,the various modules were put together and tested incrementally again. So once the AST could be generated, we moved on to test the semantic analysis and code generation.

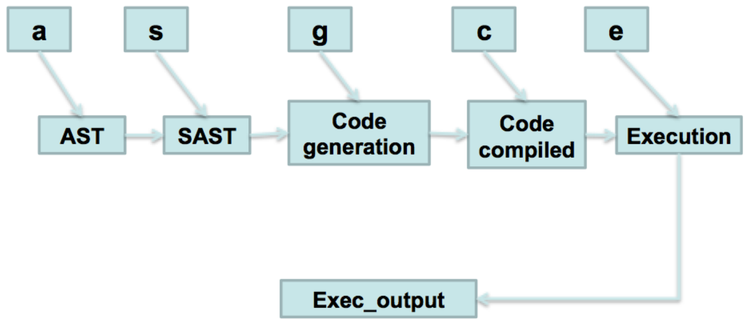
6.1.3 System Testing

System testing entailed end to end testing of our entire language framework. The input program written in QLang is fed to the compiler and it gives out the final output of the program, having passed through the parsing, scanning, compiling, code generation and execution phases. The final results were piped to an output file where we could see all the outputs.

6.2 Automation and Implementation

A shell script was written in order to automate the test cases at each level, syntax, semantic, code generation and accurate execution. Our file is called runTests.sh, located in the 'test' folder. It takes a folder having QLang program files, and the operation to be done on them as arguments. The outputs of the respective operation can be seen in the corresponding output file.

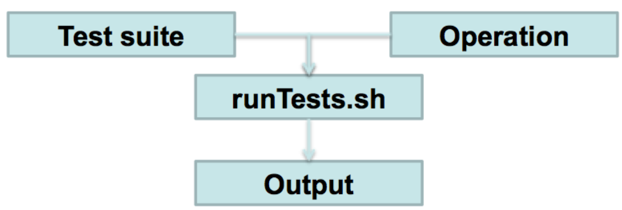
The operation options available are :
a : Parsing, scanning and AST generation.
s : SAST generation.
g : Code generation.
c : Generated code is compiled.
e : Generated executable is run, to generate the program's outputs.



The operations mentioned above are each inclusive of the operations mentioned above them. That means, if you enter the 'g' option, runTests.sh will perform the tasks under 'a','s' and then the operations specific to 'g' as well.

The second argument is the folder that has the input program files. We have acronyms for two folder that are standard to our implementation, the SemanticSuccess and the SemanticFailures. So to run the sast generation on the files in SemanticSuccess folder, we would write :

```
sh runTests.sh s ss.
```



The entire code of this script can be seen in the appendix. The Test Suites were chiefly created by Winnie Narang, and everyone else also contributed test cases. The script runTests.sh was created by Winnie Narang and Christopher Campbell.

6.3 Sample test programs

The effort has been to exhaustively test every kind of execution scenario, in what can be a typical user program. We have created many test files to showcase varied kinds of programs that can be written in QLang, as can be seen in the contents of the SemanticSuccess and SemanticFailures folders.

The rationale is to make sure that syntactically or semantically incorrect programs are not compiled and echo corresponding meaningful error messages to the user, and that correct programs are accepted and executed correctly.

Hence, we have separate test programs to test all kinds of unary and binary operations on all datatypes that our language supports, and also for all kinds of statements and possible combinations of expressions. Though the test suite is too large to be included in this section, here are a few sample success and failure cases that showcase different applications of our language :

For instance, break_continue.ql is a QLang program as follows :

```
def func_test(int a) : int ret_name {

        int i;

        for(i from 0 to 2 by 1)
        a=a+5;

        for(i from 2 to 0 by -1)
        {
            a=a*10;
            print(a);
            break;
        }

        for(i from 1 to 5)
        {
            print(a);
            continue;
            a=a*10;

        }

    ret_name = a;
}

def compute(): int trial {

   trial = func_test(20);
}
```

It generates break_continue.cpp as below upon passing it through the code generation code

```
#include <iostream>
#include <complex>
#include <cmath>
#include <Eigen/Dense>
#include <qlang>
using namespace Eigen;
using namespace std;

int func_test (int a )
{
  int i;
  int ret_name;


    for (int i = 0; i < 2; i = i + 1){
          a = a + 5;

        }
    for (int i = 2; i < 0; i = i +   -1){

  {
  a = a * 10;

  cout << a << endl;

break;
  }
```

```
        }
    for (int i = 1; i < 5; i = i + 1){

  {
  cout << a << endl;

continue;
  a = a * 10;

  }

        } ret_name = a;

  return ret_name;
}
int main ()
{
  int trial;

  trial = func_test(20);

  std::cout << trial << endl;

  return 0;
}
```

and the generated output of this is :

```
30
30
30
30
30
```

Another example we consider is mat_qubit.ql

```
def func_test(mat a, mat b) : mat ret_name {

        ret_name = a*b;

}


def compute(int a):mat trial {

   mat zero;
   mat one;

   zero = |0>;
   one  = |1>;

     trial = func_test(H,zero);
     printq(trial);

     trial = func_test(H,one);
     printq(trial);

}
```

It generates mat_qubit.cpp as below :

```
#include <iostream>
#include <complex>
#include <cmath>
#include <Eigen/Dense>
#include <qlang>
using namespace Eigen;
using namespace std;

MatrixXcf func_test (MatrixXcf a,MatrixXcf b )
{
  MatrixXcf ret_name;

  ret_name = a * b;

  return ret_name;
}
int main ()
{
  MatrixXcf zero;
  MatrixXcf one;
  MatrixXcf trial;

  zero = genQubit("0",0);
  one = genQubit("1",0);
  trial = func_test(H,zero);
  cout << vectorToBraket(trial) << endl;
  trial = func_test(H,one);
  cout << vectorToBraket(trial) << endl;

  std::cout << trial << endl;

  return 0;
}
```

and it generates the qubits in the output as well, like :

```
(0.707107)|0> + (0.707107)|1>
(0.707107)|0> + (-0.707107)|1>
(0.707107,0)
(-0.707107,0)
```

One more program we can show here is a demonstration of the capacity of QLang to emulate Quantum algorithms. The following program runs the Deutsch-Jozsa algorithm.

```
def measure (mat top) : mat outcome{

        mat ad;

        ad = adj(top);
        outcome = top * ad;
}

def hadamard (int n) : mat gate{

        int i;
        gate = H;

        for (i from 0 to n-1 by 1){
```

```
            gate = gate @ H;
        }
}

def topqubit (int n) : mat input{

        int i;
        input = |0>;

        for (i from 0 to n-1 by 1){
                input = input @ |0>;
        }
}

def deutsch (int n, mat U) : float outcomeZero{

        mat bottom; mat top; mat input;
        mat hadtop; mat meas;

        bottom = |1>;
        top = topqubit(n);
        input = top @ bottom;

        hadtop = hadamard(n);
        input = (hadtop @ H)*input;
        input = U * input;
        input = (hadtop @ IDT)*input;
        meas = measure(top);

        input = (meas @ IDT)* input;
        outcomeZero = norm(input);
}


def compute () : float outcome{

        int n; mat Ub; mat Uc;

        n = 1;
        Ub = [(1,0,0,0)(0,1,0,0)(0,0,0,1)(0,0,1,0)];
        Uc = [(1,0,0,0)(0,1,0,0)(0,0,1,0)(0,0,0,1)];

        outcome = deutsch(n, Ub);
        print(outcome);

        outcome = deutsch(n, Uc);
        print(outcome);

        n = 2;
        Ub = [(1,0,0,0,0,0,0,0)
              (0,1,0,0,0,0,0,0)
              (0,0,1,0,0,0,0,0)
              (0,0,0,1,0,0,0,0)
              (0,0,0,0,0,1,0,0)
              (0,0,0,0,1,0,0,0)
              (0,0,0,0,0,0,0,1)
              (0,0,0,0,0,0,1,0)];

        outcome = deutsch(n, Ub);
}
```

It creates the C++ code as follows :

```
#include <iostream>
#include <complex>
#include <cmath>
#include <Eigen/Dense>
#include <qlang>
using namespace Eigen;
using namespace std;

MatrixXcf measure (MatrixXcf top )
{
  MatrixXcf ad;
  MatrixXcf outcome;

  ad =   top.adjoint();
  outcome = top * ad;

  return outcome;
}
MatrixXcf hadamard (int n )
{
  int i;
  MatrixXcf gate;

  gate = H;

    for (int i = 0; i < n - 1; i = i + 1){

  {
  gate = tensor(gate, H);

  }

        }
  return gate;
}
MatrixXcf topqubit (int n )
{
  int i;
  MatrixXcf input;

  input = genQubit("0",0);

    for (int i = 0; i < n - 1; i = i + 1){

  {
  input = tensor(input, genQubit("0",0));

  }

        }
  return input;
}
float deutsch (int n,MatrixXcf U )
{
  MatrixXcf bottom;
  MatrixXcf top;
  MatrixXcf input;
  MatrixXcf hadtop;
  MatrixXcf meas;
  float outcomeZero;

  bottom = genQubit("1",0);
  top = topqubit(n);
  input = tensor(top, bottom);
```

```
  hadtop = hadamard(n);
  input = tensor(hadtop, H) * input;
  input = U * input;
  input = tensor(hadtop, IDT) * input;
  meas = measure(top);
  input = tensor(meas, IDT) * input;
  outcomeZero =   input.norm();

  return outcomeZero;
}
int main ()
{
  int n;
  MatrixXcf Ub;
  MatrixXcf Uc;
  float outcome;

  n = 1;
  Ub = (Matrix<complex<float>, Dynamic, Dynamic>(4,4) <<1,0,0,0,0,1,0,0,0,0,0,1,0,0,1,0).
    finished();
  Uc = (Matrix<complex<float>, Dynamic, Dynamic>(4,4) <<1,0,0,0,0,1,0,0,0,0,1,0,0,0,0,1).
    finished();
  outcome = deutsch(n,Ub);
  cout << outcome << endl << endl;
  outcome = deutsch(n,Uc);
  cout << outcome << endl << endl;
  n = 2;
  Ub = (Matrix<complex<float>, Dynamic, Dynamic> (8,8)
    <<1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,

  .finished();
  outcome = deutsch(n,Ub);

  std::cout << outcome << endl;

  return 0;
}
```

The output of this exceution is :

```
0

1

0
```

Following programs show the ability of the semantic analyzer to catch incorrect programs. For instance, the program:

```
def func_test1(int z) : int ret_name {
        int a;
        int b;
        int d;
        a = z;
        ret_name = z;

}
def func_test1(int z) : int ret_name2 {

        ret_name2 = z;
```

```
}
def compute( int a):int trial {

        trial = func_test1(4);
}
```

gives the error :

```
Fatal error: exception Analyzer.Except("Invalid function declaration: func_test1 was already
    declared")
```

whereas the sample program

```
def func_test(float z) : float ret_name {

        float a;
        a = 5.8;

        ret_name = z;
}
```

would give the error :

```
Fatal error: exception Analyzer.Except("Missing 'compute' function")
```

More such pass and fail test cases can be found in the appendix and in our project folder.

Chapter 7

Lesson Learned

7.1 Christopher Champbell

I learned many lessons from this project, most of which were related to group dynamics. I learned that, depending on how they are managed and leveraged, every group member's differences (i.e. differences in ideas, opinions, abilities, etc.) can either be beneficial or detrimental to the group and the project. In order to effectively leverage differences in opinion, all group member's opinions should be heard and considered by the group, and if a clear winner does not emerge the leader for that part of the project should make a decisive decision. This situation highlights another aspect of group dynamics that I learned - leaders are important. In order to keep the different parts of the project focused and progressing, each part should have a group member that leads its development. Leading the development of a part of the project entails having expertise in the associated domain, resolving tough issues and questions with it, and driving its development from beginning to end.In addition to the lessons I learned involving group dynamics, I also learned lessons, and re-learned lessons that I should have already known, that apply to project work in general. Among these lessons learned were: start early and manager your time well, thoroughly research ideas before you begin implementing them, and maintain a big picture view of the project.

7.2 Sankalpa Khadka

I realized that one of the important aspects of doing a big project is to make incremental progress, however small, over time. In the beginning, it is not always possible to have a global view of how each component of project fits in together. This can be discouraging factor at times, however this should not deter anyone from building the components of the project. Teamwork is very crucial to the success of the project. From the very beginning of the project, it is important to delegate responsibilities and making sure that each member of team is contributing to the project. Any disruption to this can affect the work balance.

Finally, it is a very fulfilling experience to design a programming language from CS perspective. This experience draws from both theory and application aspect of CS. Everyone doing similar projects in future should try to participate, contribute and enjoy the process.

7.3 Winnie Narang

I learned that one should always work while keeping in the mind the shape of the end result. That helps in making sure your efforts are not wasted, and helps you make decisions more easily. Also, start early. And always test every change as you go. If you code everything at once and then it doesn't work, it gets very hard to debug.

Also, since we were using git as our version control system, we had to deal with numerous merge conflicts. So I learnt that one should keep committing changes, as you code as soon as you can be sure however much you have written is correct, no matter how small the change. this helps makes sure you are not causing any faults or conflicts for the other team members and also for you as an individual.

7.4 Jonathan Wong

At the start of the semester, the task of creating a new programming language seemed to be an impossibility. However, over the course of the semester, I learned and a gained an appreciation for the amount of work and though that goes into the creation of languages.

I have learned that communication is key. Without our regular meetings, I would have been floundering whenever I was off working independently. It is necessary to have a clear picture of what is needed to be done everytime you sit down to work on the project. Effective communication also allowed us to flesh out the gritty details of the language. What could have been improved is how quickly a concensus on specifics could be reached. It would have been better to have one person decide on these things and work could have been started immediatedly.

I know this is probably a common sentiment, but starting this project early is key. We did not really start pushing until the start of November. Ideally, once we covered the lectures on the structure of the compiler we should have hit the ground running. I have also learned that even though git can be great at what it does, improper use of it can lead to a great deal of frustration if one pushes bad code, or someone else deletes good working code.

Appendix A

More on Quantum Computing

A.1 Common quantum gates

Pauli Operators

The *Pauli operators* are the special single qubit gates which are represented by the Pauli matrices $\{I, X, Y, Z\}$ as follows

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \qquad Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}.$$

For example, the application of X causes bit-flip in following ways:

$$X|0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle$$

$$X|1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle.$$

Hadamard Gate

The *Hadamard gate* is defined by the matrix:

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.$$

The Hadamard gate maps the computational basis states into superposition of states. The Hadamard gate is significant since it produces maximally entangled states from basis states in the following ways:

$$H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle).$$

Controlled-U Gates

A *controlled-U gate* is the quantum gate in which the U operator acts on the n^{th} n-qubit only if the value of the preceeding qubit is 1.
For example: In a Controlled-NOT gate, the NOT operator flips the second qubit if the first qubit is 1.

$$\mathsf{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\mathsf{CNOT}|00\rangle = |00\rangle$$
$$\mathsf{CNOT}|01\rangle = |01\rangle$$
$$\mathsf{CNOT}|10\rangle = |11\rangle$$
$$\mathsf{CNOT}|11\rangle = |10\rangle.$$

A.2 Tensor product and its properties

Let $A = (a_{i,j})$ be a matrix with respect to the ordered basis $\mathcal{A} = (u_1, \ldots, u_n)$ and $B = (b_{i,j})$ be a matrix with respect to the ordered basis $\mathcal{B} = (v_1, \ldots, v_m)$. Consider the ordered basis $\mathcal{C} = (u_i \otimes v_j)$ ordered by lexicographic order, that is $u_i \otimes v_j \leq u_l \otimes v_k$ if if $i < l$ or $i = l$ and $j < k$. The matrix of $A \otimes B$ with respect to $\mathcal{C}$ is :

$$A \otimes B = \begin{bmatrix} a_{1,1}B & a_{1,2}B & \ldots & a_{1,n}B \\ a_{2,1}B & a_{2,2}B & \ldots & a_{2,n}B \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1}B & a_{n,2}B & \ldots & a_{n,n}B \end{bmatrix}$$

This matrix is called the tensor product of the matrix A with the matrix B.

- $A \otimes B \otimes C = (A \otimes B) \otimes C = A \otimes (B \otimes C)$
- $a(|x\rangle \otimes |y\rangle) = a|x\rangle \otimes |y\rangle = |x\rangle \otimes a|y\rangle$
- $(A \otimes B) \cdot (|y\rangle|z\rangle) = A|y\rangle \otimes B|z\rangle$
- $(A \otimes B) \cdot (C \otimes D) = AC \otimes BD$
- $(A \otimes B)^H = A^H \otimes B^H$
- If A and B unitary, $A \otimes B$ is unitary.
- If $|x\rangle = |x_1\rangle|x_2\rangle$ and $|y\rangle = |y_1\rangle|y_2\rangle$ then $\langle x|y\rangle = \langle x_1|y_1\rangle\langle x_2|y_2\rangle$

Appendix B

Source Code

B.1 Scanner

scanner.mll

```
(* Christopher Campbell, Winnie Narang*)
{ open Parser }

let whitespace = [' ' '\t' '\r' '\n']
let name = ['a'-'z' 'A'-'Z'] ['a'-'z' 'A'-'Z' '0'-'9' '_']*
let integers = ['0'-'9']+
let floats = ['0'-'9']+ '.' ['0'-'9']*

rule token = parse
  whitespace { token lexbuf }
| '#'        { comment lexbuf }

| "int"      { INT }     (* Integer type *)
| "float"    { FLOAT }   (* Float type *)
| "comp"     { COMP }    (* Complex type *)
| "mat"      { MAT }     (* Matrix *)

| "C"        { C }       (* Start of complex number *)
| "I"        { I }       (*  Imaginary component *)

| "def"      { DEF }     (* Define function *)

| '='        { ASSIGN } (* Assignment *)
| ','        { COMMA }  (* Separate list elements *)
| ':'        { COLON }  (* Separate matrix rows *)
| ';'        { SEMI }   (* Separate matrix columns *)
| '('        { LPAREN } (* Surround expression *)
| ')'        { RPAREN }
| '['        { LBRACK } (* Surround vectors/matricies *)
| ']'        { RBRACK }
| '{'        { LBRACE } (* Surround blocks *)
| '}'        { RBRACE }
| '<'        { LCAR }    (* Open bra- *)
| '>'        { RCAR }    (* Close -ket *)
| '|'        { BAR }     (* Close bra- and Open -ket *)

| '+'        { PLUS }    (* Addition *)
| '-'        { MINUS }   (* Subtraction *)
| '*'        { TIMES }   (* Multiplication *)
| '/'        { DIV }     (* Division *)
| '%'        { MOD }     (* Modulus *)
```

```
| '^'          { EXPN }    (* Exponentiation *)

| "eq"         { EQ }      (* Equal to (structural) *)
| "neq"        { NEQ }     (* Not equal to (structural) *)
| "lt"         { LT }      (* Less than *)
| "gt"         { GT }      (* Greater than *)
| "leq"        { LEQ }     (* Less than or equal to *)
| "geq"        { GEQ }     (* Greater than or equal to *)

| "not"        { NOT }     (* Boolean not *)
| "and"        { AND }     (* Boolean and *)
| "or"         { OR }      (* Boolean or *)
| "xor"        { XOR }     (* Boolean xor *)

| "norm"       { NORM }    (* Get norm *)
| "trans"      { TRANS }   (* Get transpose *)
| "det"        { DET }     (* Get determinant *)
| "adj"        { ADJ }     (* Get adjoint *)
| "conj"       { CONJ }    (* Get complex conjugate *)
| "unit"       { UNIT }    (* Is unit matrix? *)
| '@'          { TENS }    (* Tensor product *)
| "im"         { IM }      (* Is imaginary number? *)
| "re"         { RE }      (* Is real number *)
| "sin"        { SIN }     (* Sine *)
| "cos"        { COS }     (* Cosine *)
| "tan"        { TAN }     (* Tangent *)

| "if"         { IF }      (* If statement *)
| "else"    { ELSE } (* Else statement *)
| "for"        { FOR }     (* For loop - for(i from x to y by z) *)
| "from"       { FROM }
| "to"         { TO }
| "by"         { BY }
| "while"      { WHILE }   (* While loop *)
| "break"      { BREAK }   (* Break For or While loop *)
| "continue"   { CONT }    (* Continue to For or While loop *)

| name      as lxm  { ID(lxm) }
| integers  as lxm  { INT_LIT(lxm) }
| floats    as lxm  { FLOAT_LIT(float_of_string lxm) }

| eof               { EOF }
| _ as char         { raise (Failure("illegal character " ^ Char.escaped char)) }

and comment = parse
  ['\r' '\n']       { token lexbuf }
| _
```

B.2 Parser

parser.mly

```
(* Christopher Campbell, Sankalpa Khadka*)
%{ open Ast %}

%token C I
%token INT FLOAT COMP MAT
%token DEF
%token ASSIGN
%token COMMA COLON SEMI LPAREN RPAREN LBRACK RBRACK LBRACE RBRACE LCAR RCAR BAR
```

```
%token PLUS MINUS TIMES DIV MOD EXPN
%token EQ NEQ LT GT LEQ GEQ
%token NOT AND OR XOR
%token TENS UNIT NORM TRANS DET ADJ CONJ IM RE SIN COS TAN
%token IF ELIF ELSE FOR FROM TO BY WHILE BREAK CONT
%token EOF

%token <string> ID
%token <string> INT_LIT
%token <float> FLOAT_LIT
%token <string> COMP_LIT

%nonassoc NOELSE
%nonassoc ELSE
%right ASSIGN
%left OR XOR
%left AND
%right NOT
%left EQ NEQ
%left LT GT LEQ GEQ
%left PLUS MINUS
%left TIMES DIV MOD TENS
%right EXPN
%nonassoc RE IM NORM TRANS DET ADJ CONJ UNIT SIN COS TAN

%start program
%type <Ast.program> program

%%

vtype:
  INT     { Int }
  | FLOAT { Float }
  | COMP  { Comp }
  | MAT   { Mat }

vdecl:
  vtype ID SEMI { { typ = $1;
                    name = $2 } }
vdecl_list:
    /* nothing */    { [] }
  | vdecl_list vdecl { $2 :: $1 }

formal_params:
    /* nothing */      { [] }
  | formal_params_list { List.rev $1 }

formal_params_list:
  vtype ID                                { [{ typ = $1;
                                               name = $2; }] }
  | formal_params_list COMMA vtype ID { {  typ = $3;
                                           name = $4; } :: $1 }
actual_params:
    /* nothing */      { [] }
  | actual_params_list { List.rev $1 }

actual_params_list:
    expr                          { [$1] }
  | actual_params_list COMMA expr { $3 :: $1 }

fdecl:
   DEF ID LPAREN formal_params RPAREN COLON vtype ID LBRACE vdecl_list stmt_list RBRACE
     { { func_name = $2;
         formal_params = $4;
         ret_typ = $7;
```

```
        ret_name = $8;
        locals = List.rev $10;
        body = List.rev $11; } }

mat_row:
    expr                { [$1] }
  | mat_row COMMA expr { $3 :: $1 }

mat_row_list:
    LPAREN mat_row RPAREN               { [List.rev($2)] }
  | mat_row_list LPAREN mat_row RPAREN { List.rev($3) :: $1 }

inner_comp:
    FLOAT_LIT                      { [$1; 0.] }
  | FLOAT_LIT I                    { [0.; $1] }
  | FLOAT_LIT PLUS FLOAT_LIT I { [$1; $3] }

expr:
    ID                                { Id($1) }
  | INT_LIT                           { Lit_int(int_of_string $1) }
  | FLOAT_LIT                         { Lit_float($1) }
  | C LPAREN inner_comp RPAREN        { Lit_comp(List.hd $3, List.hd (List.rev $3)) }
  | LCAR INT_LIT BAR                  { Lit_qub($2, 0) }
  | BAR INT_LIT RCAR                  { Lit_qub($2, 1) }
  | LBRACK mat_row_list RBRACK        { Mat(List.rev($2)) }
  | LPAREN expr RPAREN                { $2 }
  | ID ASSIGN expr                    { Assign($1, $3) }
  | ID LPAREN actual_params RPAREN { Call($1, $3) }
  | MINUS expr                        { Unop(Neg, $2)}
  | NOT LPAREN expr RPAREN            { Unop(Not, $3) }
  | RE LPAREN expr RPAREN             { Unop(Re, $3) }
  | IM LPAREN expr RPAREN             { Unop(Im, $3) }
  | NORM LPAREN expr RPAREN           { Unop(Norm, $3) }
  | TRANS LPAREN expr RPAREN          { Unop(Trans, $3) }
  | DET LPAREN expr RPAREN            { Unop(Det, $3) }
  | ADJ LPAREN expr RPAREN            { Unop(Adj, $3) }
  | CONJ LPAREN expr RPAREN           { Unop(Conj, $3) }
  | UNIT LPAREN expr RPAREN           { Unop(Unit, $3) }
  | SIN LPAREN expr RPAREN            { Unop(Sin, $3) }
  | COS LPAREN expr RPAREN            { Unop(Cos, $3) }
  | TAN LPAREN expr RPAREN            { Unop(Tan, $3) }
  | expr PLUS   expr                  { Binop($1, Add,  $3) }
  | expr MINUS  expr                  { Binop($1, Sub,  $3) }
  | expr TIMES  expr                  { Binop($1, Mult, $3) }
  | expr DIV    expr                  { Binop($1, Div,  $3) }
  | expr MOD    expr                  { Binop($1, Mod,  $3) }
  | expr EXPN   expr                  { Binop($1, Expn, $3) }
  | expr TENS   expr                  { Binop($1, Tens, $3) }
  | expr EQ     expr                  { Binop($1, Eq,   $3) }
  | expr NEQ    expr                  { Binop($1, Neq,  $3) }
  | expr LT     expr                  { Binop($1, Lt,   $3) }
  | expr GT     expr                  { Binop($1, Gt,   $3) }
  | expr LEQ    expr                  { Binop($1, Leq,  $3) }
  | expr GEQ    expr                  { Binop($1, Geq,  $3) }
  | expr OR     expr                  { Binop($1, Or,   $3) }
  | expr AND    expr                  { Binop($1, And,  $3) }
  | expr XOR    expr                  { Binop($1, Xor,  $3) }

 by:
   /* nothing */ { Noexpr }
 | BY expr        { $2 }

stmt:
    expr SEMI                                          { Expr($1) }
  | LBRACE stmt_list RBRACE                            { Block(List.rev $2) }
```

```
  | FOR LPAREN expr FROM expr TO expr by RPAREN stmt { For($3, $5, $7, $8, $10) }
  | WHILE LPAREN expr RPAREN stmt                   { While($3, $5) }
  | IF LPAREN expr RPAREN stmt %prec NOELSE          { If($3, $5, Ast.Expr(Ast.Noexpr)) }
  | IF LPAREN expr RPAREN stmt ELSE stmt             { If($3, $5, $7) }
  | BREAK SEMI                                      { BreakCont(0) }
  | CONT  SEMI                                      { BreakCont(1) }

stmt_list:
    /* nothing  */ { [] }
  | stmt_list stmt { $2 :: $1 }

 rev_program:
   /* nothing */     { [] }
 | rev_program fdecl { $2 :: $1 }

program:
  rev_program { List.rev $1 }
```

B.3 AST

ast.ml

```
(* Christopher Campbell, Winnie Narang *)
(* Elementary Data Types *)
type data_type =
    Int
  | Float
  | Comp
  | Mat

(* Unary Operators *)
type un_op =
    Neg
  | Not
  | Re
  | Im
  | Norm
  | Trans
  | Det
  | Adj
  | Conj
  | Unit
  | Sin
  | Cos
  | Tan

(* Binary Operators *)
type bi_op =
    Add
  | Sub
  | Mult
  | Div
  | Mod
  | Expn
  | Tens
  | Eq
  | Neq
  | Lt
  | Gt
  | Leq
```

```
  | Geq
  | Or
  | And
  | Xor

(* Expressions *)
type expr =
    Lit_int of int
  | Lit_float of float
  | Lit_comp of float * float
  | Lit_qub of string * int
  | Mat of expr list list
  | Id of string
  | Unop of un_op * expr
  | Binop of expr * bi_op * expr
  | Assign of string * expr
  | Call of string * expr list
  | Noexpr

(* Statements *)
type stmt =
    Expr of expr
  | Block of stmt list
  | If of expr * stmt * stmt
  | For of expr * expr * expr * expr * stmt
  | While of expr * stmt
  | BreakCont of int

(* Statement Lists *)
type stmt_list =
  stmt list

(* Variables Declaration *)
type var_decl =
  {
    typ : data_type;
    name : string;
  }

(* Function Declaration *)
type func_decl =
  {
    ret_typ : data_type;
    ret_name : string;
    func_name : string;
    formal_params : var_decl list;
    locals : var_decl list;
    body : stmt list;
  }

(* Program *)
type program =
  func_decl list

(* Pretty Printer *)
let rec string_of_expr = function
    Lit_int(n) -> string_of_int n
  | Lit_float(n) -> string_of_float n
  | Lit_comp(f1,f2) -> string_of_float f1 ^ " + " ^ string_of_float f2 ^ "i"
  | Lit_qub(s,t) -> let typ = string_of_int t in (match typ with
                       "0" -> "Qub-bra of "^ s
                     | _ -> "Qub-ket of "^ s)
  | Mat(l) ->  string_of_mat l
  | Id(s) -> s
  | Unop(un1,exp1) ->
```

```
    (match un1 with
      Neg -> " -"
    | Not -> " ! "
    | Re -> " Re "
    | Im -> " Im "
    | Norm -> " Norm "
    | Trans -> " Trans "
    | Det -> " Det "
    | Adj -> " Adj "
    | Conj -> " Conj "
    | Unit -> " Unit "
    | Sin -> " Sin "
    | Cos -> " Cos "
    | Tan -> " Tan ") ^ string_of_expr exp1

  | Binop(ex1,binop,ex2) -> string_of_expr ex1 ^
    (match binop with
      Add -> " + "     | Sub -> " - "       | Mult -> " * "
    | Div -> " / "     | Mod -> " % "       | Expn -> " ^ " | Tens -> " @ "
    | Eq-> " == "      | Neq -> " != "      | Lt -> " < "
    | Leq -> " <= "    | Gt -> " > "        | Geq -> " >= "
    | Xor -> " XOR "   | And -> " && "      | Or -> " || ") ^ string_of_expr ex2
  | Assign(str,expr) -> str ^ " = " ^ string_of_expr expr
  | Call(str,expr_list) -> "Calling " ^ str ^ " on " ^string_of_exprs expr_list
  | Noexpr -> ""

and string_of_mat l =
  let row_strs =
    List.map string_of_row l
  in
    "[" ^ String.concat "" row_strs ^ "]"

and string_of_row r =
  let row_str =
    String.concat "," (List.map string_of_expr r)
  in
    "(" ^ row_str ^ ")"

and string_of_exprs exprs =
  String.concat "\n" (List.map string_of_expr exprs)

and string_of_stmt = function
    Expr(exp) -> string_of_expr exp ^ "\n"
  | Block(stmt_list) -> "{\n" ^ string_of_stmts stmt_list ^ "\n}"
  | If(e, s, Block([])) -> "if (" ^ string_of_expr e ^ ")\n" ^ string_of_stmt s
  | If(e, s1, s2) ->  "if (" ^ string_of_expr e ^ ")\n" ^string_of_stmt s1 ^ "else\n" ^
    string_of_stmt s2
  | For(ex1,ex2,ex3,ex4,stmt) -> "For args : " ^ string_of_expr ex1 ^ " " ^ string_of_expr
    ex2 ^ " "^ string_of_expr ex3 ^
                                  " "^ string_of_expr ex4 ^ "\nstatement :\n" ^
    string_of_stmt stmt
  | While(expr,stmt) -> "While condition : " ^ string_of_expr expr ^ "\nstatement : " ^
    string_of_stmt stmt
  | BreakCont(t) -> string_of_breakcont t

and string_of_breakcont t =
  if (t = 0) then
  "break"
  else
  "continue"

and string_of_stmts stmts =
  String.concat "\n" (List.map string_of_stmt stmts)

and string_of_var_decl var_decl =
```

```
  "vdecl: typ: " ^
    (match var_decl.typ with
      Int -> "int," ^ " name: " ^ var_decl.name^ "  "
    | Float -> "float," ^ " name: " ^ var_decl.name^ "  "
    | Comp -> "comp," ^ " name: " ^ var_decl.name^ "  "
    | Mat -> "mat," ^ " name: " ^ var_decl.name^ "  ")

and string_of_fdecl fdecl =
  "\nfdecl:\nret_typ: " ^
    (match fdecl.ret_typ with
      Int -> " int "
    | Float -> " float "
    | Comp -> " comp "
    | Mat -> " mat ") ^
      "\nret_name: " ^ fdecl.ret_name ^ "\nfunc_name: "  ^ fdecl.func_name ^  "\n(" ^
        String.concat "" (List.map string_of_var_decl fdecl.formal_params) ^ ")\n{\n" ^
          String.concat "" (List.map string_of_var_decl fdecl.locals) ^ "\n" ^
            String.concat "" (List.map string_of_stmt fdecl.body) ^ "}"

and string_of_program (funcs) =
  "program:\n" ^ String.concat "\n" (List.map string_of_fdecl funcs)
```

B.4 Analyzer

analyzer.ml

```
(* Christopher Campbell *)
open Ast
open Sast

(***************
 * Environment *
 ***************)

type symbol_table =
  { ret_typ : Sast.sdata_type;
    ret_nam : string;
    func_nam : string;
    mutable formal_param : svar_decl list;
    mutable local : svar_decl list;
    builtin : svar_decl list; }

type environment =
  { scope : symbol_table;
    mutable functions : Sast.sfunc_decl list; }

let builtin_vars =
  [ { styp = Sast.Float; sname = "e"; builtinv = true; };
    { styp = Sast.Float; sname = "pi"; builtinv = true; };
    { styp = Sast.Mat; sname = "X"; builtinv = true; };
    { styp = Sast.Mat; sname = "Y"; builtinv = true; };
    { styp = Sast.Mat; sname = "Z"; builtinv = true; };
    { styp = Sast.Mat; sname = "H"; builtinv = true; };
    { styp = Sast.Mat; sname = "IDT"; builtinv = true; }; ]

let builtin_funcs =
  [ { sret_typ = Sast.Void;
      sret_name = "null";
      sfunc_name = "print";
      sformal_params = [{ styp = Sast.Poly; sname = "print_val"; builtinv = true; };];
```

```
      slocals  = [];
      sbody = [Sast.Sexpr(Sast.Expr(Sast.Noexpr, Sast.Void))];
      builtinf = true; };

    { sret_typ = Sast.Void;
      sret_name = "null";
      sfunc_name = "printq";
      sformal_params = [{ styp = Sast.Mat; sname = "printq_val"; builtinv = true; };];
      slocals  = [];
      sbody = [Sast.Sexpr(Sast.Expr(Sast.Noexpr, Sast.Void))];
      builtinf = true; };

    { sret_typ = Sast.Int;
      sret_name = "null";
      sfunc_name = "rows";
      sformal_params = [{ styp = Sast.Mat; sname = "rows_val"; builtinv = true; };];
      slocals  = [];
      sbody = [Sast.Sexpr(Sast.Expr(Sast.Noexpr, Sast.Void))];
      builtinf = true; };

    { sret_typ = Sast.Int;
      sret_name = "null";
      sfunc_name = "cols";
      sformal_params = [{ styp = Sast.Mat; sname = "rows_val"; builtinv = true; };];
      slocals  = [];
      sbody = [Sast.Sexpr(Sast.Expr(Sast.Noexpr, Sast.Void))];
      builtinf = true; };

    { sret_typ = Sast.Comp;
      sret_name = "null";
      sfunc_name = "elem";
      sformal_params = [{ styp = Sast.Mat; sname = "elem_mat"; builtinv = true; };
                        { styp = Sast.Int; sname = "elem_row"; builtinv = true; };
                        { styp = Sast.Int; sname = "elem_col"; builtinv = true; };];
      slocals  = [];
      sbody = [Sast.Sexpr(Sast.Expr(Sast.Noexpr, Sast.Void))];
      builtinf = true; }; ]

let root_symbol_table =
  { ret_typ = Sast.Void;
    ret_nam = "";
    func_nam = "";
    formal_param = [];
    local = [];
    builtin = builtin_vars; }

let root_environment =
  { scope = root_symbol_table;
    functions = builtin_funcs; }

(*************
 * Exceptions *
*************)

exception Except of string

let matrix_error t = match t with
    0 -> raise (Except("Invalid matrix: incorrect type"))
  | _ -> raise (Except("Invalid matrix"))

let qub_error t = match t with
    0 -> raise (Except("Invalid qubit: incorrect use of |expr>"))
  | 1 -> raise (Except("Invalid qubit: incorrect use of <expr|"))
  | _ -> raise (Except("Invalid qubit"))

```

```
let assignment_error s =
  raise (Except("Invalid assignment to variable: " ^ s))

let var_error s =
  raise (Except("Invalid use of a variable: " ^ s ^ " was not declared" ))

let func_error s =
  raise (Except("Invalid function call: " ^ s ^ " was not declared" ))

let var_decl_error s =
  raise (Except("Invalid variable declaration: " ^ s ^ " was already declared" ))

let func_decl_error s =
  raise (Except("Invalid function declaration: " ^ s ^ " was already declared" ))

let unop_error t = match t with
    Ast.Neg -> raise (Except("Invalid use of unop: '-expr'"))
  | Ast.Not -> raise (Except("Invalid use of unop: 'Not(expr)'"))
  | Ast.Re -> raise (Except("Invalid use of unop: 'Re(expr)'"))
  | Ast.Im -> raise (Except("Invalid use of unop: 'Im(expr)'"))
  | Ast.Norm -> raise (Except("Invalid use of unop: 'Norm(expr)'"))
  | Ast.Trans -> raise (Except("Invalid use of unop: 'Trans(expr)'"))
  | Ast.Det -> raise (Except("Invalid use of unop: 'Det(expr)'"))
  | Ast.Adj -> raise (Except("Invalid use of unop: 'Adj(expr)'"))
  | Ast.Conj -> raise (Except("Invalid use of unop: 'Conjexpr)'"))
  | Ast.Unit -> raise (Except("Invalid use of unop: 'Unit(expr)'"))
  | Ast.Sin -> raise (Except("Invalid use of unop: 'Sin(expr)'"))
  | Ast.Cos -> raise (Except("Invalid use of unop: 'Cos(expr)'"))
  | Ast.Tan -> raise (Except("Invalid use of unop: 'Tan(expr)'"))

let binop_error t = match t with
    Ast.Add -> raise (Except("Invalid use of binop: 'expr + expr'"))
  | Ast.Sub -> raise (Except("Invalid use of binop: 'expr - expr'"))
  | Ast.Mult -> raise (Except("Invalid use of binop: expr * expr'"))
  | Ast.Div -> raise (Except("Invalid use of binop: 'expr / expr'"))
  | Ast.Mod -> raise (Except("Invalid use of binop: 'expr % expr'"))
  | Ast.Expn -> raise (Except("Invalid use of binop: 'expr ^ expr'"))
  | Ast.Or -> raise (Except("Invalid use of binop: 'expr or expr'"))
  | Ast.And -> raise (Except("Invalid use of binop: 'expr and expr'"))
  | Ast.Xor -> raise (Except("Invalid use of binop: 'expr xor expr'"))
  | Ast.Tens -> raise (Except("Invalid use of binop: 'expr @ expr'"))
  | Ast.Eq -> raise (Except("Invalid use of binop: 'expr eq expr'"))
  | Ast.Neq -> raise (Except("Invalid use of binop: 'expr neq expr'"))
  | Ast.Lt -> raise (Except("Invalid use of binop: 'expr lt expr'"))
  | Ast.Gt -> raise (Except("Invalid use of binop: 'expr gt expr'"))
  | Ast.Leq -> raise (Except("Invalid use of binop: 'expr leq expr'"))
  | Ast.Geq -> raise (Except("Invalid use of binop: 'expr geq expr'"))

let expr_error t = match t with
  _ -> raise (Except("Invalid expression"))

let call_error t = match t with
    0 -> raise (Except("Invalid function call: function undeclared"))
  | 1 -> raise (Except("Invalid function call: incorrect number of parameters"))
  | 2 -> raise (Except("Invalid function call: incorrect type for parameter"))
  | _ -> raise (Except("Invalid function call"))

let stmt_error t = match t with
    0 -> raise (Except("Invalid use of statment: 'if'"))
  | 1 -> raise (Except("Invalid use of statment: 'for'"))
  | 2 -> raise (Except("Invalid use of statment: 'while'"))
  | _ -> raise (Except("Invalid statement"))

let program_error t = match t with
    0 -> raise (Except("Missing 'compute' function"))
```

```
  | 1 -> raise (Except("'compute' function must be of type int"))
  | _ -> raise (Except("Invalid program"))

(********************
 * Utility Functions *
********************)

let var_exists name scope =
  if (List.exists (fun vdecl -> name = vdecl.sname) scope.formal_param) then true
  else if (List.exists (fun vdecl -> name = vdecl.sname) scope.formal_param) then true
  else List.exists (fun vdecl -> name = vdecl.sname) scope.builtin

let func_exists name env =
  List.exists (fun fdecl -> name = fdecl.sfunc_name) env.functions

let lookup_var name scope =
  let vdecl_found =
  try List.find (fun vdecl -> name = vdecl.sname) scope.formal_param
  with Not_found ->
    try List.find (fun vdecl -> name = vdecl.sname) scope.local
    with Not_found ->
      try List.find (fun vdecl -> name = vdecl.sname) scope.builtin
      with Not_found -> var_error name in
  vdecl_found

let lookup_func name env =
  let fdecl_found =
    try
      List.find (fun fdecl -> name = fdecl.sfunc_name) env.functions
    with Not_found -> func_error name
  in
    fdecl_found

(**********
 * Checks *
**********)

let rec check_qub_expr i =
  let r = i mod 10 in
   if (r = 0 || r = 1) then
     let i = i / 10 in
       if (i != 0)
        then
         check_qub_expr i
       else 1
     else 0

and check_qub i t =
  let int_expr =
    int_of_string i
  in
    if (check_qub_expr int_expr = 1) then
        (match t with
            0 -> Sast.Expr(Sast.Lit_qub(i, 1), Sast.Mat)
          | 1 -> Sast.Expr(Sast.Lit_qub(i, 0), Sast.Mat)
          | _ -> qub_error 2)
    else
      qub_error t

and check_mat l env =
  let mat =
    List.map (fun row -> check_mat_rows row env) l
  in
    Sast.Expr(Sast.Mat(mat), Sast.Mat)

```

```
and check_mat_rows l env =
  let row =
    List.map (fun e -> check_mat_row e env) l
  in row

and check_mat_row e env =
  let se =
    check_expr env e
  in
    match se with
       Sast.Expr(_, t) ->
        match t with
            Sast.Int -> se
          | Sast.Float -> se
          | Sast.Comp -> se
          | _ -> matrix_error 0

and check_id name env =
  let vdecl =
    lookup_var name env.scope
  in
    let typ = vdecl.styp in
      Sast.Expr(Sast.Id(name), typ)

and check_unop op e env =
  let e = check_expr env e in
    match e with
      Sast.Expr(q, t) ->
        (match op with
            Ast.Neg ->
            (match t with
                Sast.Int -> Sast.Expr(Sast.Unop(op, e), Sast.Int)
              | Sast.Float -> Sast.Expr(Sast.Unop(op, e), Sast.Float)
              | Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ -> unop_error op)
          | Ast.Not ->
            (match t with
                Sast.Int -> Sast.Expr(Sast.Unop(op, e), Sast.Int)
              | _ ->  unop_error op)
          | Ast.Re ->
            (match t with
                Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ ->  unop_error op)
          | Ast.Im ->
            (match t with
                Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ ->  unop_error op)
          | Ast.Unit ->
            (match t with
                Sast.Mat -> Sast.Expr(Sast.Unop(op, e), Sast.Int)
              | _ ->  unop_error op)
          | Ast.Norm ->
            (match t with
                Sast.Mat -> Sast.Expr(Sast.Unop(op, e), Sast.Float)
              | _ ->  unop_error op)
          | Ast.Det ->
            (match t with
                Sast.Mat -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ ->  unop_error op)
          | Ast.Trans | Ast.Adj ->
            (match t with
                Sast.Mat -> Sast.Expr(Sast.Unop(op, e), Sast.Mat)
              | _ ->  unop_error op)
          | Ast.Conj ->
            (match t with
```

```
                Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | Sast.Mat -> Sast.Expr(Sast.Unop(op, e), Sast.Mat)
              | _ ->  unop_error op)
          | Ast.Sin ->
            (match t with
                Sast.Int -> Sast.Expr(Sast.Unop(op, e), Sast.Int)
              | Sast.Float -> Sast.Expr(Sast.Unop(op, e), Sast.Float)
              | Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ ->  unop_error op)
          | Ast.Cos ->
            (match t with
                Sast.Int -> Sast.Expr(Sast.Unop(op, e), Sast.Int)
              | Sast.Float -> Sast.Expr(Sast.Unop(op, e), Sast.Float)
              | Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ ->  unop_error op)
          | Ast.Tan ->
            (match t with
                Sast.Int -> Sast.Expr(Sast.Unop(op, e), Sast.Int)
              | Sast.Float -> Sast.Expr(Sast.Unop(op, e), Sast.Float)
              | Sast.Comp -> Sast.Expr(Sast.Unop(op, e), Sast.Comp)
              | _ ->  unop_error op))

and check_binop e1 op e2 env =
    let e1 = check_expr env e1 and e2 = check_expr env e2 in
      match e1 with
          Sast.Expr(_, t1) ->
          (match e2 with
              Sast.Expr(_, t2) ->
              (match op with
                  Ast.Add | Ast.Sub ->
                  (match t1 with
                      Sast.Int ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                        | _ -> binop_error op)
                    | Sast.Float ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                        | _ -> binop_error op)
                    | Sast.Comp ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                        | _ -> binop_error op)
                    | Sast.Mat ->
                      (match t2 with
                          Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Mat)
                        | _ -> binop_error op)
                    | _ -> binop_error op)
                | Ast.Mult | Ast.Div ->
                  (match t1 with
                    Sast.Int ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                        | Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Mat)
                        | _ -> binop_error op)
                    | Sast.Float ->
                      (match t2 with
```

```
                     Sast.Int | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                    | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                    | Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Mat)
                    | _ -> binop_error op)
                  | Sast.Comp ->
                   (match t2 with
                     Sast.Int | Sast.Float | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                    | Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Mat)
                    | _ -> binop_error op)
                  | Sast.Mat ->
                   (match t2 with
                     Sast.Int | Sast.Float | Sast.Comp | Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Mat)
                    | _ -> binop_error op)
                  | _ -> binop_error op)
                | Ast.Mod | Ast.Expn ->
                 (match t1 with
                  Sast.Int ->
                   (match t2 with
                     Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                    | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                    | _ -> binop_error op)
                  | Sast.Float ->
                   (match t2 with
                     Sast.Int | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Float)
                    | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                    | _ -> binop_error op)
                  | Sast.Comp ->
                   (match t2 with
                     Sast.Int | Sast.Float | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Comp)
                    | _ -> binop_error op)
                  | _ -> binop_error op)
                | Ast.Tens ->
                 (match t1 with
                  Sast.Mat ->
                   (match t2 with
                     Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Mat)
                    | _ -> binop_error op)
                  | _ -> binop_error op)
                | Ast.Eq | Ast.Neq ->
                 (match t1 with
                  Sast.Int ->
                   (match t2 with
                     Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | _ -> binop_error op)
                  | Sast.Float ->
                    (match t2 with
                     Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                     | _ -> binop_error op)
                  | Sast.Comp ->
                   (match t2 with
                     Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                    | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                   | _ -> binop_error op)
                  | Sast.Mat ->
```

```
                        (match t2 with
                            Sast.Mat -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                          | _ -> binop_error op)
                    | _ -> binop_error op)
                | Ast.Lt | Ast.Gt | Ast.Leq | Ast.Geq ->
                  (match t1 with
                    Sast.Int ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | _ -> binop_error op)
                    | Sast.Float ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | _ -> binop_error op)
                    | _ -> binop_error op)
                | Ast.Or | Ast.And | Ast.Xor ->
                  (match t1 with
                    Sast.Int ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | _ -> binop_error op)
                    | Sast.Float ->
                        (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                          | _ -> binop_error op)
                    | Sast.Comp ->
                      (match t2 with
                          Sast.Int -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Float -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | Sast.Comp -> Sast.Expr(Sast.Binop(e1, op, e2), Sast.Int)
                        | _ -> binop_error op)
                    | _ -> binop_error op)))

and check_assign name e env =
  let vdecl = lookup_var name env.scope in
  let e = check_expr env e in
  match e with
    Sast.Expr(_, t1) ->
      let t2 = vdecl.styp in
        if (t1 = t2) then
          Sast.Expr(Sast.Assign(name, e), t1)
        else
          assignment_error name

and check_call_params formal_params params =
  if ((List.length formal_params) = 0)
    then true
  else
    let fdecl_arg = List.hd formal_params in
    let param = match (List.hd params) with
      Sast.Expr(_, t) -> t in
      if (fdecl_arg.styp = Sast.Poly || (fdecl_arg.styp = param))
        then check_call_params (List.tl formal_params) (List.tl params)
      else false

and check_call name params env =
  let fdecl =
    try
      lookup_func name env
```

```
    with Not_found -> call_error 0 in
    let params = List.map (check_expr env) params in
      if ((List.length fdecl.sformal_params) != (List.length params))
        then call_error 1
      else
        if ((check_call_params fdecl.sformal_params params) = true)
          then Sast.Expr(Sast.Call(name, params), fdecl.sret_typ)
        else
          call_error 2

and check_expr env = function
    Ast.Lit_int(i) -> Sast.Expr(Sast.Lit_int(i), Sast.Int)
  | Ast.Lit_float(f) -> Sast.Expr(Sast.Lit_float(f), Sast.Float)
  | Ast.Lit_comp(f1, f2) -> Sast.Expr(Sast.Lit_comp(f1, f2), Sast.Comp)
  | Ast.Lit_qub(i, t) -> check_qub i t
  | Ast.Mat(l) -> check_mat l env
  | Ast.Id(s) -> check_id s env
  | Ast.Unop(op, e) -> check_unop op e env
  | Ast.Binop(e1, op, e2) -> check_binop e1 op e2 env
  | Ast.Assign(s, e) -> check_assign s e env
  | Ast.Call(s, l) -> check_call s l env
  | Ast.Noexpr -> Sast.Expr(Sast.Noexpr, Sast.Void)

and check_block stmts env =
  let sstmts = List.map (fun stmt -> check_stmt env stmt) stmts in
  Sast.Block(sstmts)

and check_if e s1 s2 env =
    let se = check_expr env e in
      match se with
        Sast.Expr(_,t) ->
          (match t with
            Sast.Int ->
              let ss1 = check_stmt env s1 in
              let ss2 = check_stmt env s2 in
              Sast.If(se, ss1, ss2)
            | _ -> stmt_error 0)

and check_for e1 e2 e3 e4 s env =
  let se1 = check_expr env e1 in
  match se1 with
    Sast.Expr(Sast.Id(_), Sast.Int) ->
      let se2 = check_expr env e2 in
      (match se2 with
         Sast.Expr(_, Sast.Int) ->
           let se3 = check_expr env e3 in
           (match se3 with
              Sast.Expr(_, Sast.Int) ->
              let se4 = check_expr env e4 in
              (match se4 with
                 Sast.Expr(_, t) ->
                 (match t with
                    Sast.Int ->
                      let ss = check_stmt env s in
                      Sast.For(se1, se2, se3, se4, ss)
                  | Sast.Void ->
                      let ss = check_stmt env s in
                      Sast.For(se1, se2, se3, Sast.Expr(Sast.Lit_int(1), Sast.Int), ss)
                | _ -> stmt_error 1))
            | _ -> stmt_error 1)
        | _ -> stmt_error 1)
    | _ -> stmt_error 1

and check_while e s env =
  let se = check_expr env e in
```

```
    match se with
      Sast.Expr(Sast.Binop(_, op, _), Sast.Int) ->
        (match op with
          Ast.Eq | Ast.Neq | Ast.Lt | Ast.Gt | Ast.Leq | Ast.Geq ->
            let ss = check_stmt env s in
              Sast.While(se, ss)
          | _ -> stmt_error 2)
    | _ -> stmt_error 2

and check_stmt env = function
    Ast.Expr(e) -> Sast.Sexpr(check_expr env e)
  | Ast.Block(l) -> check_block l env
  | Ast.If(e, s1, s2) -> check_if e s1 s2 env
  | Ast.For(e1, e2, e3, e4, s) -> check_for e1 e2 e3 e4 s env
  | Ast.While(e, s) -> check_while e s env
  | Ast.BreakCont(t) -> Sast.BreakCont(t)

and vdecl_to_sdecl vdecl =
  match vdecl.typ with
      Ast.Int -> { styp = Sast.Int; sname = vdecl.name; builtinv = false; }
    | Ast.Float -> { styp = Sast.Float; sname = vdecl.name; builtinv = false; }
    | Ast.Comp -> { styp = Sast.Comp; sname = vdecl.name; builtinv = false; }
    | Ast.Mat -> { styp = Sast.Mat; sname = vdecl.name; builtinv = false; }

and formal_to_sformal scope formal_param  =
  let found = var_exists formal_param.name scope in
  if found then var_decl_error formal_param.name
  else let sdecl =  vdecl_to_sdecl formal_param in
  let new_formals = sdecl :: scope.formal_param in
  let new_scope =
    { ret_typ = scope.ret_typ;
      ret_nam = scope.ret_nam;
      func_nam = scope.func_nam;
      formal_param = new_formals;
      local = scope.local;
      builtin = scope.builtin; } in
  new_scope

and formals_to_sformals scope formal_params =
  let new_scope =
    if (formal_params = []) then scope
    else List.fold_left formal_to_sformal scope (List.rev formal_params) in
    new_scope

and local_to_slocal scope local =
  let found = var_exists local.name scope in
  if found then var_decl_error local.name
  else let sdecl = vdecl_to_sdecl local in
  let new_locals = sdecl :: scope.local in
  let new_scope =
    { ret_typ = scope.ret_typ;
      ret_nam = scope.ret_nam;
      func_nam = scope.func_nam;
      formal_param = scope.formal_param;
      local = new_locals;
      builtin = scope.builtin; } in
  new_scope

and locals_to_slocals scope locals =
  let new_scope =  List.fold_left local_to_slocal scope (List.rev locals) in
  new_scope

and ret_to_sret scope ret_typ =
  let sret_typ =
    match ret_typ with
```

```
        Ast.Int -> Sast.Int
      | Ast.Float -> Sast.Float
      | Ast.Comp -> Sast.Comp
      | Ast.Mat -> Sast.Mat
    in
    let new_scope =
      { ret_typ = sret_typ;
        ret_nam = scope.ret_nam;
        func_nam = scope.func_nam;
        formal_param = scope.formal_param;
        local = scope.local;
        builtin = scope.builtin; } in
    new_scope

and rname_to_srname scope ret_name =
  let new_scope = { ret_typ = scope.ret_typ;
                    ret_nam = ret_name;
                    func_nam = scope.func_nam;
                    formal_param = scope.formal_param;
                    local = scope.local; builtin = scope.builtin; } in
  new_scope

and fname_to_sfname scope func_name =
  let new_scope = { ret_typ = scope.ret_typ;
                    ret_nam = scope.ret_nam;
                    func_nam = func_name;
                    formal_param = scope.formal_param;
                    local = scope.local;
                    builtin = scope.builtin; } in
  new_scope

and ret_to_slocal scope name typ =
  let vdecl = { typ = typ; name = name; } in
  let sdecl =  vdecl_to_sdecl vdecl in
  let new_locals =  sdecl :: scope.local in
  let new_scope ={ ret_typ = scope.ret_typ;
                   ret_nam = scope.ret_nam;
                   func_nam = scope.func_nam;
                   formal_param = scope.formal_param;
                   local = new_locals;
                   builtin = scope.builtin; } in
  new_scope

and fdecl_to_sdecl fdecl env =
  let new_scope = ret_to_slocal env.scope fdecl.ret_name fdecl.ret_typ in
  let new_scope = formals_to_sformals new_scope fdecl.formal_params in
  let new_scope = locals_to_slocals new_scope fdecl.locals in
  let new_scope = ret_to_sret new_scope fdecl.ret_typ in
  let new_scope = rname_to_srname new_scope fdecl.ret_name in
  let new_scope = fname_to_sfname new_scope fdecl.func_name in
  let new_env = { scope = new_scope; functions = env.functions; } in
  let stmts = List.map (fun stmt -> check_stmt new_env stmt) fdecl.body in
  { sret_typ = new_scope.ret_typ;
    sret_name = new_scope.ret_nam;
    sfunc_name = new_scope.func_nam;
    sformal_params = new_scope.formal_param;
    slocals = new_scope.local;
    sbody = stmts;
    builtinf = false; }

and check_function env fdecl =
  let found = func_exists fdecl.func_name env in
  if found then func_decl_error fdecl.func_name
  else let sfdecl = fdecl_to_sdecl fdecl env in
  let new_env = { scope = env.scope; functions = sfdecl :: env.functions; } in
```

```
  new_env

and check_compute_fdecl fdecls =
  let fdecl = List.hd (List.rev fdecls) in
  let name = fdecl.func_name in
  if (name = "compute") then fdecls
  else program_error 0

and check_program fdecls =
  let fdecls = check_compute_fdecl fdecls in
  let env = List.fold_left check_function root_environment fdecls in
  let sfdecls = List.rev env.functions in
  sfdecls
```

B.5 SAST

sast.ml

```
(* Sankalpa Khadka *)
open Ast

type sdata_type =
    Int
  | Float
  | Comp
  | Mat
  | Poly
  | Void

type expr_wrapper =
    Expr of sexpr * sdata_type

and  sexpr =
    Lit_int of int
  | Lit_float of float
  | Lit_comp of float * float
  | Lit_qub of string * int
  | Mat of expr_wrapper list list
  | Id of string
  | Unop of Ast.un_op * expr_wrapper
  | Binop of expr_wrapper * Ast.bi_op * expr_wrapper
  | Assign of string * expr_wrapper
  | Call of string * expr_wrapper list
  | Noexpr

and sstmt =
    Sexpr of expr_wrapper
  | Block of sstmt list
  | If of expr_wrapper * sstmt * sstmt
  | For of expr_wrapper * expr_wrapper * expr_wrapper * expr_wrapper * sstmt
  | While of expr_wrapper * sstmt
  | BreakCont of int

and svar_decl =
  {
    styp : sdata_type;
    sname : string;
    builtinv : bool;
  }

```

```
and sfunc_decl =
  {
    sret_typ : sdata_type;
    sret_name : string;
    sfunc_name : string;
    sformal_params : svar_decl list;
    slocals : svar_decl list;
    sbody : sstmt list;
    builtinf : bool;
  }

type sprogram =
  sfunc_decl list

(* Prety Printer *)
let rec string_of_unop op e =
  (match op with
  Neg -> " -"
  | Not -> " ! "
  | Re -> " Re "
  | Im -> " Im "
  | Norm -> " Norm "
  | Trans -> " Trans "
  | Det -> " Det "
  | Adj -> " Adj "
  | Conj -> " Conj "
  | Unit -> " Unit "
  | Sin -> " Sin "
  | Cos -> " Cos "
  | Tan -> " Tan ") ^ string_of_expr_wrapper e

and string_of_binop e1 op e2 =
  string_of_expr_wrapper e1 ^
    (match op with
      Add -> " + "     | Sub -> " - "      | Mult -> " * "
      | Div -> " / "     | Mod -> " % "      | Expn -> " ^ " | Tens -> " @ "
      | Eq-> " == "      | Neq -> " != "     | Lt -> " < "
      | Leq -> " <= "    | Gt -> " > "       | Geq -> " >= "
      | Xor -> " XOR "   | And -> " && "     | Or -> " || ") ^ string_of_expr_wrapper e2

and string_of_mat l =
  let row_strs =
    List.map string_of_row l
  in
    "[" ^ String.concat "" row_strs ^ "]"

and string_of_row r =
  let row_str =
    String.concat "," (List.map string_of_expr_wrapper r)
  in
    "(" ^ row_str ^ ")"

and string_of_sexpr = function
    Lit_int(i) -> string_of_int i
    | Lit_float(f) -> string_of_float f
    | Lit_comp(f1, f2) -> string_of_float f1 ^ " + " ^ string_of_float f2 ^ "i"
    | Lit_qub(i, t) -> i
    | Mat(l) ->  string_of_mat l
    | Id(s) -> s
    | Unop(op, e) -> string_of_unop op e
    | Binop(e1, op, e2) -> string_of_binop e1 op e2
    | Assign(name, e) -> name ^ " = " ^ string_of_expr_wrapper e
    | Call(name, params) -> "Calling " ^ name ^ " on " ^ string_of_sexprs params
    | Noexpr -> "noexpr"
```

```
and string_of_expr_wrapper w =
  let sexpr =
    match w with
        Expr(Lit_int(i), Int) -> Lit_int(i)
      | Expr(Lit_float(f), Float) -> Lit_float(f)
      | Expr(Lit_comp(f1, f2), Comp) -> Lit_comp(f1, f2)
      | Expr(Mat(l), Mat) -> Mat(l)
      | Expr(Id(name), typ) -> Id(name)
      | Expr(Unop(op, e), _) -> Unop(op, e)
      | Expr(Binop(e1, op, e2), _) -> Binop(e1, op, e2)
      | Expr(Assign(name, e), t1) -> Assign(name, e)
      | Expr(Call(name, params), _) -> Call(name, params)
      | Expr(Lit_qub(i, t), _) -> Lit_qub(i, t)
      | _ -> Noexpr
    in
      string_of_sexpr sexpr

and string_of_svar_decl svar_decl =
  "svdecl: styp: " ^
    (match svar_decl.styp with
      Int -> "int," ^ " name: " ^ svar_decl.sname ^ "  "
    | Float -> "float," ^ " name: " ^ svar_decl.sname ^ "  "
    | Comp -> "comp," ^ " name: " ^ svar_decl.sname ^ "  "
    | Mat -> "mat," ^ " name: " ^ svar_decl.sname ^ "  "
    | _ -> "")

and string_of_sexprs e =
  String.concat "\n" (List.map string_of_expr_wrapper e)

and string_of_sstmt = function
    Sexpr(e) -> string_of_expr_wrapper e ^ "\n"
  | Block(l) -> "{\n" ^ string_of_sstmts l ^ "\n}"
  | If(e, s, Block([])) -> "if (" ^ string_of_expr_wrapper e ^ ")\n" ^ string_of_sstmt s
  | If(e, s1, s2) ->  "if (" ^ string_of_expr_wrapper e ^ ")\n" ^string_of_sstmt s1 ^ "else\
    n" ^ string_of_sstmt s2
  | For(e1, e2, e3, e4, s) -> "For args : " ^ string_of_expr_wrapper e1 ^ " " ^
    string_of_expr_wrapper e2 ^ " "^ string_of_expr_wrapper e3 ^
                                    " "^ string_of_expr_wrapper e4 ^ "\nstatement :\n" ^
    string_of_sstmt s
  | While(e,s) -> "While condition : " ^ string_of_expr_wrapper e ^ "\nstatement : " ^
    string_of_sstmt s
  | BreakCont(t) -> string_of_breakcont t

and string_of_breakcont t =
  if (t = 0) then
  "break"
  else
  "continue"

and string_of_sstmts sstmts =
  String.concat "\n" (List.map string_of_sstmt sstmts)

and string_of_sfdecl sfdecl =
  "\nsfdecl:\nsret_typ: " ^
    (match sfdecl.sret_typ with
      Int -> " int "
    | Float -> " float "
    | Comp -> " comp "
    | Mat -> " mat "
    | _ -> "") ^
      "\nsret_name: " ^ sfdecl.sret_name ^ "\nsfunc_name: "  ^ sfdecl.sfunc_name ^  "\n(" ^
        String.concat "" (List.map string_of_svar_decl sfdecl.sformal_params) ^ ")\n{\n" ^
          String.concat "" (List.map string_of_svar_decl sfdecl.slocals) ^ "\n" ^
            String.concat "" (List.map string_of_sstmt sfdecl.sbody) ^ "}"
```

```
and string_of_sprogram (l) =
  "program:\n" ^ String.concat "\n" (List.map string_of_sfdecl l)
```

B.6 Generator

generator.ml

```
(* Winnie Narang, Jonathan Wong, Sankalpa Khadka *)
open Sast
open Printf
open String

let builtin_funcs = ["print";"printq";"rows";"cols";"elem"]

let is_builtin_func name =
  List.exists (fun func_name -> func_name = name) builtin_funcs

(* get type *)
let type_of (a : Sast.expr_wrapper) : Sast.sdata_type =
    match a with
    | Expr(_,t)-> t

(* get expression from expression wrapper *)
let expr_of (a : Sast.expr_wrapper) : Sast.sexpr =
    match a with
    | Expr(e,_)-> e

(* generate type *)
let rec cpp_from_type (ty: Sast.sdata_type) : string =
    match ty with
    | Int -> "int"
    | Float -> "float"
    | Comp -> "complex<float >"
    | Mat -> "MatrixXcf"
    | Poly | Void -> " "

(* write program to .cpp file *)
and writeToFile fileName progString =
    let file = open_out (fileName ^ ".cpp") in
        fprintf file "%s" progString

(* entry point for code generation*)
and gen_program fileName prog =
    let cppString = writeCpp prog in
    let out = sprintf "
        #include <iostream>
        #include <complex>
        #include <cmath>
        #include <Eigen/Dense>
        #include <qlang>
        using namespace Eigen;
        using namespace std;
        %s" cppString in
    writeToFile fileName out;

(* list of function declaration*)
and writeCpp funcList =
    let outStr =
      List.fold_left (fun a b -> a ^ (cpp_funcList b)) "" funcList
    in
```

```
      sprintf "%s" outStr

(* generate functions *)
and cpp_funcList func =
    if func.builtinf then
      ""
    else
      let cppFName = func.sfunc_name
      and cppRtnType = cpp_from_type func.sret_typ
      and cppRtnValue = func.sret_name
      and cppFParam = if (func.sformal_params = []) then "" else cppVarDecl func.
    sformal_params ","
      and cppFBody = cppStmtList func.sbody
      and cppLocals = cppVarDecl func.slocals ";\n\t"
        in
      if cppFName = "compute" then
                    sprintf "\nint main ()\n{\n\t%s\n\t%s\n\tstd::cout << %s << endl;\n\n\
    treturn 0;\n}" cppLocals cppFBody cppRtnValue
      else
        if (cppFParam = "") then
        sprintf "\n%s %s ()\n{\n\t%s\n%s\n\treturn %s;\n}" cppRtnType cppFName cppLocals
    cppFBody cppRtnValue
        else
        sprintf "\n%s %s (%s)\n{\n\t%s\n%s\n\treturn %s;\n}" cppRtnType cppFName cppFParam
    cppLocals cppFBody cppRtnValue

(* generate variable declarations *)
and cppVarDecl vardeclist delim =
   let varDecStr =
    List.fold_left (fun a b -> a ^ (cppVar b delim)) "" vardeclist
  in
    let varDectrun = String.sub varDecStr 0 ((String.length varDecStr)-1)
  in
    sprintf "%s " varDectrun

(* generate variable declaration *)
and cppVar var delim =
    if not var.builtinv then
        let vartype =
          cpp_from_type var.styp
        in
          sprintf "%s %s%s" vartype var.sname delim
    else ""

(* generate list of statements *)
and cppStmtList astmtlist =
    let outStr =
      List.fold_left (fun a b -> a ^ (cppStmt b)) "" astmtlist
    in
      sprintf "%s" outStr

(* generate statement *)
and cppStmt stmts = match stmts with
    Sast.Sexpr(expr_wrap) -> "\t" ^ cppExpr (expr_of expr_wrap) ^ ";\n"
  | Sast.Block(sstmt) -> cppStmtBlock sstmt
  | Sast.If(expr_wrap , sstmt1, sstmt2) -> writeIfStmt (expr_of expr_wrap) sstmt1 sstmt2
  | Sast.For(var,init, final, increment, stmt) -> writeForStmt var init final increment stmt
  | Sast.While(expr_wrap , sstmt) -> writeWhileStmt (expr_of expr_wrap) sstmt
  | Sast.BreakCont(t) -> writeBreakCont t

(* generate break/continue statement *)
and writeBreakCont t =
  if (t =0) then
  sprintf "break;"
  else
```

```
    sprintf "continue;"

(* generate expression *)
and cppExpr expr = match expr with
      Lit_int(lit) -> string_of_int lit
    | Lit_float(flit) -> string_of_float flit
    | Lit_comp(re,im) -> " complex<float>(" ^ string_of_float re ^ "," ^ string_of_float im  ^
       ") " (* Not sure how to do this *)
    | Unop(op, expr) ->  writeUnop op expr
    | Binop(expr1, op, expr2) -> writeBinop expr1 op expr2
    | Lit_qub(vec, t) -> writeQubit vec t
    | Mat (expr_wrap) -> writeMatrix expr_wrap
    | Id(str) -> str
    | Assign(name, expr) ->  name  ^ " = " ^ cppExpr (expr_of expr)
    | Call(name,l) ->
        if is_builtin_func name then
          writeBuiltinFuncCall name l
        else
          name ^ "(" ^ writeFunCall l ^ ")"
    | Noexpr -> ""

(* generate built-in function call *)
and writeBuiltinFuncCall name l =
  match name with
      "print" -> writePrintStmt l
    | "printq" -> writePrintqStmt l
    | "rows" -> writeRowStmt l
    | "cols" -> writeColStmt l
    | "elem" -> writeElemStmt l
    | _ -> ""

(* generate row statement *)
and writeRowStmt l =
  let expr_wrap = List.hd l in
  let expr = cppExpr (expr_of expr_wrap) in
  sprintf "%s.rows()" expr

(* generate col statement *)
and writeColStmt l =
  let expr_wrap = List.hd l in
  let expr = cppExpr (expr_of expr_wrap) in
  sprintf "%s.cols()" expr

(* generate elem statement *)
and writeElemStmt l =
  let ew1 = List.hd l in
  let e1 = cppExpr (expr_of ew1)
  and ew2 = List.hd (List.tl l) in
  let e2 = cppExpr (expr_of ew2)
  and ew3 = List.hd (List.tl (List.tl l)) in
  let e3 = cppExpr (expr_of ew3) in
  sprintf "%s(%s,%s)" e1 e2 e3

(* generate print statement *)
and writePrintStmt l =
  let expr_wrap = List.hd l in
  let expr = cppExpr (expr_of expr_wrap) in
    match expr_wrap with
      Sast.Expr(_,t) ->
        (match t with
            Sast.Mat -> sprintf "cout << %s << endl" expr
          | _ -> sprintf "cout << %s << endl" expr)

(* generate qubit print statement *)
and writePrintqStmt l =
```

```
  let expr_wrap = List.hd l in
  let expr = cppExpr (expr_of expr_wrap) in
    match expr_wrap with
        Sast.Expr(_,t) ->
          (match t with
            Sast.Mat -> sprintf "cout << vectorToBraket(%s) << endl" expr
          | _ -> sprintf "cout << %s << endl" expr)

(* generate block *)
and cppStmtBlock sstmtl =
let slist = List.fold_left (fun output element ->
    let stmt = cppStmt  element in
    output ^ stmt ^ "\n") "" sstmtl in
    "\n\t{\n" ^ slist ^ "\t}\n"

(* generate if statement *)
and writeIfStmt expr stmt1 stmt2 =
  let cond = cppExpr expr in
    let body = cppStmt stmt1 in
    let ebody = writeElseStmt stmt2 in
    sprintf " if(%s)%s%s" cond body ebody

(* generate else statements *)
and writeElseStmt stmt =
    let body =
        cppStmt stmt
    in
        if ((String.compare body "\t;\n") = 0) then
            sprintf "\n"
        else
            sprintf "\telse%s" body

(* generate while statement *)
and writeWhileStmt expr stmt =
let condString = cppExpr expr
  and stmtString = cppStmt stmt in
    sprintf "while (%s)\n%s\n" condString stmtString

(* generate for statements *)
and writeForStmt var init final increment stmt =
    let varname = cppExpr (expr_of var)
    and initvalue = cppExpr (expr_of init)
    and finalvalue = cppExpr (expr_of final)
    and incrementval = cppExpr (expr_of increment)
    and stmtbody = cppStmt stmt
    in
    sprintf "
    for (int %s = %s; %s < %s; %s = %s + %s){
        %s
        }" varname initvalue varname finalvalue varname varname incrementval stmtbody

(* generate unary operators *)
and writeUnop op expr =
    let exp = cppExpr (expr_of expr) in
        let unopFunc op exp = match op with
          Ast.Neg   -> sprintf "  -%s" exp
        | Ast.Not   -> sprintf "  !(%s)" exp
        | Ast.Re    -> sprintf "  real(%s)" exp   (* assumes exp is matrix*)
        | Ast.Im    -> sprintf "  imag(%s)" exp
        | Ast.Norm  -> sprintf "  %s.norm()" exp
        | Ast.Trans -> sprintf "  %s.transpose()" exp
        | Ast.Det   -> sprintf "  %s.determinant()" exp
        | Ast.Adj   -> sprintf "  %s.adjoint()" exp
        | Ast.Conj  -> sprintf "  %s.conjugate()" exp
        | Ast.Unit  -> sprintf "  (%s.conjugate()*%s).isIdentity()" exp exp     (* till here
```

```
     *)
        | Ast.Sin    -> sprintf "  sin((double)%s)" exp
        | Ast.Cos    -> sprintf "  cos((double)%s)" exp
        | Ast.Tan    -> sprintf "  tan((double)%s)" exp
    in unopFunc op exp

(* generate binary operations *)
and writeBinop expr1 op expr2 =
    let e1 = cppExpr (expr_of expr1)
    and t1 = type_of expr1
    and e2 = cppExpr (expr_of expr2) in
      let binopFunc e1 t1 op e2 = match op with
     Ast.Add  -> sprintf "%s + %s" e1 e2
    | Ast.Sub   -> sprintf "%s - %s" e1 e2
    | Ast.Mult  -> sprintf "%s * %s" e1 e2
    | Ast.Div   -> sprintf "%s / %s" e1 e2
    | Ast.Mod   -> sprintf "%s %% %s" e1 e2
    | Ast.Expn  -> sprintf "pow(%s,%s)" e1 e2
    | Ast.Tens  -> sprintf "tensor(%s, %s)" e1 e2
    | Ast.Eq  -> equalCaseWise e1 t1 e2
    | Ast.Neq   -> sprintf "%s != %s" e1 e2
    | Ast.Lt  -> sprintf "%s < %s" e1 e2
    | Ast.Gt  -> sprintf "%s > %s" e1 e2
    | Ast.Leq   -> sprintf "%s <= %s" e1 e2
    | Ast.Geq   -> sprintf "%s >= %s" e1 e2
    | Ast.Or  -> sprintf "%s || %s" e1 e2
    | Ast.And   -> sprintf "%s && %s" e1 e2
    | Ast.Xor   -> sprintf "%s ^ %s" e1 e2
  in binopFunc e1 t1 op e2

(* generate equality expressions (structural equality is used) *)
and equalCaseWise e1 t1 e2 = match t1 with
      Sast.Mat -> sprintf "%s.isApprox(%s)" e1 e2
     | _ -> sprintf "%s == %s" e1 e2

(* generate matrix *)
and writeMatrix expr_wrap =
    let matrixStr = List.fold_left (fun a b -> a ^ (writeRow b)) "" expr_wrap in
    let submatrix = String.sub matrixStr 0 ((String.length matrixStr)-1) in
    sprintf "(Matrix<complex<float>, Dynamic, Dynamic>(%d,%d)<<%s).finished()" (rowMatrix
    expr_wrap) (colMatrix expr_wrap) submatrix

(* generate matrix row *)
and writeRow row_expr =
    let rowStr = List.fold_left (fun a b -> a ^ (cppExpr (expr_of b)) ^ "," ) "" row_expr in
    sprintf "%s" rowStr

(* generate column matrix *)
and colMatrix expr_wrap =
  List.length (List.hd expr_wrap)

(* generate row matrix *)
and rowMatrix expr_wrap =
  List.length expr_wrap

(* generate function call *)
and writeFunCall expr_wrap =
    if expr_wrap = [] then
    sprintf ""
    else
    let argvStr = List.fold_left (fun a b -> a ^ (cppExpr (expr_of b)) ^ ",") "" expr_wrap
    in
    let argvStrCom = String.sub argvStr 0 ((String.length argvStr)-1) in
    sprintf "%s" argvStrCom
```

```
(* generate qubits *)
and writeQubit expr bra=
   (* let exp = string_of_int expr in *)
    sprintf "genQubit(\"%s\",%d)" expr bra
```

B.7 Scripts

B.7.1 Makefile

Makefile

```
#Christopher Campbell, Jonathan Wong
#stuff for compiling cpp files
CXX = g++
CPPDIR = ./cpp
INC = $(CPPDIR) ./includes/headers
INCLUDES =$(INC:%=-I%)
CXXFLAGS = -g -Wall $(INCLUDES)

OBJS = ast.cmo sast.cmo parser.cmo scanner.cmo analyzer.cmo generator.cmo qlc.cmo

.PHONY: default

default: qlc cpp/qlang.o


qlc : $(OBJS)
	ocamlc -g -o qlc $(OBJS)

scanner.ml : scanner.mll
	ocamllex scanner.mll

parser.ml parser.mli : parser.mly
	ocamlyacc parser.mly

%.cmo : %.ml
	ocamlc -g -c $<

%.cmi : %.mli
	ocamlc -g -c $<

cpp/qlang.o:
	$(MAKE) -C $(CPPDIR)


.PHONY : clean
clean :
	rm -f qlc parser.ml parser.mli scanner.ml *.cmo *.cmi
	$(MAKE) -C $(CPPDIR) clean

# Generated by ocamldep *.ml *.mli
analyzer.cmo: sast.cmo ast.cmo
analyzer.cmx: sast.cmx ast.cmx
generator.cmo: sast.cmo
generator.cmx: sast.cmx
parser.cmo: ast.cmo parser.cmi
parser.cmx: ast.cm parser.cmi
qlc.cmo: scanner.cmo sast.cmo parser.cmi ast.cmo analyzer.cmo
qlc.cmx: scanner.cmx sast.cmo parser.cmx ast.cmx analyzer.cmx
sast.cmo: ast.cmo
```

```
sast.cmx: ast.cmx
scanner.cmo: parser.cmi
scanner.cmx: parser.cmx
parser.cmi: ast.cmo
```

B.7.2 Compilation script

qlc.ml

```
(* Christopher Campbell, Winnie Narang *)
type action = Ast | Sast | Gen | Debug

let _ =
  let action =
    List.assoc Sys.argv.(1) [("-a", Ast); ("-s", Sast); ("-g", Gen); ("-d", Debug);]
  in
    let lexbuf = Lex
    ing.from_channel (open_in Sys.argv.(2)) (*stdin *) and
    output_file = String.sub Sys.argv.(2) 0 (String.length(Sys.argv.(2))-3) in
      let program = Parser.program Scanner.token  lexbuf in
        match action with
          Ast ->  print_string (Ast.string_of_program program)
          | Sast ->
            let sprogram =
              Analyzer.check_program program
            in
              print_string (Sast.string_of_sprogram sprogram)
          | Gen -> Generator.gen_program output_file (Analyzer.check_program program)
          | Debug -> print_string "debug"
```

B.7.3 Testing script

runTests.sh

```
#Christopher Campbell, Winnie Narang
#!/bin/bash

AST=0
SAST=0
GEN=0
COMP=0
EXEC=0


if [ $1 == "clean" ]
then
rm -f ast_error_log sast_error_log gen_error_log comp_error_log ast_log sast_log ast_output
    sast_output exec_output
rm -f SemanticSuccess/*.cpp SemanticSuccess/*.o
rm -f SemanticFailure/*.cpp SemanticFailure/*.o
rm -f Analyzer/*.cpp Analyzer/*.o
else

if [ $1 == "a" ]
then
AST=1
fi
```

```
if [ $1 == "s" ]
then
SAST=1
fi
if [ $1 == "g" ] || [ $1 == "c" ] || [ $1 == "e" ]
then
GEN=1
fi
if [ $1 == "c" ]
then
COMP=1
fi
if [ $1 == "e" ]
then
EXEC=1
fi

if [ $2 == "ss" ]
then
files="SemanticSuccess/*.ql"
cfiles="SemanticSuccess/*.cpp"
elif [ $2 = "sf" ]
then
files="SemanticFailures/*.ql"
cfiles="SemanticFailures/*.cpp"
elif [ $2 = "al" ]
then
files="Algorithms/*.ql"
cfiles="Algorithms/*.cpp"
fi

ASTCheck()
{
    eval "../qlc -a $1" 1>> ast_output 2>> ast_error_log
    wc ast_error_log | awk '{print $1}'
}

SASTCheck()
{
    eval "../qlc -s $1" 1>> sast_output 2>> sast_error_log
    wc sast_error_log | awk '{print $1}'
}

GenerationCheck()
{
    eval "../qlc -g $1" 2>> gen_error_log
    wc gen_error_log | awk '{print $1}'
}

CompilationCheck()
{
    eval "g++ -w $1 -I../includes/headers -L../includes/libs -lqlang" 2>> comp_error_log
    wc comp_error_log | awk '{print $1}'
}

ExecutionCheck()
{
    output=$(eval "./a.out")
    echo " " >> exec_output
    echo "Output: " >> exec_output
    echo "$output" >> exec_output
    echo "$output"
}

#Check AST
```

```
if [ $AST == 1 ]
then
echo "* AST Generation *"
rm -f ast_error_log ast_output
errors=0
prev_errors=0
for file in $files
do
errors=0
errors=$(ASTCheck $file)
if [ "$errors" -le "$prev_errors" ]
then
count=1
echo "Pass " $file
else
echo "Fail " $file
fi
prev_errors=$errors
done
echo ""
fi

#Check SAST
if [ $SAST == 1 ]
then
echo "* SAST Generation *"
rm -f sast_error_log sast_output
errors=0
prev_errors=0
for file in $files
do
errors=$(SASTCheck $file)
if [ "$errors" -le "$prev_errors" ]
then
echo "Pass: " $file
else
echo "Fail: " $file
fi
prev_errors=$errors
done
echo ""
fi

#Check Generation
if [ $GEN == 1 ]
then
cd ../cpp
make
cd ../test
echo "* Code Generation *"
rm -f gen_error_log
errors=0
prev_errors=0
for file in $files
do
errors=$(GenerationCheck $file)
if [ "$errors" -le "$prev_errors" ]
then
echo "Pass: " $file
else
echo "Fail: " $file
fi
prev_errors=$errors
done
echo ""
```

```
fi

#Check Compilation
if [ $COMP == 1 ]
then
echo "* Compilation *"
rm -f comp_error_log
errors=0
prev_errors=0
for file in $cfiles
do
errors=$(CompilationCheck $file)
if [ "$errors" -le "$prev_errors" ]
then
echo "Pass: " $file
else
echo "Fail: " $file
fi
prev_errors=$errors
done
echo ""
fi

# Execution check
if [ $EXEC == 1 ]
then
echo "* Compilation and Execution *"
rm -f comp_error_log exec_output
errors=0
prev_errors=0
exec_output=0
for file in $cfiles
do
errors=$(CompilationCheck $file)
if [ "$errors" -le "$prev_errors" ]
then
echo "Pass (compilation): " $file
exec_output=$(ExecutionCheck)
if [ "$exec_output" != "0" ]
then
echo "Pass (execution): " $file
echo $exec_output
else
echo "Fail (execution): " $file
fi
else
echo "Fail (compilation): " $file
fi
prev_errors=$errors
done
fi

fi
```

B.8 Programs

B.8.1 Demo

demo1.ql

```
# Sankalpa Khadka
def compute() : mat output{

        mat a;
        mat b;
        mat c;
        mat k;

        a = |11>;
        b = |0>;
        k = <0|;

        c = a @ b;
        printq(c);

        c = H*b;
        printq(c);

        output = b*k;
}
```

demo2.ql

```
# Sankalpa Khadka
def measure(mat top): mat outcome{
        mat ad;

        ad = adj(top);
        outcome = top*ad;
}

def outcomezero(mat bottom) : float probability{

        mat top;
        mat input;
        mat had;
        mat cnot;
        mat ynot;
        mat output;
        mat meas;

        top = |0>;
        input = top @ bottom;

        had = H @ IDT;
        cnot = [(1,0,0,0)
                (0,1,0,0)
                (0,0,0,1)
                (0,0,1,0)];


        ynot = [(1,0,0,0)
                (0,0,0,C(1.0I))
                (0,0,1,0)
                (0,C(-1.I),0,0)];

        output = (ynot*(cnot*(had*input)));

        printq(output);

        probability = norm(output);
```

```
}

def compute() : float outcome{

        mat bottom;

        bottom = |1>;
        outcome = outcomezero(bottom);
        print(outcome);

        bottom = |0>;
        outcome = outcomezero(bottom);
}
```

demo3.ql

```
# Sankalpa Khadka
# simulation of Deutsch's Algorithm
def measure (mat top) : mat outcome{
        # returns the measurement matrix for top qubit
        mat ad;

        ad = adj(top);
        outcome = top * ad;
}

def hadamard (int n) : mat gate{
        # returns Hadamard gate for n qubit system
        int i;
        gate = H;

        for (i from 0 to n-1 by 1){
            gate = gate @ H;
        }
}

def topqubit (int n) : mat input{
  # return zero qubit for n qubit system
        int i;
        input = |0>;

        for (i from 0 to n-1 by 1){
                input = input @ |0>;
        }
}

def deutsch (int n, mat U) : float outcomeZero{

        mat bottom; mat top; mat input;
        mat hadtop; mat meas;

        bottom = |1>;
        top = topqubit(n);
        input = top @ bottom;     # input qubit, tensor of top and bottom

        hadtop = hadamard(n);
        input = (hadtop @ H)*input;   # application of Hadamard gate
        input = U * input;        # application of the Oracle U
        input = (hadtop @ IDT)*input;   # application of Hadamard on top only, IDT-Identity
        meas = measure(top);

        input = (meas @ IDT)* input;    # measure zero on top register
        outcomeZero = norm(input);    # likelihood of getting zero on top register
```

```
}


def compute () : float outcome{

        int n; mat Ub; mat Uc;

  # test for n =1
        n = 1;
        # Ub - balanced , Uc - Constant Oracles
        Ub = [(1,0,0,0)(0,1,0,0)(0,0,0,1)(0,0,1,0)];
        Uc = [(1,0,0,0)(0,1,0,0)(0,0,1,0)(0,0,0,1)];

        outcome = deutsch(n, Ub);
        print(outcome);

        outcome = deutsch(n, Uc);
        print(outcome);

  #test for n=2
        n = 2;
        Ub = [(1,0,0,0,0,0,0,0)
              (0,1,0,0,0,0,0,0)
              (0,0,1,0,0,0,0,0)
              (0,0,0,1,0,0,0,0)
              (0,0,0,0,0,1,0,0)
              (0,0,0,0,1,0,0,0)
              (0,0,0,0,0,0,0,1)
              (0,0,0,0,0,0,1,0)];

        outcome = deutsch(n, Ub);
}
```

demo4.ql

```
# Sankalpa Khadka
# Simulation of Grover's Algorithm for f(0) =1
def measure (mat top) : mat outcome{
        # measurement matrix for top qubit
        mat ad;

        ad = adj(top);
        outcome = top * ad;
}

def ntensor (int n, mat k) : mat gate{
        # return k@k@...@k n times
        int i;
        gate = k;

        for (i from 0 to n-1 by 1){
            gate = gate @ k;
        }
}

def prepareU (int n) : mat gate {
  # Prepare the Uw of grover oracle
        mat i;
        mat u;

        i = [(1,0)
             (0,0)];

```

```
        u = ntensor(n+1, i);
        gate = ntensor(n+1,IDT)-2*u;
}

def prepareG (int n) : mat gate{
  # Prepare grover defusive operator
        mat s; mat sa; mat i; mat h;

        s = ntensor(n,|0>);
        sa = adj(s);
        i = ntensor(n,IDT);
        gate = 2*s*sa - i;
        h = ntensor(n, H);
        gate = h*gate*h;
        gate = gate @ IDT;
}

def grover (int n) : float outcomeZero{

        mat bottom; mat top; mat input;
        mat hadtop; mat u; mat g; mat go; mat meas;
        int i;

        bottom = |1>;
        top = ntensor(n, |0>);
        input = top @ bottom; # input is tensor of top and bottom registers

        hadtop = ntensor(n, H);
        input = (hadtop @ H)*input; # apply Hadamard gate
        u = prepareU(n);
        g = prepareG(n);

        go = g*u;          # Grover Operator

        for (i from 0 to n by 1){   # Apply grover operator over iteration
                input = go*input;
        }

        meas = measure(top);
        input = (meas @ IDT)* input;  # measure on top register
        outcomeZero = norm(input);  # likelihood to find 0 on top register
}


def compute () : float outcome{
        #simulate the grover for f(0)=1

        int n; mat Ub; mat Uc;
        n = 1;

        outcome = grover(n);
        print(outcome);

        n = 2;
        outcome = grover(n);
}
```

B.8.2 Successful Test cases

binop_comp_matrix.ql

```
#Winnie Narang
def test_func(comp a, comp b, comp c, comp d) : mat ret_val {

  mat x;

  x = [(a,b)(c,d)];

  ret_val = [(a,c)(d,b)];

  ret_val = ret_val * x;
  ret_val = ret_val + x;
  ret_val = ret_val - x;
  ret_val = ret_val / 2;
}

def compute() : mat ret_val {


  comp a;
  comp b;
  comp c;
  comp d;
    mat  k;

  a = C(4.+5.I);
  b = C(6.+6.I);
  c = C(7.+8.I);
  d = C(9.+10.I);

  ret_val = test_func(a, b, c, d);
}
```

binop_float_matrix.ql

```
#Winnie Narang
def test_func(float a, float b, float c, float d) : mat ret_val {

  mat x;

  x = [(a,b)(c,d)];

  ret_val = [(a,c)(d,b)];

  ret_val = ret_val * x;
  ret_val = ret_val + x;
  ret_val = ret_val - x;
  ret_val = ret_val / 2;

}

def compute() : mat ret_val {


  float a;
  float b;
  float c;
  float d;

  a = 3.4;
  b = 6.;
  c = 5.6;
  d = 100.0;
```

```
    ret_val = test_func(a, b, c, d);
}
```

binop_int_arith.ql

```
#Winnie Narang
def func_test(int z) : int ret_name {
        int a;
        int b;
        int d;
        a = z;
        b = 10;
        d = a+b*a+b/a-b;
        ret_name=d;
}
def compute( int a ): int trial {
      trial = func_test(34);
}
```

binop_tensor.ql

```
#Jonathan Wong
def compute():mat out {

        mat a;
        mat b;
        mat c;

        a = [(1)(0)];
        b = [(0)(1)];
        c= a@b;
        print(c);
}
```

break_continue.ql

```
#Winnie Narang
def func_test(int a) : int ret_name {

        int i;

        for(i from 0 to 2 by 1)
        a=a+5;

        for(i from 2 to 0 by -1)
        {
            a=a*10;
            print(a);
            break;
        }

        for(i from 1 to 5)
        {
            print(a);
            continue;
            a=a*10;
```

```
        }

    ret_name = a;
}

def compute(): int trial {

    trial = func_test(20);
}
```

builtin_matrix_ops.ql

```
#Sankalpa Khadka
def compute(): comp trial {

  int num_rows;
  int num_cols;
  comp val;
  mat m;

  m = [(1,2,3)(4,5,6)(7,8,9)];
  num_rows = rows(m);
  num_cols = cols(m);
  val = elem(m, 1,2);

  print(num_rows);
  print(num_cols);

  trial = val;
}
```

comp_type.ql

```
#Sankalpa Khadka
def compute(): comp trial {

  int num_rows;
  int num_cols;
  comp val;
  mat m;

  m = [(1,2,3)(4,5,6)(7,8,9)];
  num_rows = rows(m);
  num_cols = cols(m);
  val = elem(m, 1,2);

  print(num_rows);
  print(num_cols);

  trial = val;
}
```

constants.ql

```
#Jonathan Wong
def test_func(int a) : mat ret_val {

  mat x;
```

```
  mat z;
  mat y;
  mat w;

  x = X;
  z = H;
  y = Y;
  w = IDT;

  print(x);
  print(z);
  print(y);
  print(w);

  ret_val = x * z * y * w;
}

def compute() : mat ret_val {

  ret_val = test_func(0);
}
```

empty.ql

```
#Christopher Campbell
def test_func() : mat ret_val {

        mat x;

  x = [(1,2)(3,4)];

  ret_val = x;
}

def compute() : mat ret_val {

  ret_val = test_func();
}
```

float_type.ql

```
#Christopher Campbell
def func_test(float b) : float ret_name {

        float a;
  float c;

        a = 5.0;
  c = a * b;

        ret_name = c;
}

def compute() : float trial {

  trial = func_test(3.7);

}
```

for_stmt.ql

```
#Jonathan Wong
def func_test(int z) : int ret_name {

        int i;
        int a;

        for(i from 0 to 2 by 1)
        a=a+5;

        for(i from 2 to 0 by -1)
        {
            a=a*10;
            print(a);
        }

        for(i from 1 to 10 by 1)
        {
            a=a-3;
        }

  for(i from 1 to 100){
    print (a*100);
  }

    ret_name = 5;
}

def compute(int a): int trial {

   trial = func_test(20);
}
```

if_stmt.ql

```
#Winnie Narang
def func_test(int z) : int ret_name {

       int a;

      # comment before b; just checking for end of comment being correct

       int b;
       a = 10;

       if(z eq 5) a = 0;

       a = a - 2;
       if( z leq 5 )
       {
          a = 0;
       }
       else
       {
           a = 10;
           b = 24;
       }

       if( a gt 100 )
       {
           print(b); # a > 100
       }
```

```
        else
        {
            print(a);
        }

        ret_name = 8;
}
```

mat_add.ql

```
#Sankalpa Khadka
def test_func(comp a, comp b, comp c, comp d) : mat ret_val {

  mat x;

  x = [(a,b)(c,d)];

  ret_val = x;
}

def compute():mat trial {
  comp a;
  comp b;
  comp c;
  comp d;
        mat k;

  a = C(2.);
  b = C(2.);
  c = C(2.);
  d = C(2.);

  trial = test_func(a, b, c, d)+test_func(a,b,c,d);

}
```

mat_mult.ql

```
#Winnie Narang
def test_func(comp a, comp b, comp c, comp d) : mat ret_val {

  mat x;

  x = [(a,b)(c,d)];

  ret_val = x;
}

def compute():mat trial {
  comp a;
  comp b;
  comp c;
  comp d;
        mat k;

  a = C(2.);
  b = C(2.);
  c = C(2.);
  d = C(2.);

  trial = test_func(a, b, c, d)*test_func(a,b,c,d);
```

```
}
```

mat_qubit.ql

```
#Winnie Narang
def func_test(mat a, mat b) : mat ret_name {

        ret_name = a*b;

}


def compute(int a):mat trial {

   mat zero;
   mat one;

   zero = |0>;
   one = |1>;

      trial = func_test(H,zero);
      printq(trial);

      trial = func_test(H,one);
      printq(trial);

}
```

un_op_det.ql

```
#Winnie Narang
def func_test(mat z) : mat ret_name {
        mat a;
        comp b;
        a = [(1,9)(4,5)];
        b = det(a);
        ret_name = a;
}
def compute(int a):mat trial {
  mat x;
  x = [(1,2)(3,4)];
  trial = func_test(x);
}
```

un_op_trans.ql

```
def func_test(mat z) : mat ret_name {
        mat a;
        mat b;
        a=[(1,9,9)(4,5,5)];
        b = trans(a);
}
def compute(int a):int trial {
  trial = 8;
}
```

while_stmt.ql

```
#Winnie Narang
def func_test(int z) : int ret_name {
        int a;
        a = 5;


        #now checking while with comment
        while(a leq 10)
        a=a+1;

        while(a neq 1)
        {
            # Comment, inside
            a = (a+1) % 42;
        }

        ret_name = a;


}
def compute():int trial{

trial = func_test(5);
}
```

B.8.3 Execution output of successful cases

exec_output

```
Output:
(-12,76) (-11.5,98)
(-10,87.5)    (-6,114)

Output:
(21.46,0) (290.2,0)
(186.8,0)    (600,0)

Output:
364

Output:
2

Output:
(0,0)
(1,0)
(0,0)
(0,0)

Output:
30
30
30
30
30

Output:
3
3
```

```
(6,0)

Output:
(3.52,8.6)

Output:
(0,0)  (1,0)
(1,0)  (0,0)
 (0.707107,0)   (0.707107,0)
 (0.707107,0)  (-0.707107,0)
   (0,0)  (-0,-1)
   (0,1)     (0,0)
(1,0)  (0,0)
(0,0)  (1,0)
(0,-0.707107)  (0,-0.707107)
 (0,0.707107)  (0,-0.707107)

Output:
0
1
0

Output:
(1,0)  (2,0)
(3,0)  (4,0)

Output:
18.5

Output:
3275000
3275000
3275000
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5
```

```
Output:
4

Output:
10
8

Output:
20

Output:
(4,0)  (4,0)
(4,0)  (4,0)

Output:
(8,0)  (8,0)
(8,0)  (8,0)

Output:
(0.707107)|0> + (0.707107)|1>
(0.707107)|0> + (-0.707107)|1>
 (0.707107,0)
(-0.707107,0)

Output:
(0,0)  (0,0)
(0,0)  (0,0)

Output:
 (4,5)   (6,6)
 (7,8)  (9,10)

Output:
(-0,-4.5)

Output:
5
8

Output:
(0,0)  (1,0)  (1,0)  (0,0)

Output:
<01| + <10|
(0,0)  (1,0)  (1,0)  (0,0)

Output:
(1,-0)  (4,-0)
(9,-0)  (5,-0)
(9,-0)  (5,-0)

Output:


Output:
1

Output:
(1,0)  (9,0)
(4,0)  (5,0)

Output:
(4.5,0)
(0,4.5)
```

```
Output:
-5

Output:
8

Output:
1

Output:
8

Output:
8

Output:
8

Output:
1
```

B.8.4 Failed cases

comp_wrong_decl.ql

```
# Winnie Narang
def func_test(comp val1, comp val2) : comp ret_name {

  comp val3;
    val3 = 1;

  ret_name = val1 + val2 * val3;
}
def compute() : comp  ret_name {

  comp comp1;
  comp comp2;

   if (1) {1; 2+3;} else {3+6;}

  comp1 = C(7.5I);
  comp2 = C(3.2 + 1.I);

  ret_name = func_test(comp1, comp2);
}
```

func_decl_twice.ql

```
# Winnie Narang
def func_test1(int z) : int ret_name {
        int a;
        int b;
        int d;
        a = z;
        ret_name = z;

}
def func_test1(int z) : int ret_name2 {
```

```
        ret_name2 = z;

}
def compute( int a):int trial {

      trial = func_test1(4);
}
```

if_stmt.ql

```
# Winnie Narang
def func_test(int z) : int ret_name {

       int a;
       int b;
       a = 10;

       else
       {
       a = 10;
       b = 24;
       }
}


def compute(int a):int trial {

}
```

invalid_use_binop.ql

```
# Winnie Narang
def compute() : int ret_name_test
      {
        int test_int;
        ret_name_test = test_int - + test_int;

      }
```

mat_type.ql

```
# Winnie Narang
def test_func(comp a, comp b, comp c, comp d) : mat ret_val {

  mat x;
  mat f;
  x = [(a,b)(c,f)];
  ret_val = x;
}

def compute() : mat ret_val {


  comp a;
  comp b;
  comp c;
  comp d;
```

```
    a = C(4.+5.I);
    b = C(6.+6.I);
    c = C(7.+8.I);
    d = C(9.+10.I);

    ret_val = test_func(a, b, c, d);
}
```

mixed_datatypes.ql

```
# Winnie Narang
def func_test(int z) : int ret_name {
        int a;
        comp b;
        int d;
        a = z;
        b = C(7.5I);

        d = a+b*a+b/a-b;

        ret_name=d;
}
def compute( int a ): int trial {

      trial = func_test(35);
}
```

no_compute.ql

```
# Winnie Narang
def func_test(float z) : float ret_name {

        float a;
        a = 5.8;

        ret_name = z;
}
```

print_stmt.ql

```
# Winnie Narang
def func_test(int z) : int ret_name {
        int a;
        a = 5;
        a = z;
        ret_name = a;
}
def compute(int a):int trial {

        printq(a);
}
```

un_op_adj.ql

```
# Winnie Narang
def func_test(mat z) : mat ret_name {
        mat a;
        comp b;

        a =[(1,9,9)(4,5,5)];
        z = adj(b);

}


def compute(int a):int trial {

}
```

un_op_conj.ql

```
# Winnie Narang
def func_test(mat z) : mat ret_name {
        mat a;
        float b;

        a =[(1,9,9)(4,5,5)];

        b = conj(a);
}
def compute(int a):int trial {

}
```

un_op_cos.ql

```
# Winnie Narang
def func_test(int z) : int ret_name {
        int a;
        int b;
        a = 90;
        b = cos(a);

        comp d;
        d = C(7.5I);

        z = cos(d);
        ret_name=b;
}
def compute(int a):int trial {

}
```

undec_func_call.ql

```
# Winnie Narang
def func_test1(int z) : int ret_name {
        int a;
        int b;
        int d;
        a = z;
```

```
        ret_name = z;

}
def compute( int a):int trial {

        trial = func_test(4);
}
```

unmatched_args.ql

```
# Winnie Narang
def func_test1(int z, int c) : int ret_name {
        int a;
        int b;
        int d;
        a = z;

        ret_name = z;

}

def compute( int a):int trial {

      trial = func_test1(4);
}
```

var_undeclared.ql

```
# Winnie Narang
def compute() : int ret_name_test
      {
        int test_int;
        ret_name_test = test_float;

      }
```

B.8.5 Output for failed cases

test.out

```
#generated for test cases under SemanticFailures
Fatal error: exception Analyzer.Except("Invalid assignment to variable: val3")
Fatal error: exception Analyzer.Except("Invalid function declaration: func_test1 was already
     declared")
Fatal error: exception Parsing.Parse_error
Fatal error: exception Parsing.Parse_error
Fatal error: exception Analyzer.Except("Invalid matrix: incorrect type")
Fatal error: exception Analyzer.Except("Invalid assignment to variable: d")
Fatal error: exception Analyzer.Except("Missing 'compute' function")
Fatal error: exception Analyzer.Except("Invalid function call: incorrect type for parameter
    ")
Fatal error: exception Analyzer.Except("Invalid use of unop: 'Adj(expr)'")
Fatal error: exception Analyzer.Except("Invalid assignment to variable: b")
Fatal error: exception Parsing.Parse_error
Fatal error: exception Analyzer.Except("Invalid function call: func_test was not declared")
Fatal error: exception Analyzer.Except("Invalid function call: incorrect number of
    parameters")
```

```
Fatal error: exception Analyzer.Except("Invalid use of a variable: test_float was not
    declared")
```

B.9 C++ Helper files

B.9.1 qlang.cpp

```
//Jonathan Wong
#include <Eigen/Dense>
#include <iostream>
#include <complex>
#include <string>
#include <cmath>
#include "qlang.hpp"

using namespace Eigen;
using namespace std;


MatrixXcf tensor(MatrixXcf mat1, MatrixXcf mat2) {

  int mat1rows = mat1.rows();
  int mat1cols = mat1.cols();
  int mat2rows = mat2.rows();
  int mat2cols = mat2.cols();

  MatrixXcf output(mat1rows * mat2rows, mat1cols * mat2cols);

  //iterates through one matrix, multiplying each element with the whole
  //2nd matrix
  for(int m = 0; m < mat1rows; m++) {
    for(int n = 0; n < mat1cols; n++) {
      output.block(m*mat2rows,n*mat2cols,mat2rows,mat2cols) =
        mat1(m,n) * mat2;
    }
  }

  return output;

}

Matrix4cf control(Matrix2cf mat) {
  Matrix4cf output;
  output.topLeftCorner(2,2) = IDT;
  output.topRightCorner(2,2) = Matrix<complex<float>,2,2>::Zero();
  output.bottomLeftCorner(2,2) = Matrix<complex<float>,2,2>::Zero();
  output.bottomRightCorner(2,2) = mat;

  return output;
}

MatrixXcf genQubit(string s, int bra) {

  int slen = s.length();
  int qlen = pow(2,slen); //length of vector

  int base10num = 0;

  //iterates through qstr. Whenever digit is a 1, it adds the associated
```

```
  //power of 2 for that position to base10num
  const char * cq = s.c_str();
  char * c = new char();
  for(int i = 0; i < slen; i++) {
    strncpy(c,cq+i,1);
    base10num += strtol(c,NULL,10) * pow(2,(slen-1-i));
  }
  delete c;

  //creates the vector and sets correct bit to 1
  MatrixXcf qub;
  if(bra) {
    qub = MatrixXcf::Zero(1,qlen);
    qub(0,qlen-1-base10num) = 1;
  } else if(!bra){
    qub = MatrixXcf::Zero(qlen,1);
    qub(base10num,0) = 1;
  }

  return qub;
}

string vectorToBraket(MatrixXcf qub) {
  int bra;
  int qlen;

  //determines whether bra or ket
  if(qub.rows() == 1) { qlen = qub.cols(); bra = 1; }
  else if(qub.cols() == 1) { qlen = qub.rows(); bra = 0;}
  else { //prints reg matrix if not row or column vector
    //cerr << "Incorrect matrix size for vectorToBraket" << endl;
    //exit(1);
    ostringstream  test;
    test << qub << endl;
    return test.str();
  }

  //gets position of 1 in the qubit
  complex<float> zero(0,0);
  int xi = 0;
  int yi = 0;
  int number;
  int index;
  string result;
  int count = 0;
  for(index = 0; index < qlen; index++) {
    if(bra) { xi = index; }
    else { yi = index; }

    if(qub(yi,xi) != zero) {
      //if(bra) { number = qlen-1-index; }
      //else { number = index; }
      number = index;

      //converts position to binary number reversed
      string bin = "";
      do {
        if ( (number & 1) == 0 )
          bin += "0";
        else
          bin += "1";

        number >>= 1;
      } while ( number );

```

```
      int outQubLen = sqrt(qlen);

      //adds necessary 0s
      for(int i = bin.length(); i < outQubLen; i++) {
        bin += "0";
      }

      reverse(bin.begin(), bin.end()); //reverses

      ostringstream convert;
      float re = qub(yi,xi).real();
      float im = qub(yi,xi).imag();
      string oper = "";
      string rstr = "";
      string istr = "";

      //adds constant expression
      convert << "(";
      if(re != 0) { convert << re; }
      if(re != 0 && im != 0) { convert << "+"; }
      if(im != 0) { convert << im << "i"; }
      convert << ")";

      //cleans up (1) and (1i) cases
      string constant = convert.str();
      if(constant.compare("(1)") == 0) { constant = ""; }
      else if(constant.compare("(1i)") == 0) { constant = "i"; }

      //generates appropriate bra or ket representation
      string qubstr;
      if(bra) { qubstr = constant + "<" + bin + "|"; }
      else { qubstr = constant + "|" + bin + ">"; }

      if(count > 0) {
        result += " + " + qubstr;
      } else { result = qubstr; }
      count++;
    }
  }
  return result;
}
```

B.9.2 qlang.hpp

```
//Jonathan Wong
#ifndef QLANG_HPP_
#define QLANG_HPP_

using namespace Eigen;
using namespace std;

//CONSTANTS
const Matrix2cf H = (Matrix2cf() << 1/sqrt(2), 1/sqrt(2),
        1/sqrt(2), -1/sqrt(2)).finished();
const Matrix2cf IDT = Matrix2cf::Identity();
const Matrix2cf X = (Matrix2cf() << 0, 1, 1, 0).finished();
const Matrix2cf Y = (Matrix2cf() << 0, -std::complex<float>(0,1),
        std::complex<float>(0,1), 0).finished();
const Matrix2cf Z = (Matrix2cf() << 1, 0, 0, -1).finished();

```

```
//METHODS
MatrixXcf tensor(MatrixXcf mat1, MatrixXcf mat2);
Matrix4cf control(Matrix2cf mat);
MatrixXcf genQubit(string s, int bra);
MatrixXcf genQubits(string s);
string vectorToBraket(MatrixXcf qub);


#endif
```