QuantC: A CUDA-Inspired Language for Quantum Computing

Crash Course in Quantum Computing: Qubits

- *Qubits* are like bits, but are based on some quantum phenomenon with a binary set of states when measured
- Can store 0 and 1 like a regular bit, but can also be in a *superposition* of 0 and 1
- Measuring a qubit causes it to *collapse* into either a 0 or 1 if it's in a superposition

Crash Course in Quantum Computing: Gates and Measuring

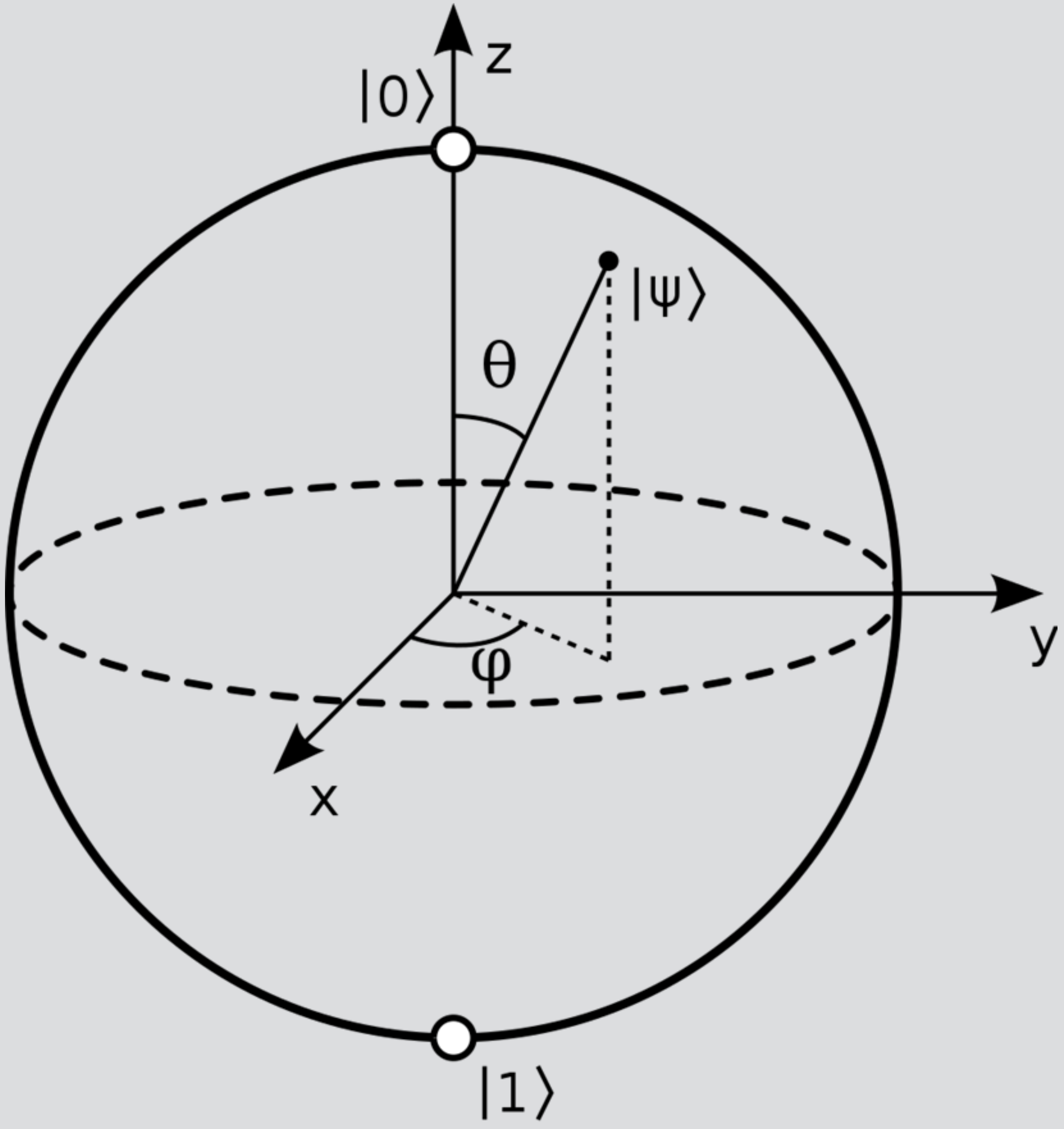
- A common representation of computations on qubits is as a circuit, with operations represented as *quantum logic gates*
- Quantum circuits are just as computationally powerful as classical circuits
- However, quantum circuits do have some constraints classical versions don't have
    - Gates/circuits must be reversible; at minimum, the # outputs = # inputs
    - Gates can't be used to copy or delete arbitrary quantum states

Crash Course in Quantum Mechanics

- Value of a qubit is represented by a normalized vector in $\mathbb{C}^2$
  - First coefficient is always taken to be real
- Gates are unitary matrices in $\mathbb{C}^{2^n \times 2^n}$
  - Unitary: $UU^\dagger = U^\dagger U = I$
- Measurement corresponds to randomly picking a base state, where the probability of picking it is based on the coefficient in the qubit vector

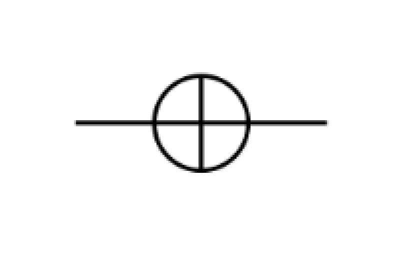
$$|\psi\rangle = \sin\left(\frac{\theta}{2}\right)|0\rangle + \cos\left(\frac{\theta}{2}\right)e^{i\varphi}|1\rangle$$

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

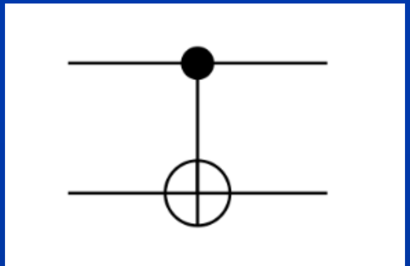


Examples of Quantum Gates

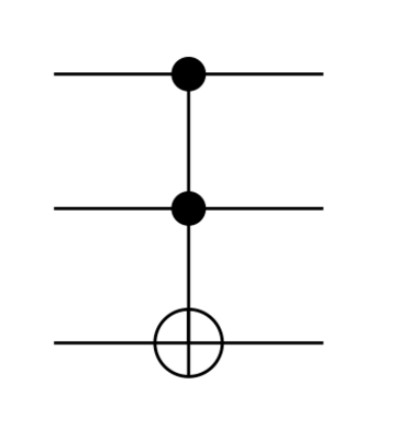
Classically Equivalent Gates



NOT (a.k.a X-gate)

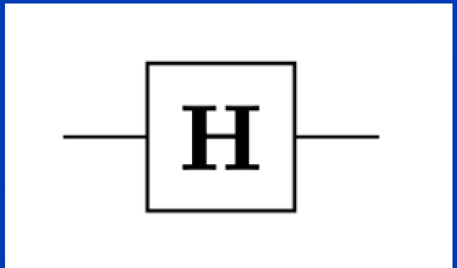


XOR
(a.k.a Controlled NOT, CNOT)

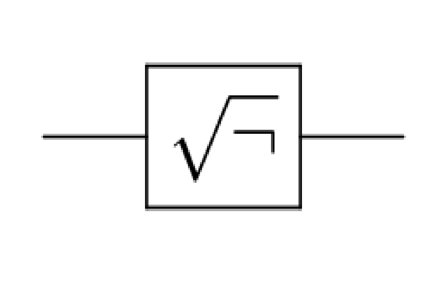


AND (a.k.a Toffoli gate, CCNOT)

Purely Quantum Gates



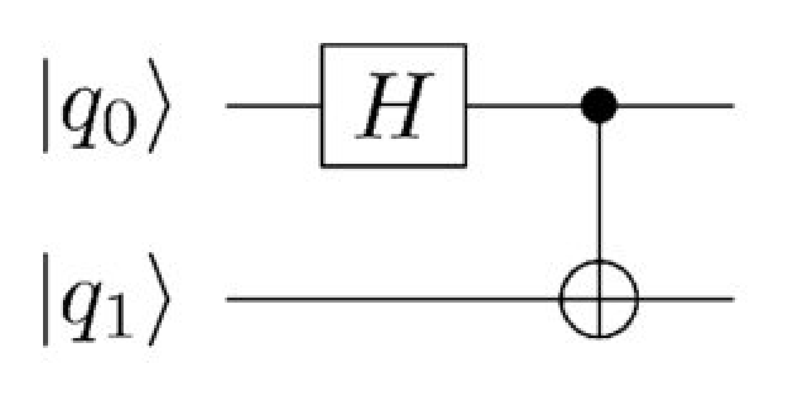
Hadamard gate



$\sqrt{NOT}$ gate

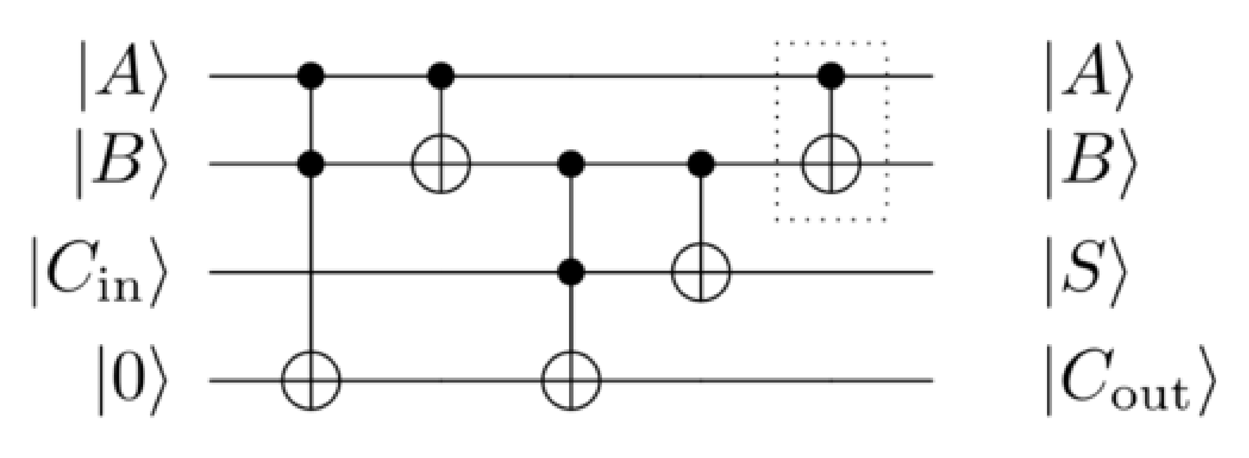
Simple Circuit Examples

Entanglement Circuit



$$|00\rangle \rightarrow \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Full Adder



Design Goals

- Create a language with syntax to support creating programs with both classical and quantum components
- Minimize the overhead for learning the language
    - Extend an existing language, rather than start from scratch
    - Make distinguishing the two parts of code clear
    - Only introduce new syntax for new concepts
    - Avoid overloading the meaning of existing symbols for quantum code unless the semantics are closely related
- Abstract communication between the classical and quantum computers

Standard C Code

```c
void saxpy(int n, float a,
           float *x, float *y)
{
  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}

int N = 1<<20;



// Perform SAXPY on 1M elements
saxpy(N, 2.0, x, y);
```

C with CUDA extensions

```c
__global__
void saxpy(int n, float a,
           float *x, float *y)
{
  int i = blockIdx.x*blockDim.x + threadIdx.x;
  if (i < n) y[i] = a*x[i] + y[i];
}

int N = 1<<20;
cudaMemcpy(x, d_x, N, cudaMemcpyHostToDevice);
cudaMemcpy(y, d_y, N, cudaMemcpyHostToDevice);

// Perform SAXPY on 1M elements
saxpy<<<4096,256>>>(N, 2.0, x, y);

cudaMemcpy(d_y, y, N, cudaMemcpyDeviceToHost);
```

Storage Classifier: quantum

- Keyword on functions to distinguish between classical code and quantum code
- Inside quantum functions, variables can also be marked as quantum to differentiate between qubits and bits

```
quantum int hello_quantum() {
    int a,b;
    quantum int q0,q1;
```

Calling Quantum Functions

- When calling a quantum function in classical code, the compiler substitutes it with a call to a function to transmit the compiled quantum code to the quantum computer
    - The quantum *intermediate representation* (IR) is stored as a string created by the compiler
    - It's assumed that any additional translation from the quantum IR to quantum machine instructions is handled by the quantum computer itself
- Constraints on quantum functions
    - Can have quantum arguments, but they must be pass by reference (pointer)
    - Only functions with exclusively classical arguments passed by value can be called from classical code
    - They can return values, but only classical values
    - Recursive calls are not allowed

```
int main() {
    hello_quantum(...);
}
```

```
char * hello_quantum_str = "...";

int main() {
    _quant_comm(hello_quantum_str, ...);
}
```

```
quantum void qfunc1();                   // Okay
quantum int  qfunc2();                   // Okay
quantum void qfunc3(int a);              // Okay
quantum void qfunc4(quantum int * a);    // Okay
quantum void qfunc5(quantum int a);      // Error
```

Semantics of Quantum Variables

- With qubits, what assignment means becomes tricker to define
  - Between two quantum variables, assignment has *move semantics* rather than *copy semantics*
  - The variables being assigned to must be uninitialized, and the variables being used in the assignment expression can't be used again
  - When working with expressions with multiple variables, need to establish a 1-to-1 mapping of names across assignment
  - This is all checked by the compiler at compile time

```
quantum int hello_quantum() {
    int a, b;
    quantum int q0, q1, q2, q3;

    ...

    a = b;      // Allowed; classical assignment acts like normal
    q1 = a;     // Allowed; classical to quantum assignment simply sets
                // qubits to corresponding base states.
    a = q1;     // Denied; assignment from quantum to classical memory
                // needs to have the qubit measured first.
    a = %M q1;  // Allowed; Measurement operator
                // collapses `q1` state and stores result in `a`
    q2 = q1;    // Allowed, but `q1` is no longer usable

    auto [q2, q3] = q0 <> q1;  // Allowed, but only if q2, q3 are unitiialized

    ...
```

Quantum Operations (Classical)

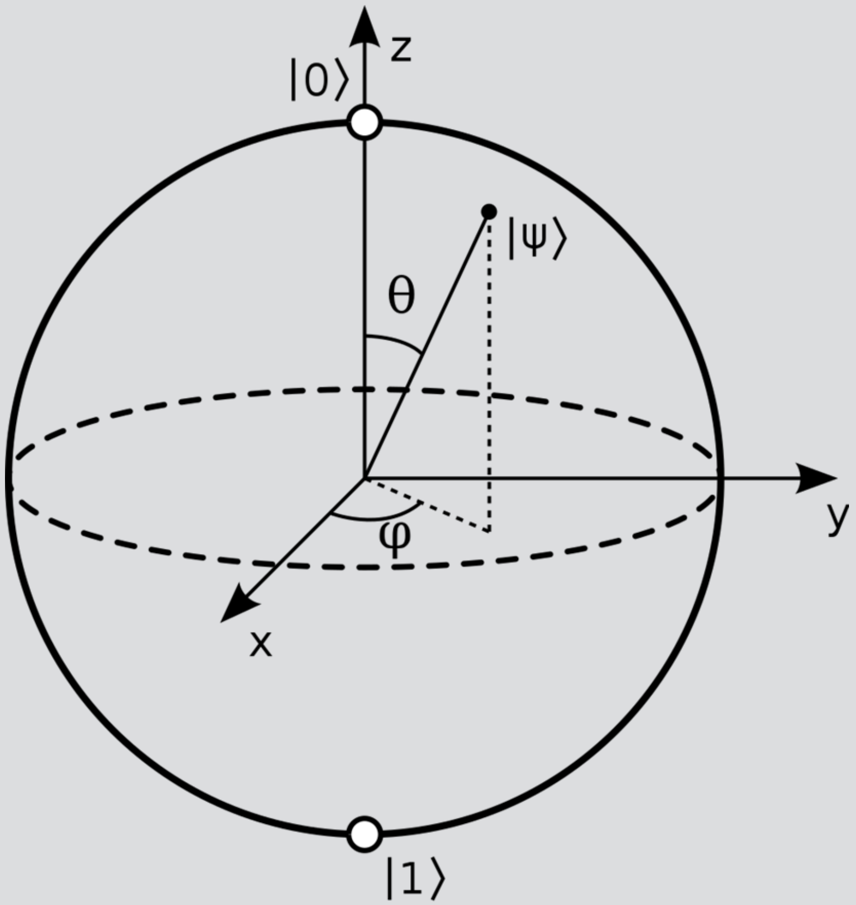
```
// Classical gates
~q1;              // NOT (also called X gate);
q1 ^ q2;          // Implictly CNOT; q2 becomes q1 XOR q2
q1 & q2 : result; // Implictly Toffoli (CCNOT)
                  // result becomes result XOR q1 AND q2;
q1 | q2 : result; // Implicitly Toffoli + NOT gates
                  // result becomes result XOR q1 OR q2;
```

Quantum Operations (Unary)

```
%I q1; // Identity gates (does not change qubit)
%Y q1; // Pauli Y gate
%Z q1; // Pauli Z gate
%H q1; // Hadamard
```

```
// Phase gates
// Parameters of gates must be a float
%PHASE(angle) q1; // General phase gates, parametrized by an angle
%S q1; // phase gate with angle = pi/2
%T q1; // phase gate with angle = pi/4
```

```
// Rotation gates
// Parameters of gates must be a float
%RX(angle) q1;
%RY(angle) q1;
%RZ(angle) q1;
```



Quantum Operations (Binary)

```
// Swap gates
// Parameters of gates must be a float
q1 <P>(angle) q2; // General swap; parametrized by an angle
q1 <> q2; // Classical swap; angle = 0
q1 <I> q2; // Imaginary swap; angle = pi/2
```

Quantum Operations (Modifiers)

```
// Controlled gates
// You can add control qubits to any gate by postfixing with +c(qubit)
%H+C(q2) q1;

// Reverse gate
// Prefixing a gate with ~> apllies the inverse of that gate
~>%H (%H q2); // same as %I q2;
```

Implementation

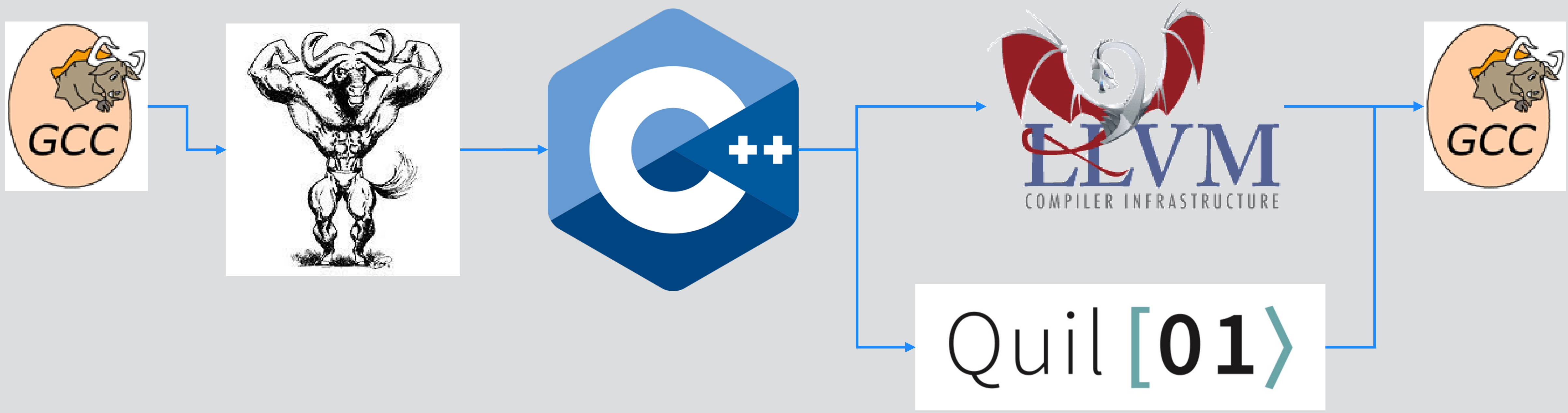
Preprocessing:
GCC

Lexer & Parser:
Flex & Bison

AST & Semantics
Checking:
Hand-coded

Code generation:
LLVM (Classical)
Quil (Quantum)

Linking:
GCC



Progress

- Established compilation of minimal amount of classical/quantum code
  - Basically, can compile main() and make a call to a quantum function
  - Can compile down to Linux object files/executables
  - Can link with standard C library code
- Created a basic version of code that can communicate quantum code with a local simulator (QVM) over HTTP
- Next Phase
  - Complete quantum operation code generation
  - Handle assignment of quantum variables
  - Handle generate code for multiple quantum functions in the same translation unit
  - Add all/most classical constructs (if/else, for loop, etc.) to both kinds of code

Demo