Quantum Computing II

CSCI 2050U - Computer Architecture

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Outline

- Qubits
  - A comparison with bits
  - Qubit implementations
    - Photons
    - Electrons
- Quantum circuits
  - Initialization
  - Transformations
  - Measurement

Qubits

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Qubits

- A quantum bit (aka a qubit) is the most basic unit of data in a quantum computer
  - Like a bit, it can have the value zero (0) or one (1)
  - Unlike a bit, however, a qubit can be in a superposition
    - i.e. A given qubit can be *some* zero and *some* one
    - Examples:
      - 0 with 100% probability
      - 1 with 100% probability
      - 0 with 50% probability and 1 with 50% probability
      - 0 with 33% probability and 1 with 67% probability
      - etc.

Qubit Implementations

- Photons
  - As we've already seen, one physical concept that experiences quantum effects is a photon (w.r.t. polarization)
  - Photons can be measured with respect to some alignment, and the result will be horizontal vs. vertical (photons can be in a superposition of the two)
- Electrons
  - Electron "spin" is very similar, since an electron's spin can be in a superposition of "spin up" and "spin down"
    - More info on electron "spin": https://www.youtube.com/watch?v=3k5IWlVdMbo
  - This tends to be a bit more popular for actual quantum computer construction, since electrons tend to hang around longer

Quantum Circuits

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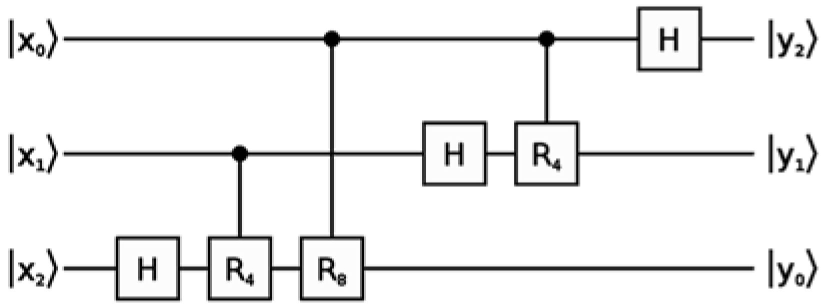
Quantum Circuits

- Quantum computing doesn't involve programs as we know them (at least not exclusively)
- To perform a quantum computation, we build a quantum circuit
  - Like a digital circuit, a quantum circuit is made up of various **inputs**, **gates**, and **outputs**



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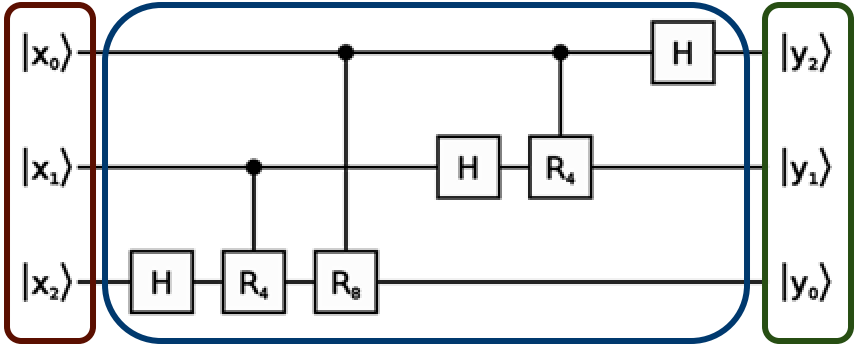
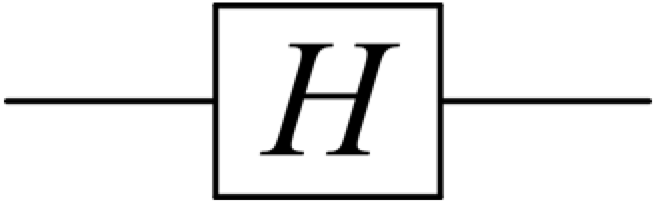


Quantum Circuits

- Quantum circuits involve three phases:
  - Initializing the qubits
  - Performing various transformations on one or more qubits at a time
  - Measuring the qubit values

1. Initialization

- We may want to initialize our qubits in one of several ways:
  - Initialize to zero (0) (notation |0>)
  - Initialize to one (1) (notation |1>)
  - Initialize to a superposition: 50% probability of zero (0), 50% probability of one (1)
  - etc.
- For option #3, there is a quantum gate called a Hadamard gate
  - This puts a single qubit into superposition, where it is equally probable for it to be measured as 0 and 1
- Initialization is irreversible

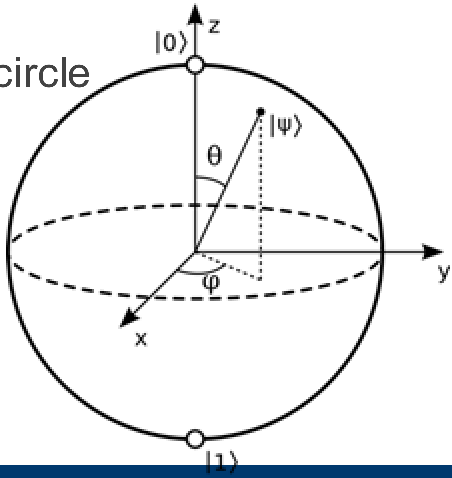


2. Transformations

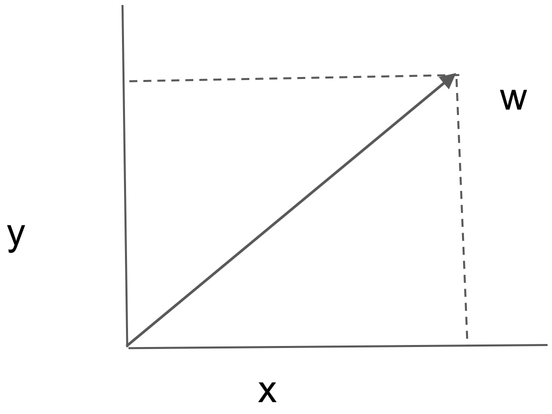
- Much like in digital circuits, a number of gates are used to transform the qubits
  - X (Pauli-X gate, an inverter)
  - Z (Pauli-Z gate, another kind of inverter)
  - CNOT (conditional NOT)
- There are many more, but these few should be enough for us to build something interesting

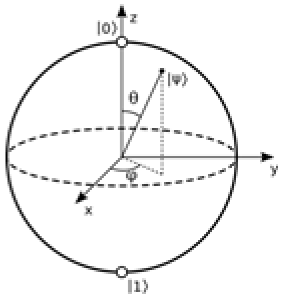
2. Transformations

- Since a qubit can be partly 0 and partly 1 (when in superposition), we often use a circle to represent the state of a qubit
  - *Note: A sphere would be more appropriate (called a Bloch sphere), since the coefficients are actually complex numbers, not necessarily real numbers*
  - The state of a qubit is represented as a vector on this circle (sphere)
- Transformations are typically rotations of these vectors, around the circle (sphere)
  - Since rotations are reversible, so are these transformations



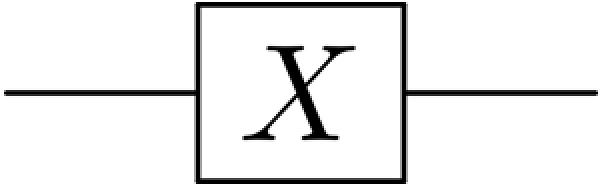
2. Transformations





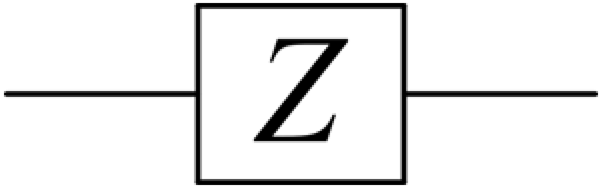
w = **a** * x + **b** * y

2. Transformations (X)



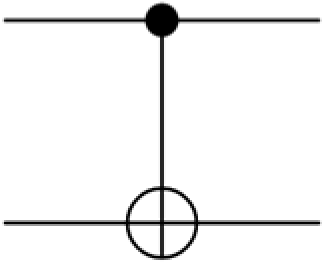
- X gate
  - |0> is transformed to |1>
  - |1> is transformed to |0>
  - 30% |0> and 70% |1> is transformed to 70% |0> and 30% |1>
- *Hint: Think of any quantum state as some amount of each possible binary state*
  - e.g. α|0> + β|1>
    1. |0> can be re-written as 1.0|0> + 0.0|1>
    2. |1> can be re-written as 0.0|0> + 1.0|1>
    3. 30% |0> and 70% |1> can be re-written as √0.3|0> + √0.7|1>

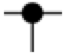
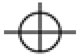
2. Transformations (Z)



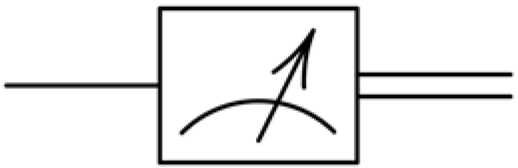
- Z gate
  - Flips the sign of the 2nd co-efficient
  - |0> (i.e. 1.0|0> + 0.0|1>) is transformed to |0> (i.e. 1.0|0> + -0.0|1>)
  - |1> (i.e. 0.0|0> + 1.0|1>) is transformed to 0.0|0> + -1.0|1>
  - 0.3|0> + 0.7|1> is transformed to 0.3|0> + -0.7|1>

2. Transformations (CNOT)



- CNOT (conditional NOT) gate
  - Our first two-qubit quantum gate
    - First bit - control bit 
  - Operation:
    - If the first bit is |0>, the second bit is unchanged 
    - If the first bit is |1>, the second bit is inverted (like the X gate)
- Some quantum gates operate on three or more qubits (e.g. Toffoli)

3. Measurement



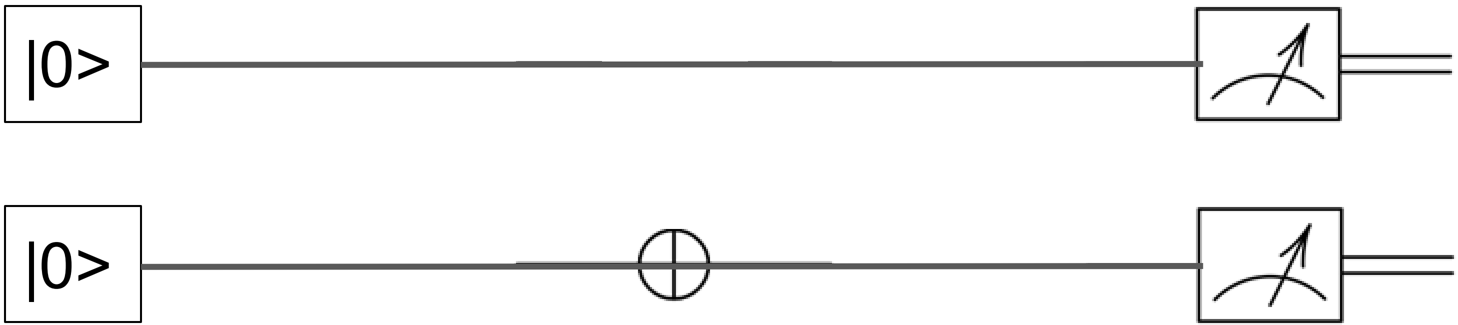
- Measurement must be done carefully, since:
    - The output of a measurement is binary (e.g. spin up vs. spin down)
    - Measurement actually changes the value
- With qubits in superposition, the only way to know the actual value is to repeat the computation many times
    - The result will be a set of probabilities
    - e.g. out of 1000 executions, 342 of them resulted in zero, and 658 of them resulted in one
- Measurement is irreversible

Details

- Quantum computing can be simulated in software using linear algebra
  - Quantum states are represented as vectors
  - Quantum gates are represented as matrices
- As this math isn't covered until 2nd year, we can only scratch the surface of what you can do with quantum computing
  - If you are interested in quantum computing, check out CSCI 4140U (Quantum Computing Software and Applications)
  - Quantum computing requires some math background, but surprisingly very little physics

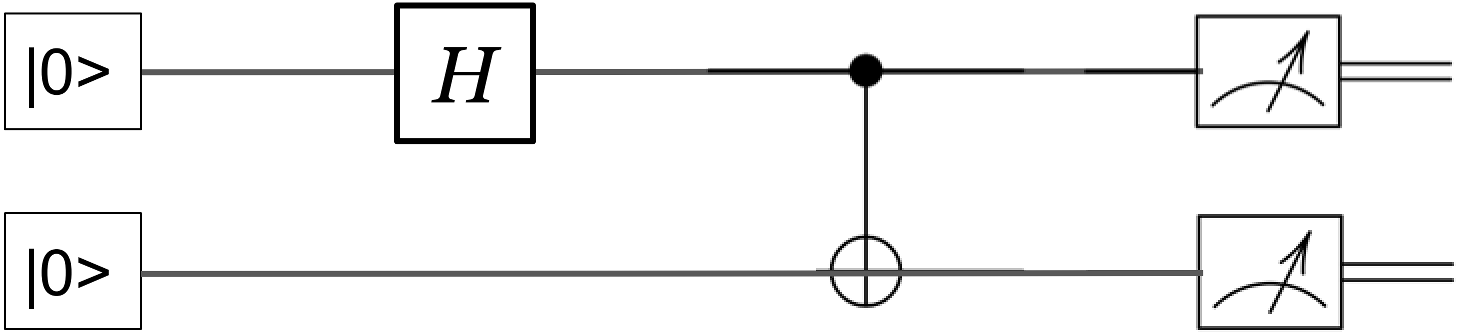
Example - Inverter

- This circuit is very similar to classical circuits



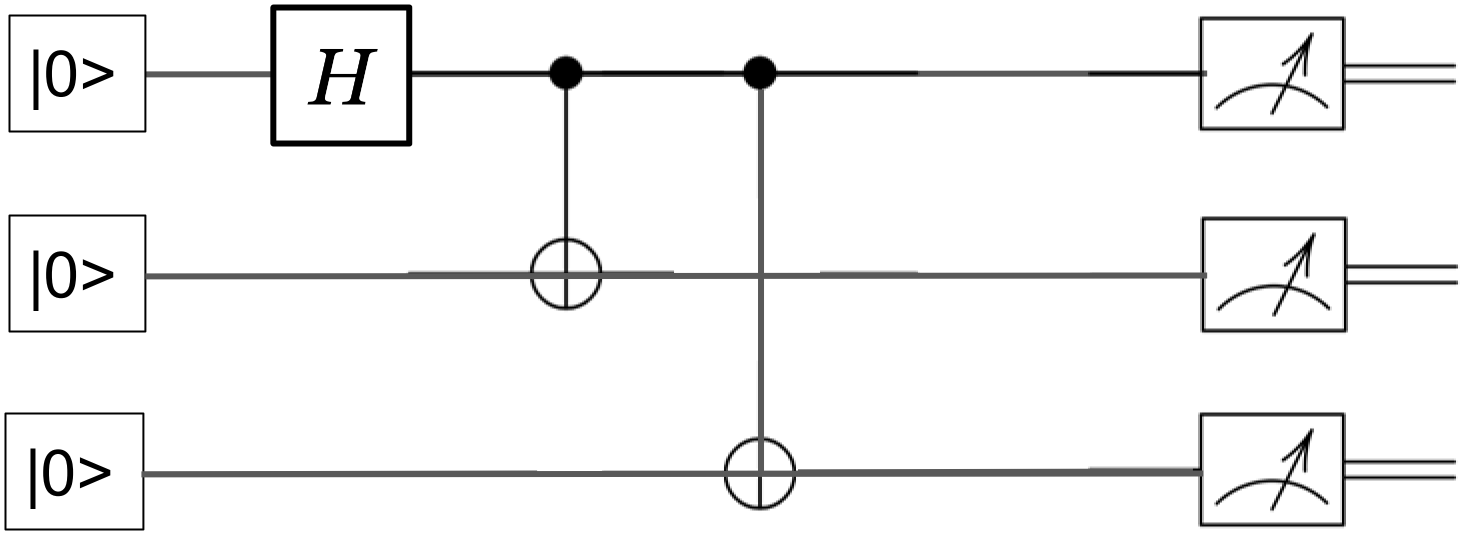
Example - Bell Test

- Two qubit entanglement



Example - GHZ State

- Three qubit entanglement



Wrap-up

- Qubits
  - A comparison with bits
  - Qubit implementations
    - Photons
    - Electrons
- Quantum circuits
  - Initialization
  - Transformations
  - Measurement

What is next?

- This is the end of this lecture, but if you want to find out more you can read about it on IBM's Quantum Computing Field Guide:
    - https://quantum-computing.ibm.com/composer/docs/iqx/guide

- Want to try out some quantum circuits on your own?
    - https://quantum-computing.ibm.com/composer
    - You need an account, but it is free and you can even run your circuits on one of IBM's real (mostly 7 qubit) quantum computers