University
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THE UNIVERSITY OF
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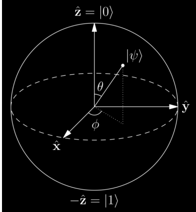
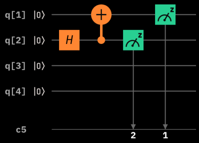
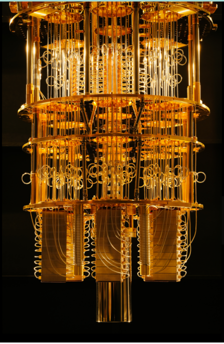
Pritzker School of
Molecular Engineering

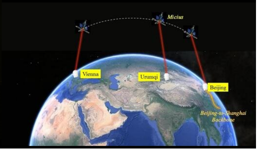
The IBM Quantum Computing Platform

Martin Koppenhöfer
https://www.quantumtheory-bruder.physik.unibas.ch/









Online resources

`https://www.quantumtheory-bruder.physik.unibas.ch/`
`people/martin-koppenhoefer/`
`quantum-computing-and-robotic-science-workshop.html`

- installation guide
- **material for this session**
- slides

Outline

1. Recap
    - Overview of quantum-computing platforms
    - Bell states
2. Programming the quantum computer with python
    - The qiskit framework
    - Programming session 1
3. Superdense coding
    - Programming session 2
4. Quantum algorithms
    - Deutsch algorithm
    - Programming session 3

Recap

- spins in large molecules + NMR
- ions in electromagnetic traps
- neutral atoms in optical lattices
- optical quantum computing
- ^{31}P donor atoms in silicon
- electron spins in semiconductor quantum dots
- superconducting electrical circuits
  - flux qubit
  - charge qubit
  - phase qubit
  - transmon qubit
- topological qubits

IONQ

XANADU

IBM *

rigetti *

Google

Microsoft

* online access

Recap

Bell states

$$|\beta_{00}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

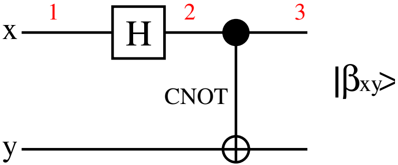
$$|\beta_{01}\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\beta_{10}\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\beta_{11}\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

General expression:

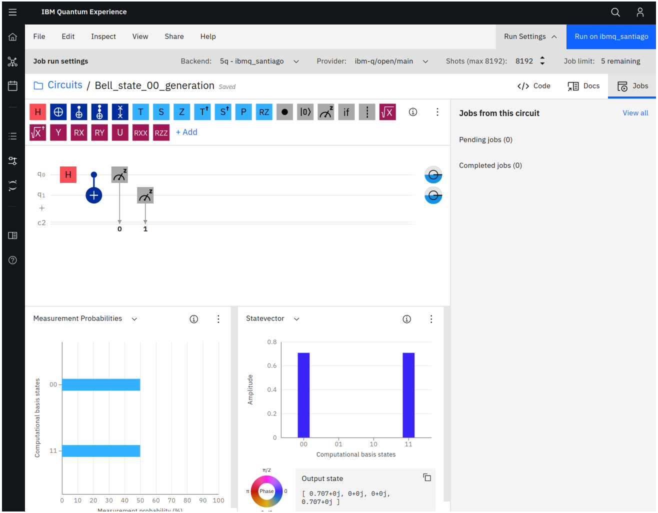
$$\boxed{|\beta_{xy}\rangle = \frac{1}{\sqrt{2}}(|0y\rangle + (-1)^x |1\bar{y}\rangle)}$$



1. input state: $|xy\rangle = |00\rangle$
2. apply Hadamard gate $\hat{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$: $\frac{1}{\sqrt{2}}(|00\rangle + |10\rangle)$
3. apply CNOT gate: $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) = |\beta_{00}\rangle$

Recap

Bell states



Job run settings

Backend: 5q - ibmq_santiago

Provider: ibm-q/open/main

Shots (max 8192): 8192

Job limit: 5 remaining

Circuits / Bell_state_00_generation *Saved*

Jobs from this circuit

Pending jobs (0)

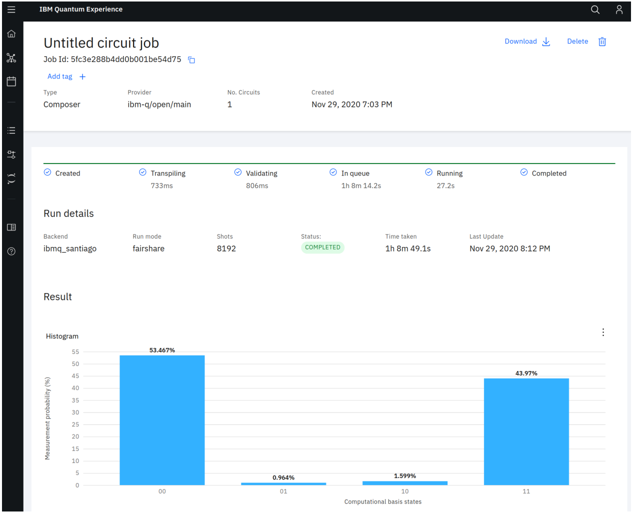
Completed jobs (0)

Output state

```
[ 0.707+0j, 0+0j, 0+0j,
0.707+0j ]
```

Recap

Bell states on a real quantum processor



Untitled circuit job

Job Id: 5fc3e288b4dd0b001be54d75

Type	Provider	No. Circuits	Created
Composer	ibm-q/open/main	1	Nov 29, 2020 7:03 PM

Created	Transpiling	Validating	In queue	Running	Completed
	733ms	806ms	1h 8m 14.2s	27.2s	

Run details

Backend	Run mode	Shots	Status:	Time taken	Last Update
ibmq_santiago	fairshare	8192	COMPLETED	1h 8m 49.1s	Nov 29, 2020 8:12 PM

Result

Programming the quantum computer with python

The qiskit framework

Programming the quantum computer with python

The qiskit framework

Terra

- define quantum algorithms by quantum circuits / pulses
- adapt quantum circuits to the hardware (transpilation)
- connect to the quantum hardware
- visualize results

Aer

- simulate quantum algorithms

Ignis

- characterize quantum hardware
- reconstruct quantum states (tomography)
- compensate noise and errors (mitigation)

Aqua

- predefined algorithms for typical applications

Programming the quantum computer with python

Programming session 1

Content

- defining quantum circuits in python (Terra)
- state-vector simulator (Aer)
- QASM simulator (Aer)
- device imperfections

Programming the quantum computer with python

Programming session 1

Agenda

- you will be split into small teams (in breakout rooms)
- in each breakout room, introduce you quickly to your teammates
- one participant turns on screen sharing
- discuss and code together the exercise
- after a while, the host will close the breakout rooms and let you return to the main session

Superdense coding

Idea

- two parties: Alice (A) and Bob (B)
- Alice wants to transmit 2 classical bits of information to Bob
- classically, she needs to send two bits to Bob
- quantum-mechanically, she can send one qubit to Bob!

Superdense coding

Idea

- Bell states

$$|\beta_{00}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \qquad |\beta_{01}\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$
$$|\beta_{10}\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle) \qquad |\beta_{11}\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

- Consider that Alice and Bob share a Bell state $|\beta_{00}\rangle$
- Alice can convert this Bell state into any other Bell state herself (with no help from Bob)

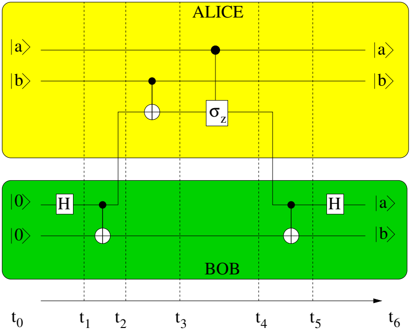
$$\hat{\sigma}_x \otimes \mathbb{1}\, |\beta_{00}\rangle = |\beta_{01}\rangle$$
$$\hat{\sigma}_z \otimes \mathbb{1}\, |\beta_{00}\rangle = |\beta_{10}\rangle$$
$$i\hat{\sigma}_y \otimes \mathbb{1}\, |\beta_{00}\rangle = |\beta_{11}\rangle$$

- $i\hat{\sigma}_y = \hat{\sigma}_z\hat{\sigma}_x$

Superdense coding

Protocol

- A single qubit can transmit two classical bits of information



- t_0: $|a\rangle\,|b\rangle\,|0\rangle\,|0\rangle$
- t_1: $|a\rangle\,|b\rangle\left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)|0\rangle$
- t_2: $|a\rangle\,|b\rangle\left(\frac{|00\rangle+|11\rangle}{\sqrt{2}}\right)$

  i.e. $|a\rangle\,|b\rangle\,|\beta_{00}\rangle$
- t_3: $|a\rangle\,|b\rangle\,|\beta_{0b}\rangle$
- t_4: $|a\rangle\,|b\rangle\,|\beta_{ab}\rangle$
- t_6: $|a\rangle\,|b\rangle\,|a\rangle\,|b\rangle$

- The information about *a* and *b* is encoded in the entangled state of the two-qubit system shared by Alice and Bob

Superdense coding

Programming session 2

Content

- transpiling quantum circuits (Terra)
- error mitigation (Ignis)

Quantum algorithms

Deutsch algorithm

Is $f(x) : \{0,1\} \rightarrow \{0,1\}$ balanced or constant?

- balanced if $f(0) = \overline{f(1)} \Leftrightarrow f(0) \oplus f(1) = 1$
- constant if $f(0) = f(1) \Leftrightarrow f(0) \oplus f(1) = 0$

- $\hat{U}_f : |x, y\rangle \rightarrow |x, y \oplus f(x)\rangle$ quantum circuit implementing $y + f(x) \mod 2$ in the second qubit
- example: input $|x\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, $|y\rangle = |0\rangle$ leads to

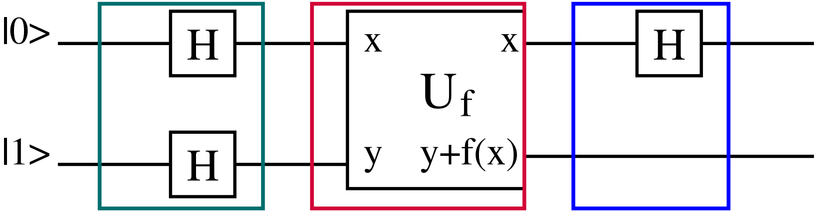
$$\frac{1}{\sqrt{2}}\left(|0, f(0)\rangle + |1, f(1)\rangle\right)$$

  $\Rightarrow$ one "application" of f results in both $f(0)$ and $f(1)$!
- but: measurement gives either $|0, f(0)\rangle$ or $|1, f(1)\rangle$
- so, quantum parallelism does not help ...?

Quantum algorithms

Deutsch algorithm

- ...it does if we transform the information in a clever way:



generate superposition

use quantum parallelism

use interference

- final state is $\propto |f(0) \oplus f(1)\rangle \otimes (|0\rangle - |1\rangle)$

  $\Rightarrow$ measuring the first qubit gives a global property of f, namely $f(0) \oplus f(1)$, using only one evaluation of $f(x)$

- this is impossible on a classical computer!

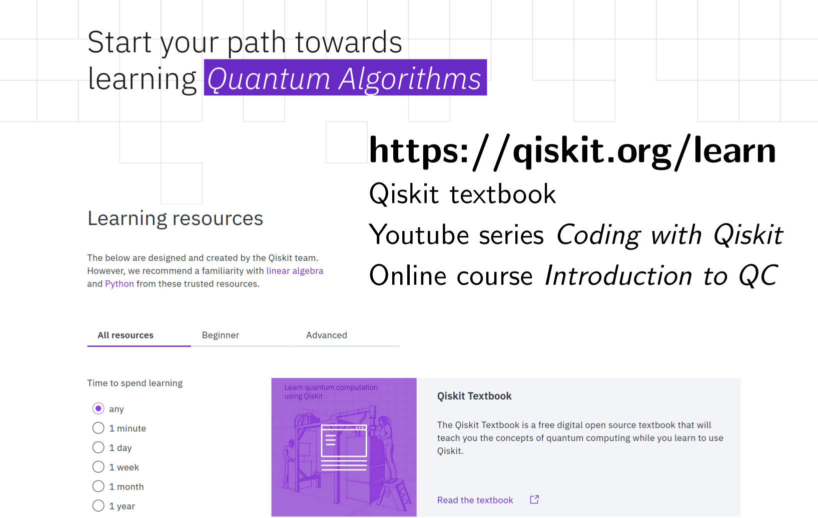
Quantum algorithms

Programming session 3

Content

- predefined quantum algorithms (Aqua)

Educational material



Start your path towards learning *Quantum Algorithms*

Learning resources

The below are designed and created by the Qiskit team. However, we recommend a familiarity with linear algebra and Python from these trusted resources.

Time to spend learning

● any
○ 1 minute
○ 1 day
○ 1 week
○ 1 month
○ 1 year

Qiskit Textbook

The Qiskit Textbook is a free digital open source textbook that will teach you the concepts of quantum computing while you learn to use Qiskit.

https://qiskit.org/learn

Qiskit textbook

Youtube series *Coding with Qiskit*

Online course *Introduction to QC*

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Thank you

for your attention.