Quark

The Team

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Why Quark?

Quantum computing has the potential to become a reality in the next few decades. We're thinking ahead of the curve and have developed a language that makes it easy to build quantum circuits, which consist of quantum gates and quantum registers holding qubits.

Quantum Computing will allow us to:

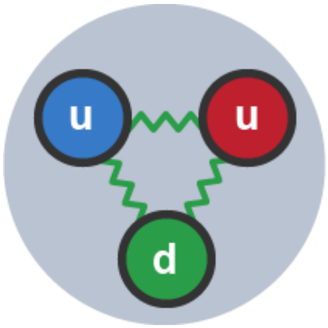
- Factorize large integers in polynomial time (Shor's algorithm)
- Search unsorted database in sublinear time (Grover's Search)
- Build the Infinite Improbability Drive and solve intergalactic travel

What is Quark?

"QUantum Analysis and Realization Kit"

A high-level language for quantum computing that encapsulates mathematical operations and quantum computing specific components like quantum registers.

A futuristic compiler on your laptop.



Features

- Easy-to-use, high-level language influenced by MATLAB and Python
- Useful built-in data types for fractions and complex numbers
- Support for matrices and matrix operations
- Quantum registers and ability to query them
- Built-in quantum gate functions
- Imports
- Informative semantic error messages
- Cross-platform

How did we do it?

Compiler flow:

- Preprocessor
- Scanner
- Parser
- AST
- Semantic Checker
- SAST
- Code Generator
- OS-aware g++ invocation
- Quantum Simulator (Quark++)

Preprocessor

- Resolves import statements before the scanner and parser stages
- Recursively finds all imports and prepends them to the file
- Handles cyclic and repetitive imports

Scanner

Based on MicroC

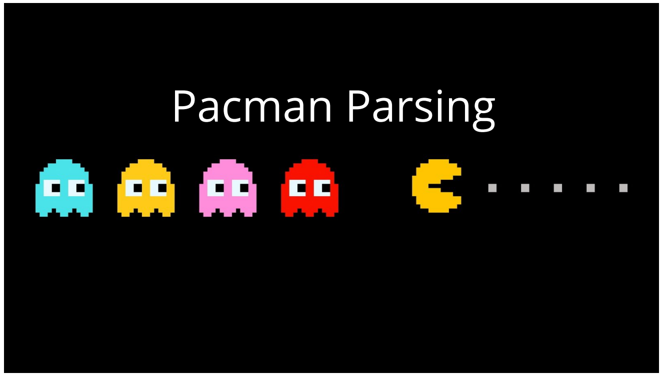
All the usual tokens + specific ones for

- fractions : 1$2
- complex numbers : i(3, 4)
  - i can still be used as a variable, not a function
- matrix operations : [|1,2; 3,4|], A', A ** B
- quantum registers and querying : qreg, <|10,1|>, q ? [1:5], q ?' 3

Parser

Grammar was developed incrementally

- Quantum registers query
- Matrix and high dimensional array literals
- Membership
- Fractions, complex numbers
- Pythonic for-loops



Some example rules

```
expr:
  ...
  /* Query */
  | expr ? expr
  | expr ? [ : expr ]
  | expr ? [expr : expr ]
  ...
  /* Membership testing with keyword 'in' */
  | expr in expr
  ...
  /* literals */
  | expr $ expr
  | [| matrix_row_list |]
  | i( expr , expr )
  | <| expr , expr |>

iterator:
  | ident in [range]
  | datatype ident in [range]
  | datatype ident in expr
```

Lexical and syntactical analysis complete

Now we need semantic checks

Valid syntax doesn't always make sense

The importance of semantic checks in real life

Semantic Checker

- StrMap hashtables
  - Variable table

```
type var_info = {
  v_type: A.datatype;
  v_depth: int; (* how deep in scope *)
}
```

  - Function table

```
type func_info = {
  f_args: A.datatype list;
  f_return: A.datatype;
  f_defined: bool; (* for forward declaration *)
}
```

Semantic Checker

- Environment struct

```
type environment = {
    var_table: var_info StrMap.t;
    func_table: func_info StrMap.t;
    (* current function name waiting for 'return' *)
    (* if "", we are not inside any function *)
    func_current: string;
    depth: int;
    is_returned: bool;
    in_loop: bool;  (* check break/continue validity *)
}
```

Semantic Checker

- From AST to SAST

```
and expr =
  | Binop of expr * binop * expr
  | AssignOp of lvalue * binop * expr
  | Queryop of expr * queryop * expr * expr
  | Unop of unop * expr
  | PostOp of lvalue * postop
  | Assign of lvalue * expr
  | IntLit of string
  | BoolLit of string
  | FractionLit of expr * expr
  | QRegLit of expr * expr
  | FloatLit of string
  | StringLit of string
  | ArrayLit of expr list
  | ArrayCtor of datatype * expr
  | MatrixLit of expr list list
  | MatrixCtor of datatype * expr * expr
```

```
and expr =
  | Binop of expr * A.binop * expr * op_tag
  | Queryop of expr * A.queryop * expr * expr * op_tag
  | Unop of A.unop * expr * op_tag
  | PostOp of lvalue * A.postop
  | Assign of lvalue * expr
  | IntLit of string
  | BoolLit of string
  | FloatLit of string
  | StringLit of string
  | FractionLit of expr * expr
  | QRegLit of expr * expr
  | ComplexLit of expr * expr
  | ArrayLit of A.datatype * expr list
  | ArrayCtor of A.datatype * expr (* int size of new a
  | MatrixLit of A.datatype * expr list * int (* column
  | MatrixCtor of A.datatype * expr * expr (* int, int
)
```

Semantic Checker

- Traverse AST recursively to produce SAST

```
| A.ComplexLit(real_ex, im_ex) ->
  let env, s_real_ex, real_type = gen_s_expr env real_ex in
  let env, s_im_ex, im_type = gen_s_expr env im_ex in (
  match real_type, im_type with
  | A.DataType(T.Int), A.DataType(T.Int)
  | A.DataType(T.Int), A.DataType(T.Float)
  | A.DataType(T.Float), A.DataType(T.Int)
  | A.DataType(T.Float), A.DataType(T.Float) ->
    env, S.ComplexLit(s_real_ex, s_im_ex), A.DataType(T.Complex)
  | _ -> failwith @@ compound_type_err_msg "complex" real_type im_type
  )
```

Semantic Checker

- Tag the SAST with op_tag constants to facilitate code generation

```
(* tag what operator is actually used in C++ *)
type op_tag =
  | OpVerbatim  (* no change to the operator *)
  | CastComplex1 (* cast the first arg to complex *)
  | CastComplex2 (* cast the second arg to complex *)
  | CastFraction1 (* cast the first arg to fraction *)
  | CastFraction2 (* cast the second arg to fraction *)
  | OpFloatComparison (* equality/inequality with tolerance *)
  | OpArrayConcat
  | OpStringConcat
  | OpMatrixKronecker
  | OpMatrixTranspose
  | OpQuerySingleBit (* measure only a single bit, not a range *)
```

Semantic Checker

- Tag the SAST with op_tag constants to facilitate code generation

```
let binop_math op type1 type2 =
    let notmod = op <> A.Mod in
    let notmodpow = notmod && op <> A.Pow in
    match type1, type2 with
    | T.Float, T.Int
    | T.Int,   T.Float
    | T.Float, T.Float when notmod ->
        T.Float, S.OpVerbatim
    | T.Int,   T.Int ->
        T.Int, S.OpVerbatim
    | T.Float, T.Complex
    | T.Int, T.Complex when notmod ->
        T.Complex, S.CastComplex1
    | T.Complex, T.Float
    | T.Complex, T.Int when notmod ->
        T.Complex, S.CastComplex2
    | T.Complex, T.Complex when notmod ->
        T.Complex, S.OpVerbatim
    | T.Int, T.Fraction when notmodpow ->
        T.Fraction, S.CastFraction1
    | T.Fraction, T.Int when notmodpow ->
        T.Fraction, S.CastFraction2
```

Semantic Checker

- Separate source file for built-in functions (e.g. quantum gates)
- Can be overridden by users
- print() and print_noline() support any number of args of any type

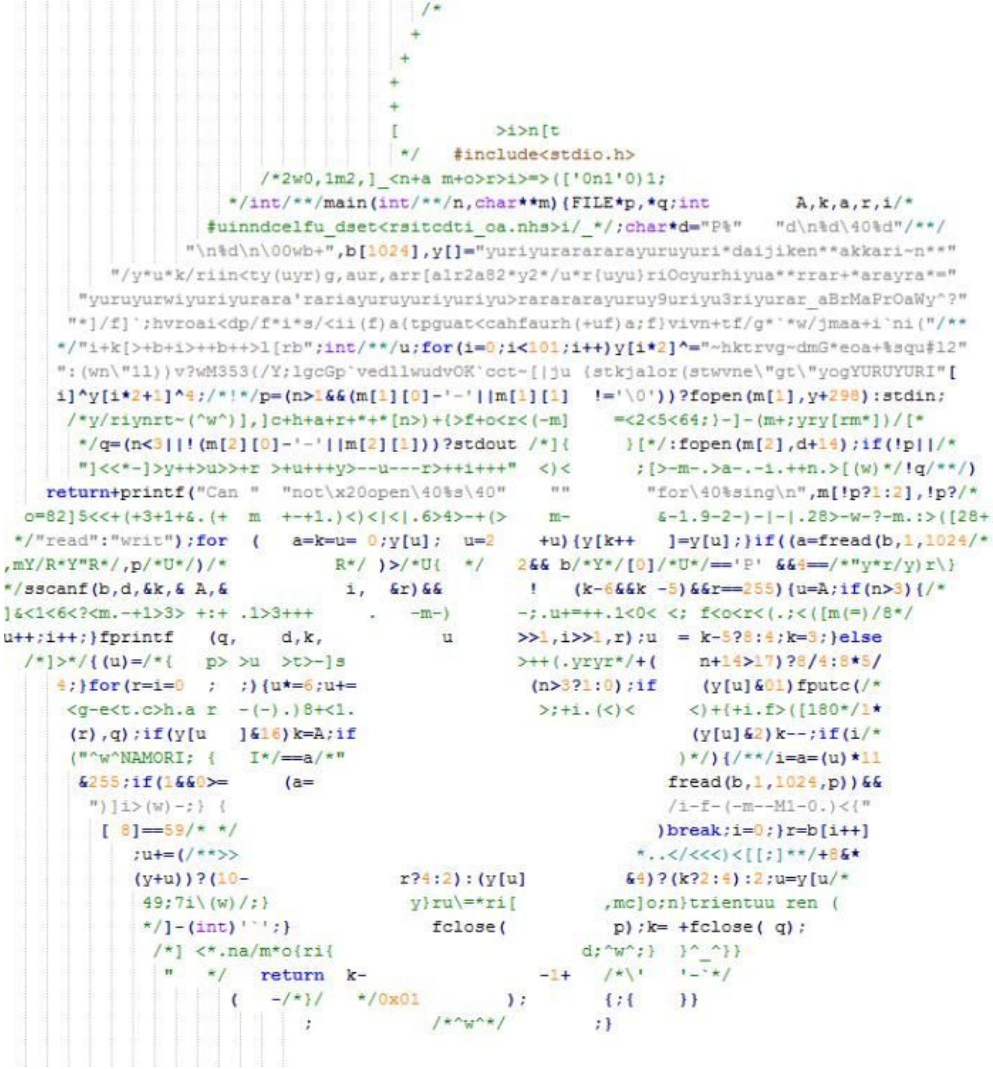
```
| "phase_scale" -> [qreg; f; i], void
| "phase_shift" -> [qreg; f; i], void
  (* multi-bit gates *)
| "generic_1gate" -> [qreg; cx_mat; i], void
| "generic_2gate" -> [qreg; cx_mat; i; i], void
| "generic_ngate" -> [qreg; cx_mat; A.ArrayType(i)], void
  (* control gates *)
| "cnot" -> [qreg; i; i], void
| "toffoli" -> [qreg; i; i; i], void
| "control_phase_shift" -> [qreg; f; i; i], void
| "ncnot" -> [qreg; A.ArrayType(i); i], void
```

Semantic Checker

Error messages

- "A function is confused with a variable: u"
- "Function foo() is forward declared, but called without definition"
- "If statement predicate must be bool, but fraction provided"
- "Array style for-loop must operate on array type, not complex[|]"
- "Matrix element unsupported: string"
- "Incompatible operands for **: string -.- fraction"
- "All rows in a matrix must have the same length"

Code Generation



Code Generation

- Recursively walks the SAST to generate a string of valid C++ program
- The generated string, concatenated with a header string, should compile with the simulator and Eigen library

```
let header_code =
 "#include \"qureg.h\"\n" ^
 "#include \"qumat.h\"\n" ^
 "#include \"qugate.h\"\n" ^
 "#include \"quarklang.h\"\n\n" ^
 "using namespace Qumat;\n" ^
 "using namespace Qugate;\n\n"
```

- No exception should be thrown at this stage

Code Generation

Type Mapping

- int → C++ int64_t
- float → C++ primitive float
- string → C++ std::string
- complex → C++ std::complex<float>
- arrays → C++ std::vector<>
- matrices → Eigen::Matrix<float, Dynamic, Dynamic>
- fraction → Quark++ Frac class
- qreg → Quark++ Qureg class

Code Generation

Op Tag

```
| S.OpVerbatim ->
  if op = A.Pow then (* special: not infix! *)
    two_arg "pow" expr1_code expr2_code
  else
    parenthize expr1_code op expr2_code
| S.CastComplex1 ->
  parenthize (cast_complex expr1_code) op expr2_code
| S.CastComplex2 ->
  parenthize expr1_code op (cast_complex expr2_code)
| S.CastFraction1 ->
  parenthize (cast_fraction expr1_code) op expr2_code
| S.CastFraction2 ->
  parenthize expr1_code op (cast_fraction expr2_code)
| S.OpArrayConcat ->
  two_arg "concat_vector" expr1_code expr2_code
| S.OpStringConcat ->
  parenthize expr1_code A.Add expr2_code
| S.OpMatrixKronecker ->
  two_arg "kronecker_mat" expr1_code expr2_code
| S.OpFloatComparison ->
  let equal_func = if op = A.Eq then
    "equal_tolerance" else "unequal_tolerance"
```

Code Generation

Pythonic for-loop

- [len(a) : 0 : step(x)]   the step size can be negative
- Whether step(x) is negative or not can only be determined at runtime
- We use system generated temp variables to handle this.
  Always prefixed with "_QUARK_" and followed by a string of 10 random chars.

Code Generation

Pythonic for-loop

```
def int step:
{
    return 2 - 4;
}

def int main:
{
    for int i in [10 : 0: step()]:
        print(i);
    return 0;
}
```

```
#include "qureg.h"
#include "qumat.h"
#include "qugate.h"
#include "quarklang.h"

using namespace Qumat;
using namespace Qugate;

int64_t step()
{
return (2 - 4);
} // end step()

int main()
{
int64_t _QUARK_5H0aq5mw6x = 0;
int64_t _QUARK_v3YH0O1B0h = step();
int64_t _QUARK_l03AMaXh6u = _QUARK_v3YH0O1B0h > 0 ? 1 : -1;
for (int64_t i = 10;
    _QUARK_l03AMaXh6u * i < _QUARK_l03AMaXh6u * 0;
    i += _QUARK_v3YH0O1B0h){
std::cout << std::boolalpha
    << std::setprecision(6) << i << std::endl;
} // end for-range
return 0;
} // end main()
```

Code Generation

More examples

```
(4 if i(9) != i(9, 0) else 3)
+ (3$7 if "sh" == "sh" else 8$19);
```

```
(Frac((unequal_tolerance(std::complex<float>(9, 0.0), std::complex<float>(9, 0)
) ? 4 : 3), 1)
 + ((std::string("sh") == std::string("sh")) ? Frac(3, 7) : Frac(8, 19)));
```

Code Generation

More examples

```
complex[|][] matarray = [
    [| i(2), i(-1); i(PI/2), i(0, -E); i(.2), i(.5) |],
    [| i(0), i(PI**2); i(.1), i(0); i(3), i(.5) |]
];
matarray[0] + complex[| 2, 3 |];
```

```
vector<Matrix<std::complex<float>, Dynamic, Dynamic>> matarray = vector<Matrix<
std::complex<float>, Dynamic, Dynamic>>{ matrix_literal(2, vector<std::complex<
float>>{ std::complex<float>(2, 0.0), std::complex<float>((-1), 0.0), std::comp
lex<float>((3.141592653589793 / 2), 0.0), std::complex<float>(0, (-2.7182818284
59045)), std::complex<float>(.2, 0.0), std::complex<float>(.5, 0.0) }), matrix_
literal(2, vector<std::complex<float>>{ std::complex<float>(0, 0.0), std::compl
ex<float>(pow(3.141592653589793, 2), 0.0), std::complex<float>(.1, 0.0), std::c
omplex<float>(0, 0.0), std::complex<float>(3, 0.0), std::complex<float>(.5, 0.0
) }) };

(matarray[0] + Matrix<std::complex<float>, Dynamic, Dynamic>::Zero(2, 3));
```

Simulator: Quark++

Simulator: Quark++

- Written over the summer. Built from scratch except for the Eigen matrix library.
- Features optimized C++11 code for quantum register manipulation and quantum gates/operations.
- Can be used as a standalone library for any quantum computing education or research project
- Minor modification to accomodate the Quark language.

User Interface

- Command line args
  - -s: source
  - -c: generated.cpp
  - -o: excutable
  - -sc, -sco
  - -static
- Precompiled dynamic/static libraries
- Minimal user effort to install dependencies
- OS aware. Supports all major OSes

Let's look at some code

A simple Hello World

```
def int main:
{
    print("Hello, Ground!");

    return 0;
}
```

It was unfortunately a very short hello for our whale friend

Defining types

```
int i = 4;
float f = 2.0;
bool b = true;
string s = "So Long, and Thanks for All the Fish";
string[] arr = ["Ford", "Prefect", "Zaphod", "Beeblebrox"];
int[][] arr2 = [[1,2,3],[4,5,6]];

fraction f = 84$2;
complex c = i(5.0, 7.0);
float[||] = [|1.0, 2.1; 3.2, 46.1|];

qreg q = <| 42, 0 |>;
```

Special operations

```
% FRACTIONS
frac foo = 2$3;
~foo; % 3$2
int i = 5;
i > foo; % true

% COMPLEX NUMBERS
complex cnum = i(3.0, 1);
real(cnum); % 3.0
imag(cnum); % 1
complex cnum2 = i(9) % this gives us i(9, 0)

% MATRICES
float[||] mat = [| 1.2, 3.4; 5.6, 7.8 |];
mat[2, 1];
mat'; % transpose matrix

% QUANTUM REGISTERS
qreg q = <|10, 3|>;
hadamard(q);
q ? [2:10];  % measures qubit 2 to 10
```

Control flow

```
if x > 0:
    print("positive");
elif x < 0:
    print("negative");
else:
    print("zero");


while x > 42: {
    print(x);
    x = x - 1;
}


int[] arr = [1,2,3];
for int i in arr:
    print i;


int i;
for i in [1:10]
for int i in [1:10:2]
```

Imports

```
import ../lib/mylib1;
import ../lib/herlib2;

import imported_file;

def int main:
{
    return imported_file.function(5);
}
```

So Fancy!

Simple GCD

```
def int gcd: int x, int y
{
    while y != 0:
    {
        int r = x mod y;
        x = y;
        y = r;
    }
    return x;
}

def int main:
{
    % prints the greatest common divisor of 10 and 20
    print(gcd(10, 20));
    return 0;
}
```

Quantum Computing Demo Time

Hang on to your Towel!

Let's see **Shor's algorithm** and **Grover's Search** in action! Real quantum computing programs running on a not-so-real quantum computer (our simulator)

What did we learn?

Start early!!!

OCaml:

[oh-kam-uh l]

Mostly harmless

Interacting with other homo sapiens

- Group projects are painful (more so than Vogon poetry)
- Allocating work strategically avoids bottlenecks in pipeline
- Better communication saves time and headaches
- Dictatorship > Democracy when it comes to software