Quantum computing in the cloud!

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Zakopane, 8-10 March 2017

What I want to talk about

- Introduction
  - Classical computers
  - Quantum computers — overview
- Postulates of quantum mechanics
  - Quantum state
  - Evolution of quantum systems
  - Quantum measurement
  - Composition of quantum systems
- Quantum computers in the cloud
  - Entanglement
  - Teleportation
- Notes on quantum buzz
- Propaganda — Rewolucja Stanu (State Revolution)

What I do not want to talk about

- Quantum angel healing http://www.quantumangel.com/
- Healing domestic animals using quantum teleportation http://www.quantummansite.com/
- Quantum soul http://www.deepakchopra.com
- Quantum life http://www.quantum-life.com/

Outline for section 1

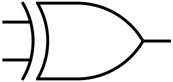
Classical computers — overview

Classical register

0	1	0	1	1	0	0	1

Classical gates

XOR



in_1	in_2	out
0	0	0
0	1	1
1	0	1
1	1	0

Information is lost during computation.

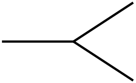
Classical computers — overview

Classical register

0	1	0	1	1	0	0	1

Classical gates

FANOUT



in	out_1	out_2
0	0	0
1	1	1

We can copy information.

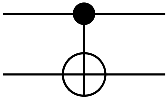
Quantum computers

Quantum register

$$\alpha_{10101010}\,|10101010\rangle + \alpha_{10110101}\,|10110101\rangle + \alpha_{11110000}\,|11110000\rangle$$

Quantum gates

CNOT



in_1	in_2	out_1	out_2
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Information is not lost during computation! They are reversible.

Quantum computers

Quantum register

$$\alpha_{10101010}\,|10101010\rangle + \alpha_{10110101}\,|10110101\rangle + \alpha_{11110000}\,|11110000\rangle$$

Quantum gates

HADAMARD	$-\boxed{H}-$	$\|0\rangle \to \frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)$, $\|1\rangle \to \frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle)$

Information is not lost during computation! They are reversible.

Quantum computers

Quantum register

$$\alpha_{10101010}\,|10101010\rangle + \alpha_{10110101}\,|10110101\rangle + \alpha_{11110000}\,|11110000\rangle$$

Quantum gates

UNITARY	$-\boxed{U}-$	$U\,|\psi_1\rangle = |\psi_2\rangle$, $U^\dagger\,|\psi_2\rangle = |\psi_1\rangle$

Information is not lost during computation! They are reversible.

No-cloning theorem

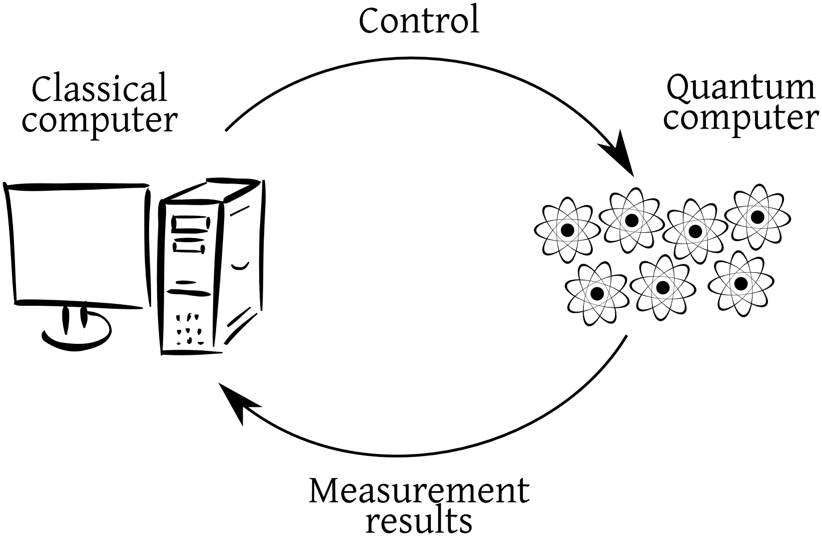
It is not possible to copy quantum information.

$$|\psi 0\rangle \nrightarrow |\psi\psi\rangle$$

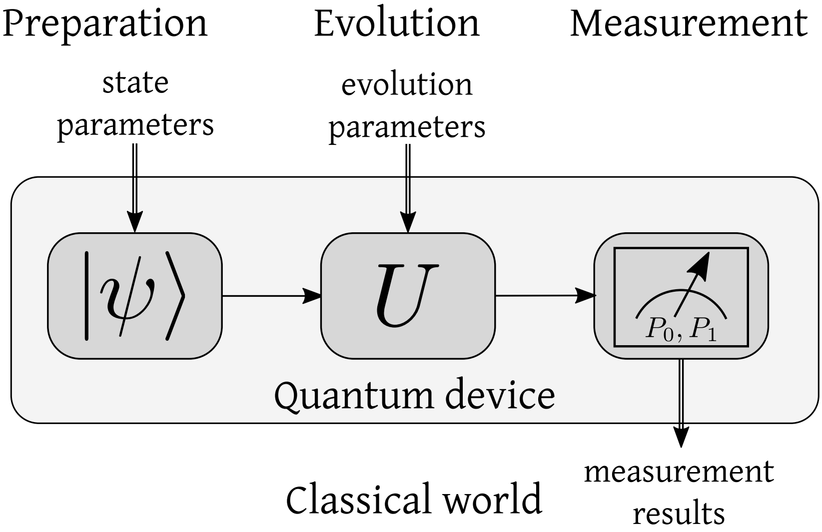
Source: `http://openclipart.org/user-detail/TheStructorr`,

©TheStructorr, public domain.

Quantum computation control loop



Computation as experiment



Outline for section 2

Quantum state

We recall the postulates of quantum mechanics, upon which the proposed method is derived. The state of quantum system is represented by a complex unit vector from n-dimensional euclidean vector space $\mathbb{C}^n$. We denote quantum states using bra-ket notation. Let us introduce an orthonormal complete set of vectors

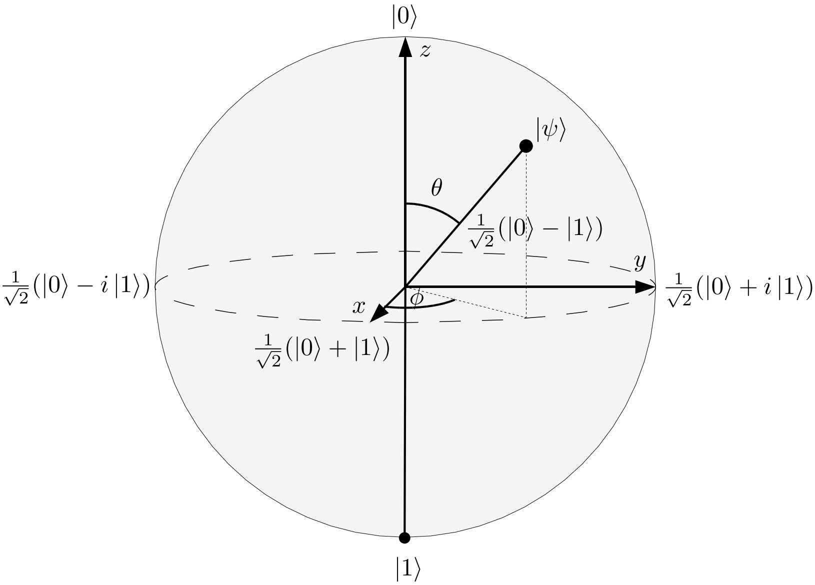
$$|0\rangle = \begin{bmatrix} 1 \\ \vdots \\ 0 \end{bmatrix}, \ldots, \ |n-1\rangle = \begin{bmatrix} 0 \\ \vdots \\ 1 \end{bmatrix}. \tag{1}$$

The $|x\rangle$ vector is called 'ket' and its Hermitian conjugation $(|x\rangle)^\dagger = \langle x|$ is called 'bra'.
We can represent any valid state of a n-level quantum state $|\psi\rangle$ as normalized linear combination of the basis vectors:

$$|\psi\rangle = \alpha_1 |0\rangle + \cdots + \alpha_n |n-1\rangle, \tag{2}$$

where $\alpha_1, \ldots, \alpha_n \in \mathbb{C}$ and $\sum_{i=1}^{n} |\alpha_i|^2 = 1$.
We assume that two vectors $|\psi\rangle$ and $|\phi\rangle$ represent the same physical state if $|\psi\rangle = e^{\mathrm{i}\theta} |\phi\rangle$, for $\theta \in \mathbb{R}$.

Qubit, Bloch sphere



The evolution of quantum systems is governed by the Schrödinger equation

$$\frac{d\left|\psi\right\rangle}{dt} = e^{-\mathrm{i}tH}. \tag{3}$$

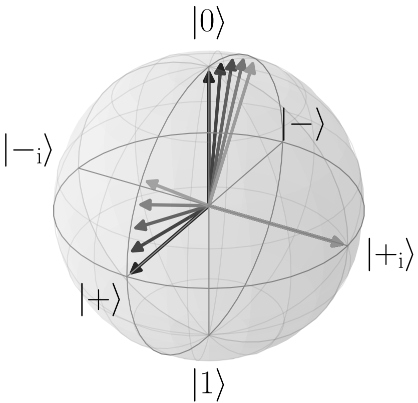
Where H is a hermitian operator *i.e.* $H = H^\dagger$ called Hamiltonian of the system. Here we put Planck constant equal to one.
Solutions of the (3) are given by

$$\left|\psi_{t_1}\right\rangle = U(t_0, t_1)\left|\psi_{t_0}\right\rangle, \tag{4}$$

where $\left|\psi_{t_0}\right\rangle$ is the initial state of the system, $\left|\psi_{t_1}\right\rangle$ is final state of the system, and $U(t_0, t_1)$ is unitary operator driving the system from time t_0 to t_1.
Assuming that Hamiltonian H is time is constant between time t_0 and t_1 $U(t_0, t_1)$ can be obtained from equation

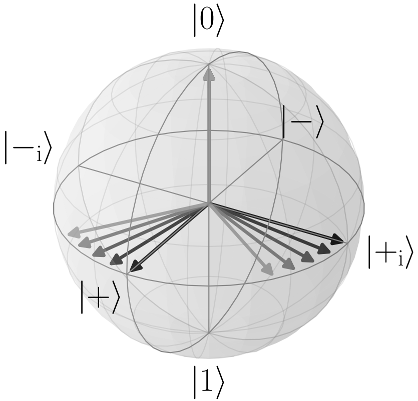
$$U(t_0, t_1) = e^{-\mathrm{i}(t_1 - t_0)H}. \tag{5}$$

Unitary gates, quantum evolution



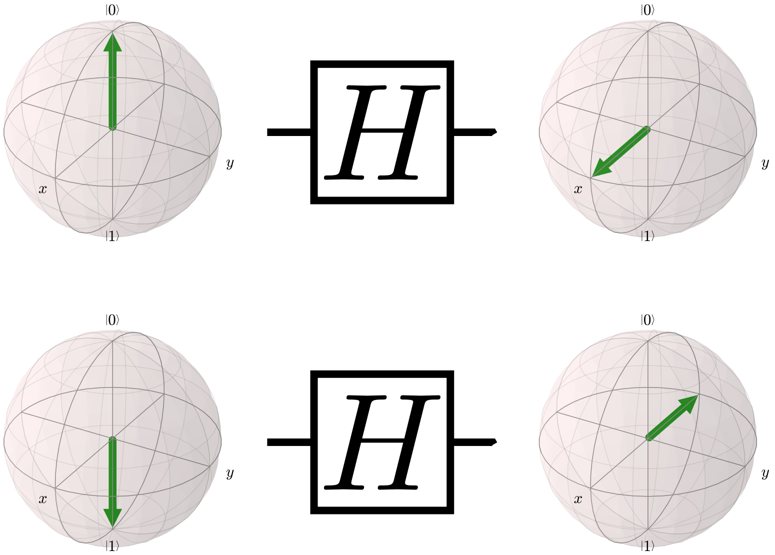
Rotation around y-axis

Unitary gates, quantum evolution



Rotation around z-axis

Unitary gates, quantum evolution



Measurement

In order to measure the state of a quantum system one has to chose a quantum measurement that is a function μ from finite set of measurements outcomes $A = \{a_i\}_{i=1}^{n}$ to set the of projection operators $P = \{P_i\}_{i=1}^{n}$ such that

$$\sum_{i=1}^{n} P_i = \mathbb{1}. \tag{6}$$

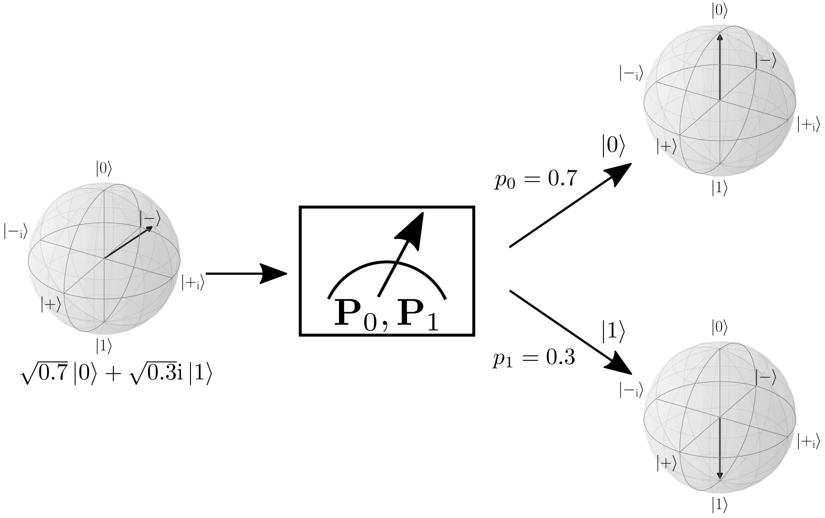
The probability of measuring outcome a_i given the quantum system in in state $|\psi\rangle$ is

$$p(a_i) = \langle\psi| P_i |\psi\rangle . \tag{7}$$

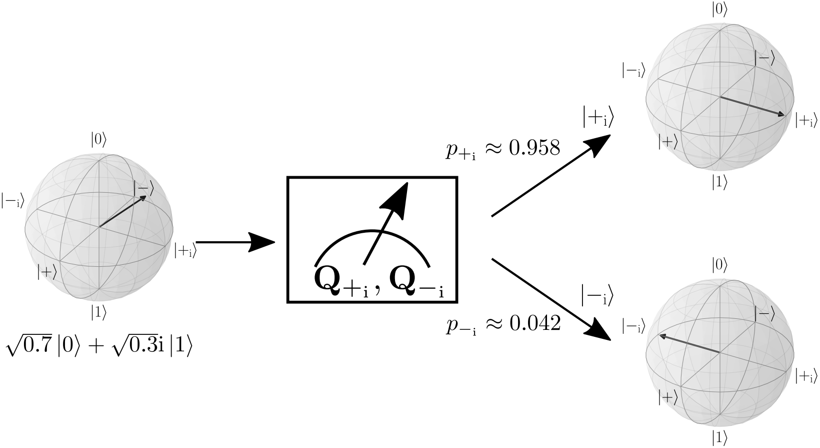
The state of the quantum system after the measurement outcome a_i was obtained becomes

$$|\psi\rangle_{a_i} = \frac{P_i |\psi\rangle}{\sqrt{\langle\psi| P_i |\psi\rangle}}. \tag{8}$$

Measurement



Measurement



Composition of quantum systems

The operation which allows us to join two independent quantum systems is the tensor product. Lets take two qubit states

$$|\psi\rangle = \begin{bmatrix} \psi_0 \\ \psi_1 \end{bmatrix} = \psi_0 |0\rangle + \psi_1 |1\rangle ,$$

$$|\phi\rangle = \begin{bmatrix} \phi_0 \\ \phi_1 \end{bmatrix} = \phi_0 |0\rangle + \phi_1 |1\rangle , \tag{9}$$

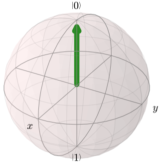
then we can write their joint state in $\mathbb{C}^2 \otimes \mathbb{C}^2$ as

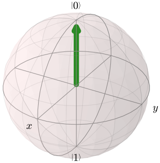
$$|\psi\rangle \otimes |\phi\rangle = \begin{bmatrix} \psi_0\phi_0 \\ \psi_0\phi_1 \\ \psi_1\phi_0 \\ \psi_1\phi_1 \end{bmatrix} . \tag{10}$$

Outline for section 3

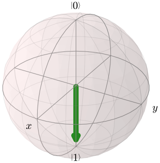
Entanglement — theory

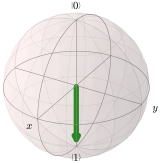
$\frac{1}{\sqrt{2}} \Bigg($





$+$





$\Bigg)$

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

Entanglement — realisation

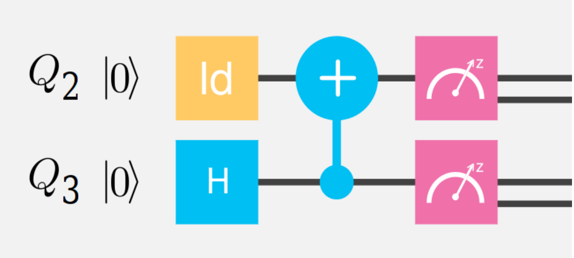


Figure: Entangling quantum circuit

Entanglement — computer

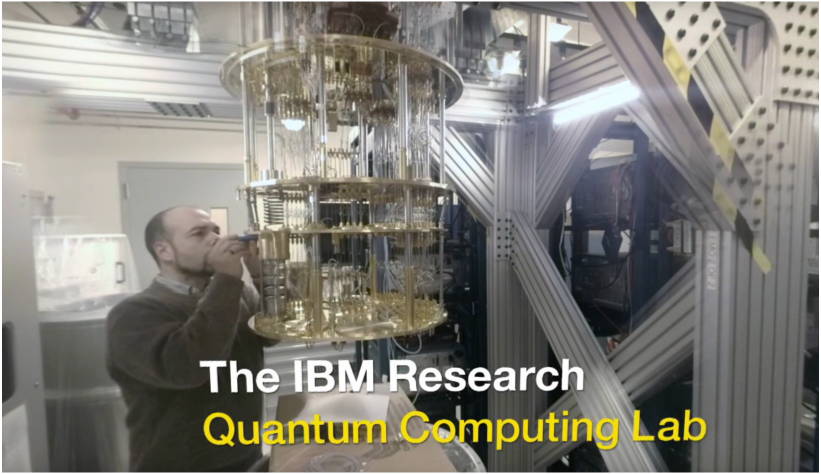


Figure: Explore our 360 Video of the IBM Research Quantum Lab.
https://youtu.be/jf7D8snlsnQ

Entanglement — program

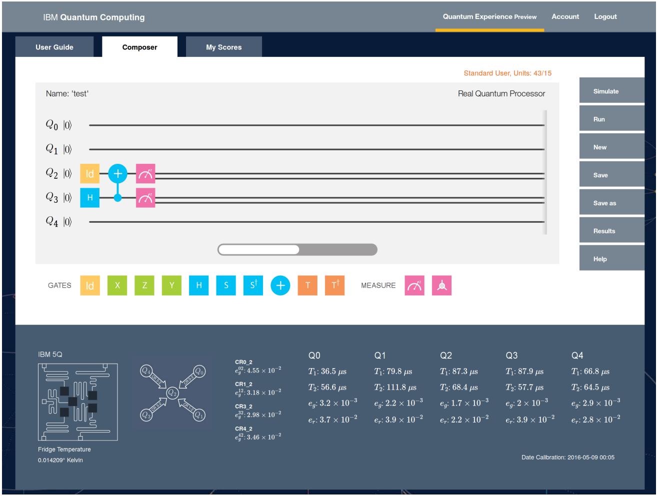


Figure: Programming interface

http://www.research.ibm.com/quantum/

Entanglement — result

Executed on: May 9, 2016 1:53:01 PM

Results date: May 9, 2016 1:53:17 PM

Number of shots: 1024

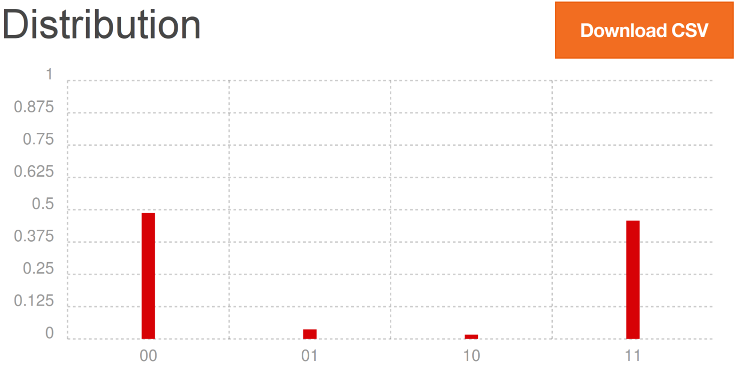
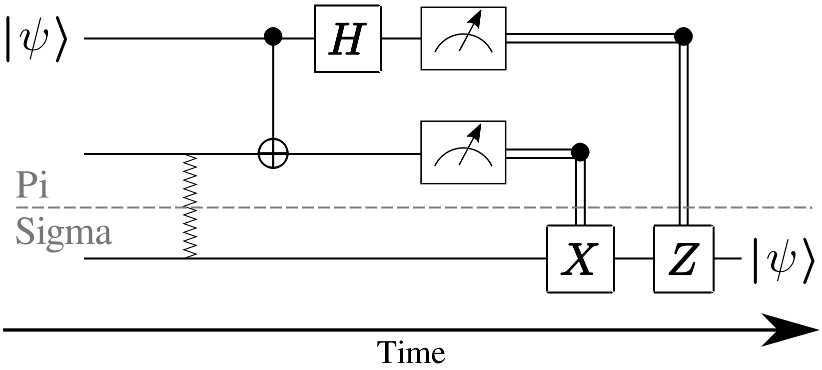


Figure: Program execution result

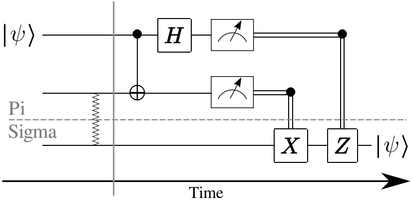
Teleportation — vision

Source: `http://xkcd.com/465/` ©Randall Munroe 2015, CC-BY/2.5.

Teleportation — theory



Teleportation — theory

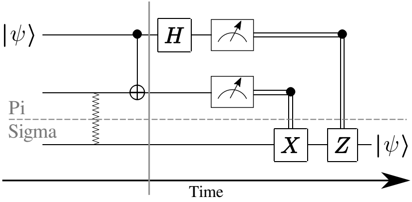


$$|\psi_{t=0}\rangle = |\psi\rangle \otimes \left|\Phi^+\right\rangle =$$

$$= (\alpha\,|0\rangle + \beta\,|1\rangle) \otimes \frac{1}{\sqrt{2}}\,(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle) =$$

$$= \frac{1}{\sqrt{2}}\,(\alpha\,|000\rangle + \alpha\,|011\rangle + \beta\,|100\rangle + \beta\,|111\rangle)$$

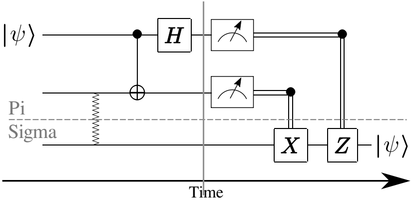
Teleportation — theory



$$|\psi_{t=1}\rangle = (CNOT_1^2 \otimes \mathbb{1}) \frac{1}{\sqrt{2}} \left(\alpha\,|000\rangle + \alpha\,|011\rangle + \beta\,|100\rangle + \beta\,|111\rangle\right) =$$

$$= \frac{1}{\sqrt{2}} \left(\alpha\,|000\rangle + \alpha\,|011\rangle + \beta\,|110\rangle + \beta\,|101\rangle\right).$$

Teleportation — theory



$$|\psi_{t=2}\rangle = (H \otimes \mathbb{1} \otimes \mathbb{1}) \frac{1}{\sqrt{2}} \left(\alpha |000\rangle + \alpha |011\rangle + \beta |110\rangle + \beta |101\rangle\right) =$$

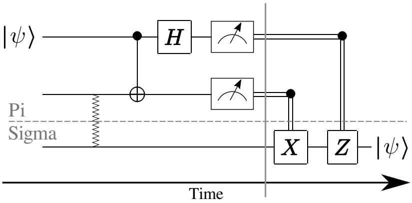
$$= \frac{1}{\sqrt{2}} \Big(\alpha \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \otimes (|00\rangle + |11\rangle) +$$

$$+ \beta \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle) \otimes (|10\rangle + |01\rangle) \Big) =$$

$$= \frac{1}{2} (\alpha |000\rangle + \alpha |100\rangle + \alpha |011\rangle + \alpha |111\rangle +$$

$$+ \beta |010\rangle + \beta |001\rangle - \beta |110\rangle - \beta |101\rangle)$$

Teleportation — theory

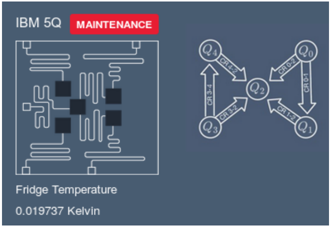


$$\mathcal{P} = \{P_{00?} = |0\rangle\langle 0| \otimes |0\rangle\langle 0| \otimes \mathbb{1}, P_{01?} = |0\rangle\langle 0| \otimes |1\rangle\langle 1| \otimes \mathbb{1},$$
$$P_{10?} = |1\rangle\langle 1| \otimes |0\rangle\langle 0| \otimes \mathbb{1}, P_{11?} = |1\rangle\langle 1| \otimes |1\rangle\langle 1| \otimes \mathbb{1}\}$$

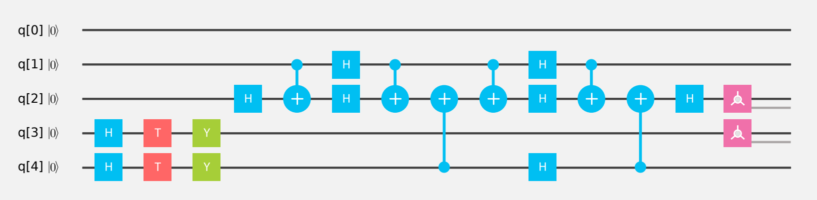
- result 00?: $\frac{1}{\sqrt{2}}(\alpha|000\rangle + \beta|001\rangle) = \frac{1}{\sqrt{2}}(|00\rangle \otimes |\psi\rangle)$,
- result 01?: $\frac{1}{\sqrt{2}}(\alpha|011\rangle + \beta|010\rangle) = \frac{1}{\sqrt{2}}(|01\rangle \otimes Z|\psi\rangle)$,
- result 10?: $\frac{1}{\sqrt{2}}(\alpha|100\rangle - \beta|101\rangle) = \frac{1}{\sqrt{2}}(|10\rangle \otimes X|\psi\rangle)$,
- result 11?: $\frac{1}{\sqrt{2}}(\alpha|111\rangle - \beta|110\rangle) = \frac{1}{\sqrt{2}}(|11\rangle \otimes XZ|\psi\rangle)$

Teleportation — practice

Architecture



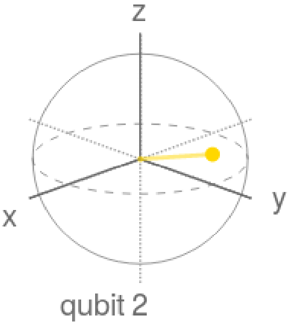
Circuit[1]



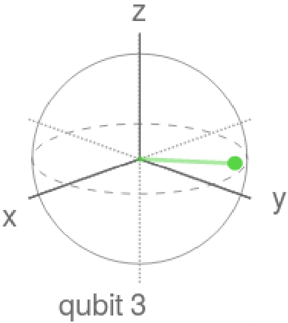
[1] https://quantumexperience.ng.bluemix.net/qstage/#/user/herrier

Teleportation — practice

Results



x: -0.596, y: 0.417, z: 0.001



x: -0.695, y: 0.642, z: -0.054

Teleportation — practice

QASM 2.0

```
include "qelib1.inc";
qreg q[5];
creg c[5];

h q[3];
h q[4];
t q[3];
t q[4];
y q[3];
y q[4];
h q[2];
cx q[1],q[2];
h q[1];
h q[2];
cx q[1],q[2];
cx q[4],q[2];
cx q[1],q[2];
h q[1];
h q[2];
h q[4];
cx q[1],q[2];
cx q[4],q[2];
h q[2];
bloch q[2];
bloch q[3];
```

Outline for section 4

News

Yorktown Heights, N.Y. - 06 Mar 2017: IBM[2]

[...] IBM aims at constructing commercial IBM Q systems with 50 qubits in the next few years [...]

[2] http://research.ibm.com/ibm-q/

D-Wave machine

D-Wave 2000Q™

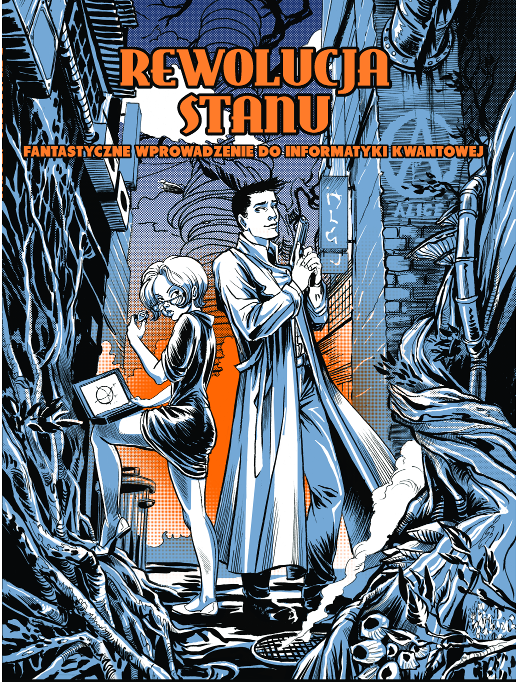
- It is an adiabatic “quantum computer” using 2000 qubits.
- It is not an universal quantum computer.
- Academic critique of the system is provided by Scott Aaronson[3].

[3] http://scottaaronson.com/blog/?s=dwave

Outline for section 5

REWOLUCJA STANU

FANTASTYCZNE WPROWADZENIE DO INFORMATYKI KWANTOWEJ



pomysł: **Piotr Gawron**, scenariusz: **Michał Cholewa**, rysunki: **Katarzyna Kara**

Thank you for your attention!

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