MARIST

School of Computer Science and Mathematics

Introduction to Quantum Computer Algorithms and Programming

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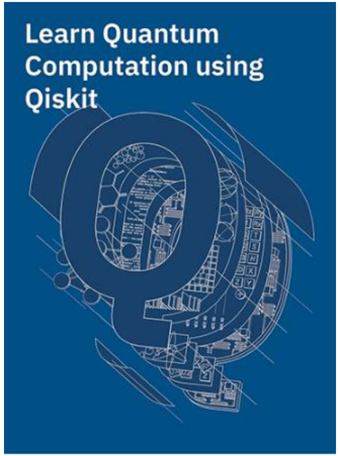


Enterprise Computing Conference (ECC)
June 7-9, 2020
Hosted on a virtual platform
https://ecc.marist.edu/web/conference2020

Overview

- What is quantum computing?
  - How is it different from digital computing
  - What kind of problems can it solve
  - Qubits, superposition, entanglement
  - Example Algorithm using IBM Q Systems
  - Summary and Conclusions

Marist Course Overview

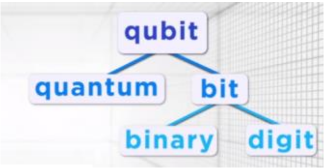
- **12 week online course presented by Marist College IDCP**
- **Earn a Digital Badge recognized by IBM and many other companies**
- **Topics to be covered include:**
  - **Fundamentals of quantum computing (qubits, entanglement, superposition, quantum gates)**
  - **Sample quantum computing algorithms (Simon, Grover, Shor, etc.)**
  - **How to program the IBM Q System quantum computer with Qiskit**
- **Background Material**
  - **Familiarity with Linear Algebra and Matrix Multiplication (all the required math will be covered in this class)**
  - **Familiarity with Python and Jupyter notebooks (class includes an introductory tutorial)**

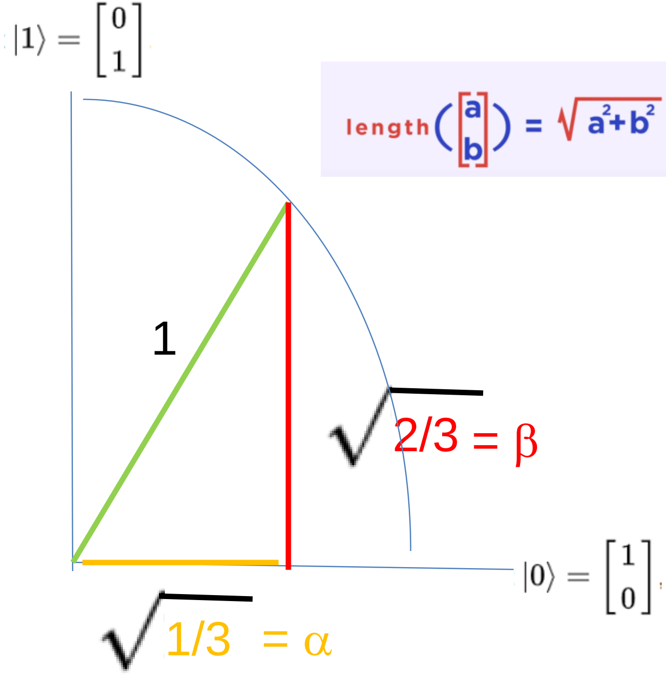
https://idcp.marist.edu/

Limits of Conventional Computing

- **Exponential execution time**
  - **Problems with exponential speedup (chess board example)**
    64 squares: 1+2+4+8… = 18,446,744,073,709,551,615 or $2^{64} - 1$
    about 1,199,000,000,000 metric tons of wheat
    or about 1600 times the global supply in 2019!
- **What kinds of problems can't be solved by classical computers?**
  - **Simulating the real world (chemistry limited to a few atoms)**
  - **Optimization (best way to seat 10 people at a dinner table, selecting the "best" route for thousands of cars traveling through a large city or the best network spanning tree)**
  - **Sorting an unordered list in square root N time (quadratic speedup)**
  - **Reversible computations (quantum computers use far less energy)**
  - **Determining prime factors of 100 digit numbers (encryption)**
- **N qubits is the equivalent of 2^N classical bits**
- **We can simulate quantum computing on conventional computers, or limit quantum computers so they act like digital computers**

Qubits and Superposition





$$\text{length}\left(\begin{bmatrix}a\\b\end{bmatrix}\right) = \sqrt{a^2+b^2}$$

The horizontal component is the square root of the probability of being in state 0, and the vertical component is the square root of the probability of being in state 1.

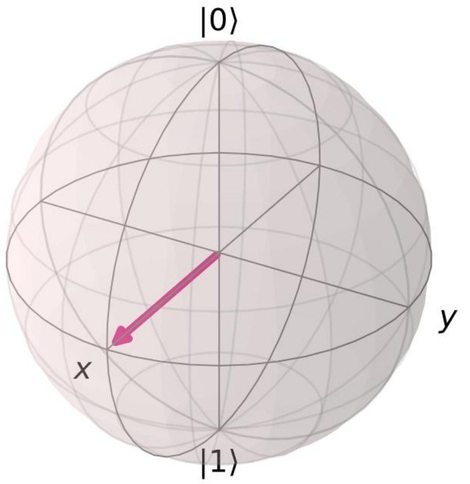
$$|q\rangle = \alpha|0\rangle + \beta|1\rangle \rightarrow \begin{bmatrix}\alpha\\\beta\end{bmatrix} \qquad \alpha, \beta \in \mathbb{C}$$

The qubit is in **superposition** between the 0 and 1 states. When measured, a qubit collapses to the state 0 with probability $|| \alpha ||^2$ and to the state 1 with probability $|| \beta ||^2$

We can also write qubits in the form

$$|q\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

if we interpret the two angles as spherical coordinates, we can visualize any qubit state on the surface of a unit sphere
(called the **Bloch Sphere**)



"We can apply all our existing knowledge and intuition about balls to our understanding of qubits."
– IBM's Learn Quantum Computation using Qiskit open source book (2019)

Entanglement

The product state of two qubits cannot be factored; one example is a **Bell Pair**

$$\begin{pmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ 0 \\ \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} \otimes \begin{pmatrix} c \\ d \end{pmatrix}$$

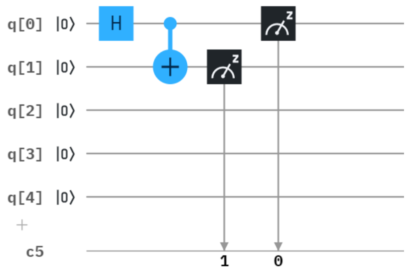
$$\begin{aligned} ac &= \frac{1}{\sqrt{2}} \\ ad &= 0 \\ bc &= 0 \\ bd &= \frac{1}{\sqrt{2}} \end{aligned}$$

In an effort to discredit quantum mechanics, Einstein and his colleagues tried to show that entanglement led to obviously absurd results (EPR Paradox).

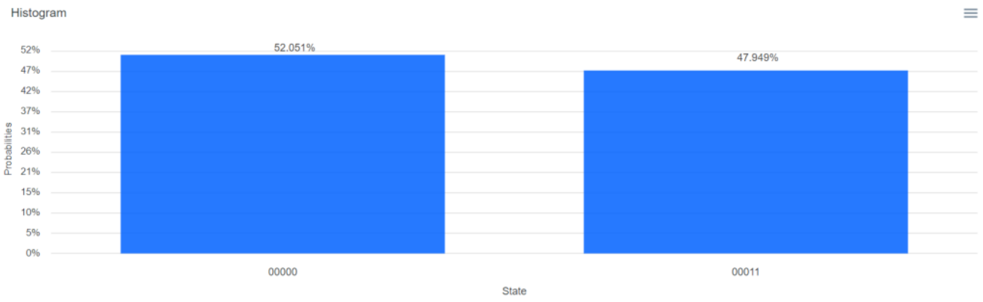
- “Spooky action at a distance”
- Using two atomic clocks spaced thousands of miles apart, scientists were able to show that this is exactly what happens!
- Leads to quantum encryption and teleportation

Try This At Home – Hello, Quantum World!

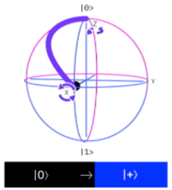
```
OPENQASM 2.0;
include "qelib1.inc";

qreg q[5];
creg c[5];

h q[0];
cx q[0],q[1];
measure q[1] -> c[1];
measure q[0] -> c[0];
```

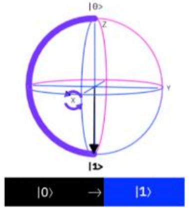


Result



$$CH_1\left(\begin{pmatrix}1\\0\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}\right) = C\left(\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}}\end{pmatrix}\otimes\begin{pmatrix}1\\0\end{pmatrix}\right) = \begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{pmatrix}\begin{pmatrix}\frac{1}{\sqrt{2}}\\0\\ \frac{1}{\sqrt{2}}\\0\end{pmatrix} = \begin{pmatrix}\frac{1}{\sqrt{2}}\\0\\0\\ \frac{1}{\sqrt{2}}\end{pmatrix}$$





Create your own entangled qubits & disprove the EPR Paradox from the comfort of your living room couch!

Summary and Conclusions

- **Motivated the study of quantum computing by postulating a number of very interesting, high impact problems which classical computers cannot solve.**
- **Just as classical computers challenged many previous assumptions, quantum computers represent a fundamentally different way of approaching problems.**
- **We introduced the qubit and discussed how properties like superposition and entanglement can be used in quantum computing.**
- **While you can get in on the ground floor & learn about quantum computers from the comfort of your home, we've got a long way to go before quantum computing is commonplace.**
- **Sign up at** https://idcp.marist.edu/ **today; Classes begin online in fall 2020**