#### Grover's Search Algorithm and the IBM Quantum Experience

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#### Overview

Introduction





**Building Quantum Circuits** 



Demonstration of Grover's algorithm on IBM QE



### Introduction

- Research Staff Member in the Experimental Quantum Computing Group at IBM
- Experiments involve superconducting quantum computing and
  - Integrating larger numbers of qubits
  - Fast qubit measurement and feedback
  - Among other things!



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Shor 1994







Shor 1994



Grover 1996







Grover 1996



Shor 1994



2017



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#### Grover's Search Algorithm

- One of the key algorithms for quantum computers
- Unstructured Search of N elements
  - Classical computer ~ N/2
  - Quantum computer ~  $\sqrt{N}$
- Not exponential speedup, but enough to matter for
  - Big Data applications
  - Subroutine for other quantum algorithms
- Requires two key ingredients that use superposition and interference
  - Oracle
  - Amplitude Amplification



#### **Classical vs Quantum Bits**



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#### **Qubit State and Measurement**

- General qubit state is a superposition  $|\psi
angle=lpha|0
angle+eta|1
angle$ 





Qubit operations (using microwave pulses) rotate the state





Black box that recognizes something when it sees it





- Black box that recognizes something when it sees it
- Distinction between verification and knowing
  - Testing whether a key opens a door vs breaking the lock





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- Encode a list of stuff in binary and define function f s.t.
  - f(x) = 0 when wrong answer
  - $-\tilde{f(w)} = 1$  when correct answer (winner!)





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$$|x\rangle \to (-1)^{f(x)}|x\rangle$$





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Index	State
1	$ 00\rangle$
2	$ 01\rangle$
3	$ 10\rangle$
4	$ 11\rangle$



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State	Oracle
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$ 01\rangle$	$ 01\rangle$
$ 10\rangle$	$- 10\rangle$
$ 11\rangle$	$ 11\rangle$
	$\begin{array}{c}  00\rangle \\  01\rangle \\  10\rangle \\  11\rangle \end{array}$



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- Oracle will act on superposition of all states
- Oracle is quantum operation  $U_f$  that performs
- Amplitude Amplification
  - Use interference to increase likelihood of measuring correct index



Index	State	Oracle
1	$ 00\rangle$	$ 00\rangle$
2	$ 01\rangle$	$ 01\rangle$
3	$ 10\rangle$	$- 10\rangle$
4	$ 11\rangle$	$ 11\rangle$



 $|x\rangle \rightarrow (-1)^{f(x)}|x\rangle$ 

We have  $N = 2^n$  items indexed by n qubits

















## **Building Quantum Circuits**



#### **Classical Gate Operations**

NOT Gate (Bit Flip)



AND Gate



OR Gate



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Many Classical Gates are "oneway": Outputs are not unique



#### **Quantum Operations**

Single Qubit Operations

Input	Output			
	X	Z	S	H
$ 0\rangle$	$ 1\rangle$	$ 0\rangle$	$ 0\rangle$	$( 0\rangle +  1\rangle)/\sqrt{2}$
$ 1\rangle$	$ 0\rangle$	$- 1\rangle$	$i 1\rangle$	$( 0\rangle -  1\rangle)/\sqrt{2}$



#### **Quantum Operations**

Single Qubit Operations



 $(|0\rangle - |1\rangle)$ 

InputOutputXZSX0100

 $|0\rangle$ 

 $-|1\rangle$ 

 $i|1\rangle$ 

**Two-qubit Operations** 

 $|1\rangle$ 



Controlled-NOT flips second qubit if first qubit is 1

 $\sqrt{2}$ 





#### **Quantum Operations**

Single Qubit Operations



Output Input XZSH $|0\rangle$  $|1\rangle$  $(|0\rangle$  $|0\rangle$  $|0\rangle$  $|0\rangle$  $i|1\rangle$  $|1\rangle$  $|1\rangle$  $(|0\rangle - |1\rangle$ 





Controlled-NOT flips second qubit if first qubit is 1



- Every operation has same number of inputs and outputs
- Every output is unique because quantum operations are reversible
- Each qubit gets a line





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# Initial State: n copies of |0> HPHUSHHPHZIOXONI-INHPHZI







Oracle flips sign of winner's amplitude







































## The Quantum Community is Growing

I've a new paper! "Quintuple: a Python 5-qubit quantum computer simulator to facilitate cloud quantum computing" arxiv.org/abs/1606.09225

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- Fifteen papers submitted
- Tweets from scientist at the South Pole
- 10+ professors using IBM Quantum Experience for education
- Featured at Undergrad Conference at University of Waterloo
- MIT edX Online Course using it (1100 students)
- Educational tool and research tool

N. Linke et al., arXiv:1702.01852

Enrichment exercise: IBM Quantum Experience

IBM generously offers open, cloud-based, access to a real quantum-circuit-capable quantum computer, which has five superconducting "transmon" qubits. Due to constraints imposed by the topology of device interconnects, only certain two-qubit gates can be implemented in a single step; also, the cloud-based interface limits single qubit operations Pauli gates,  $S, S^{\dagger}, T$ , and  $T^{\dagger}$ , and gate realizations are pretty good, but imperfect: the qubits have finite (but well-characterized)  $T_1$  and  $T_2$  coherence times.

8:24 PM - 29 Jun 2016

This realistic configuration is very interesting to explore, as we do in the following optional, problem.

IBM QE1: Five-qubit entangled state

This is a schematic diagram of IBM's five qubit chip quantum computer:





erf	ormi	ng Quantum Computing Experiments in the Cloud
Cent	er for .	Simon J. Devitt Emergent Matter Science, RIKEN, Wakashi, Saitama 315-0198, Japan.
Quir	ntupl	e: a Python 5-qubit quantum computer simulator to
		facilitate cloud quantum computing
		Christine Corbett Moran <sup>a,b,*</sup>
Qua	intum	state reconstruction made easy: a direct method for tomograph
		R. P. Rundle, <sup>1</sup> Todd Tilma, <sup>2</sup> J. H. Samson, <sup>1</sup> and M. J. Everitt <sup>1,•</sup>
		<sup>1</sup> Quantum Systems Engineering Research Group & Department of Physics, Loughborrough University, Leicestershire, LE11, STU, United Kingdom
N	lew J. Phys.	18(2016)073004 doi:10.1088/1367-2630/18/7/073
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## **Quantum Experience Demo**



## **Supplemental Slides**



#### Visualizing qubit states: the Bloch sphere

- Qubit states lie in 2D Hilbert space with orthonormal basis  $|0\rangle$  ,  $|1\rangle$
- An arbitrary state is given by:

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

$$lpha = \cos( heta/2) \ eta = e^{iarphi}\sin( heta/2)$$



### **Single-Qubit Operations**

Measure:



- Quantum non-demolition (QND) measurement: qubit remains in measured state
- Rotate:
  - NOT gate: rotate π radians around X or Y (a.k.a. "*pi pulse*")
  - But also... any arbitrary rotation allowed!  $(\pi/2 \text{ is a common one})$



#### Grover's algorithm







2 iterations, 10 two-qubit gates/iteration, 14 single-qubit locs/CCZ





[1] A. Barenco et al., "Elementary gates for quantum computation", Phys. Rev. A 52 3457 (1995)

