⟨You|Qu⟩- 2017

IBM quantum experience: Experimental implementations, scope, and limitations

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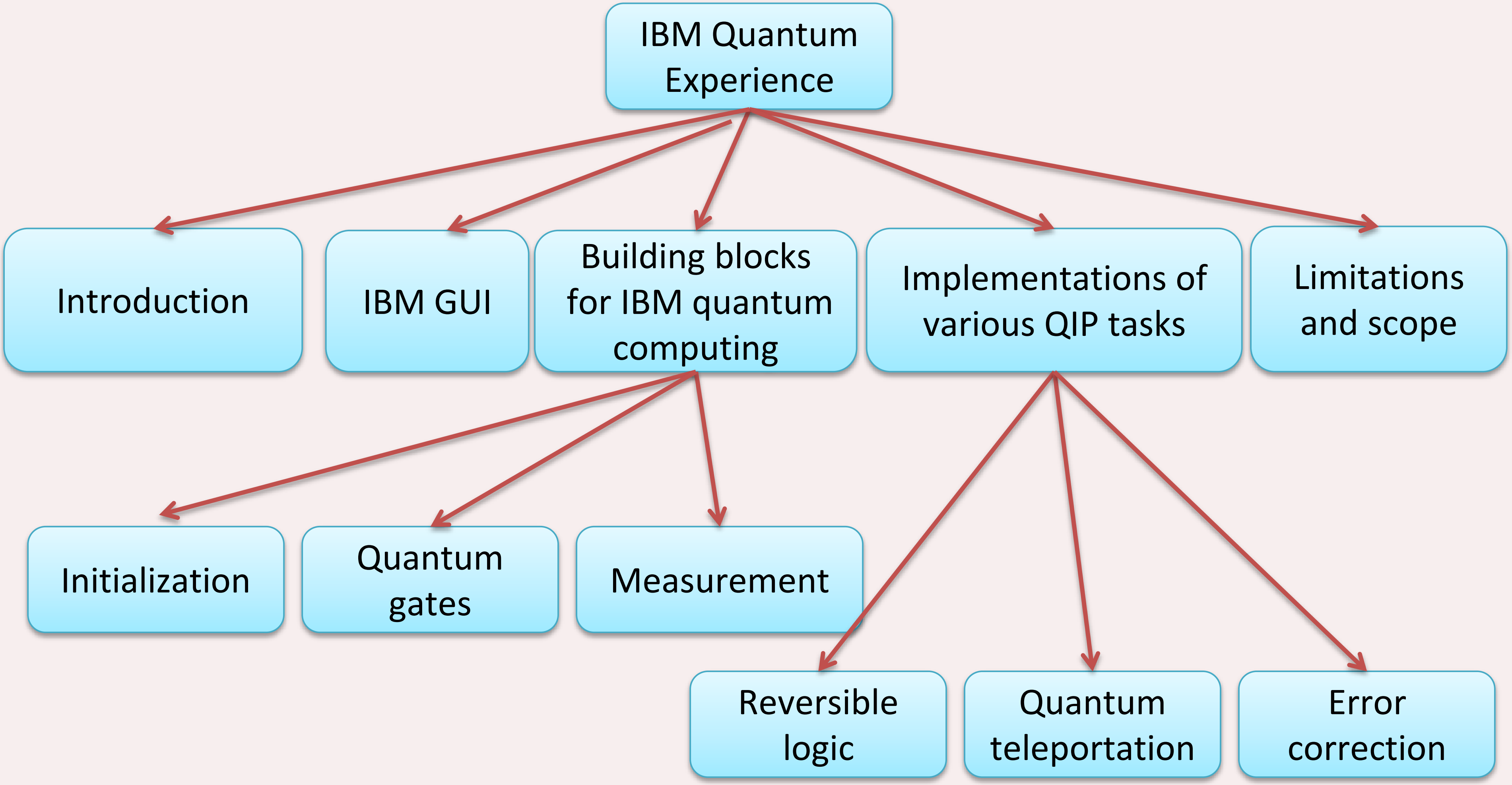
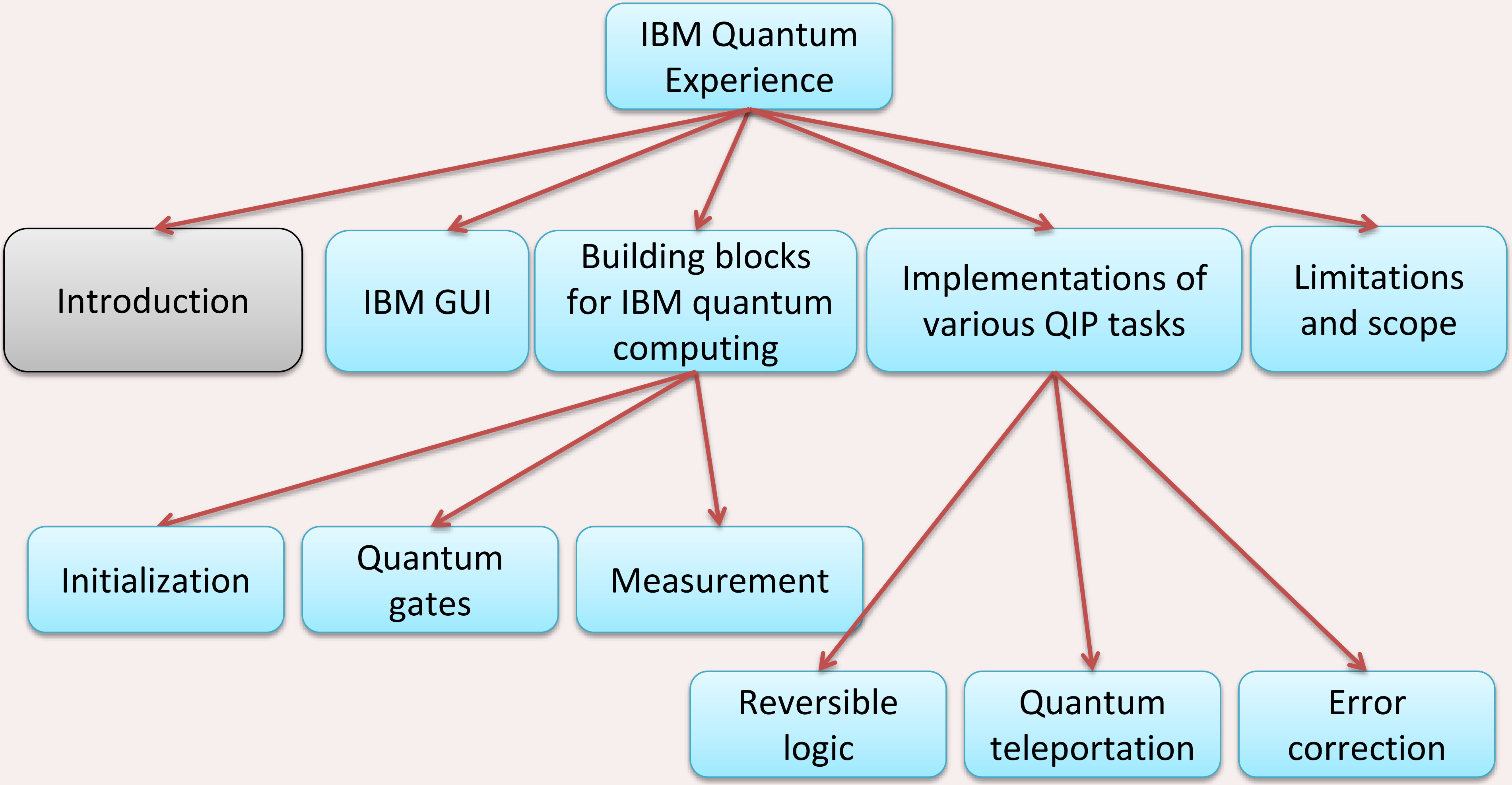
Plan of the talk

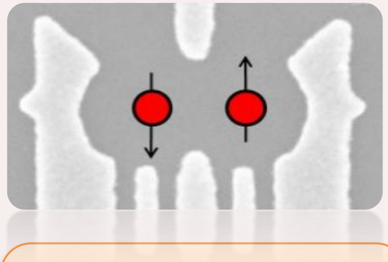


Plan of the talk



Quantum information processors

Quantum information processor (QIP)



DiVincenzo's criteria

Initialization
$|\psi\rangle = a|0\rangle + b|1\rangle$

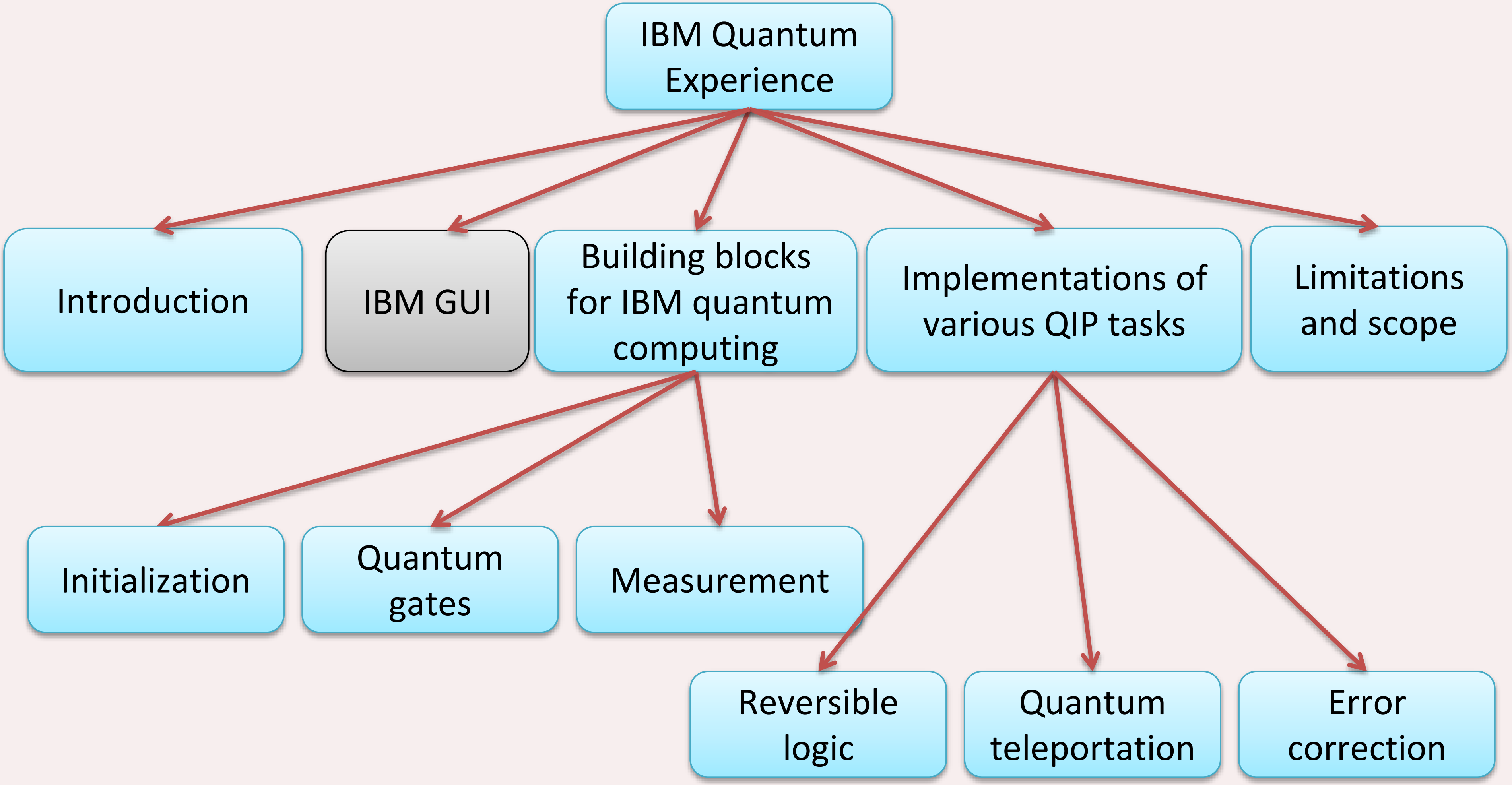
Superposition: Makes quantum processors more capable than classical computers in certain tasks

Quantum Gates
$|\psi'\rangle = U_k U_{K-1} \ldots U_1 |\psi\rangle$

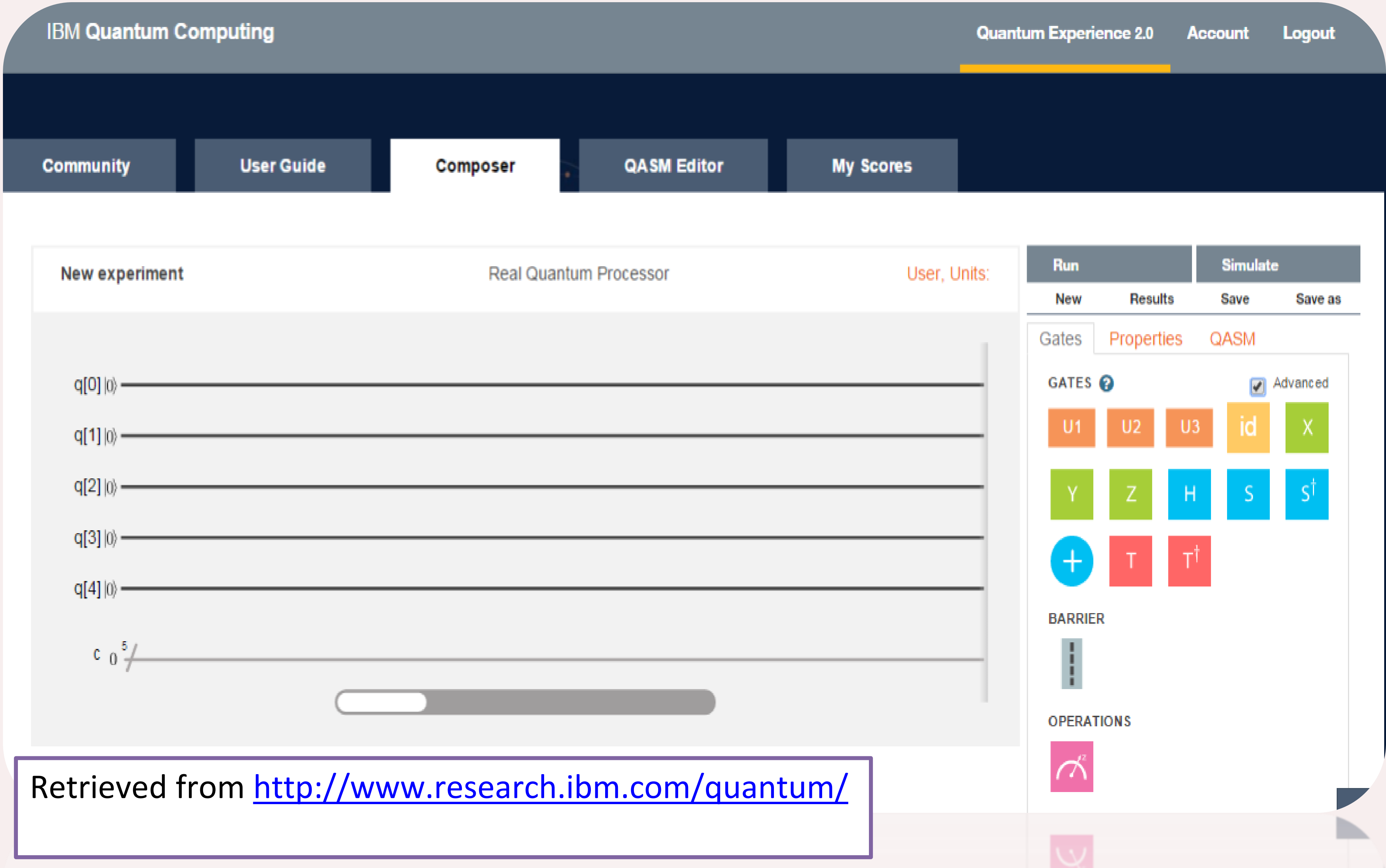
Measurement
$\langle A\rangle = \langle\psi'|A|\psi'\rangle$

- Nuclear spins: NMR
- **Josephson qubits: SQUID (IBM quantum computer)**
- Photons: Linear optics
- Ion trap
- NV and P vacancy systems: Solid state spins etc.

Plan of the talk

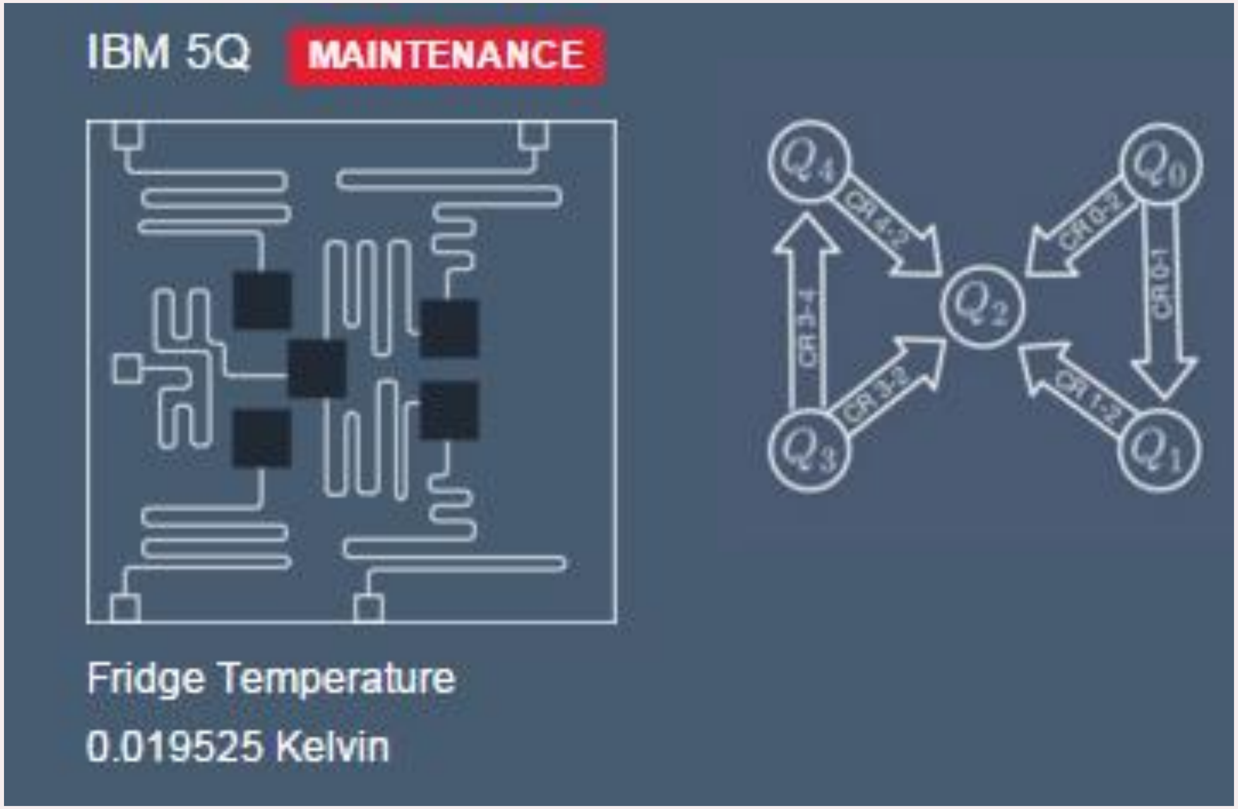


Introduction: User platform for IBM quantum computer



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

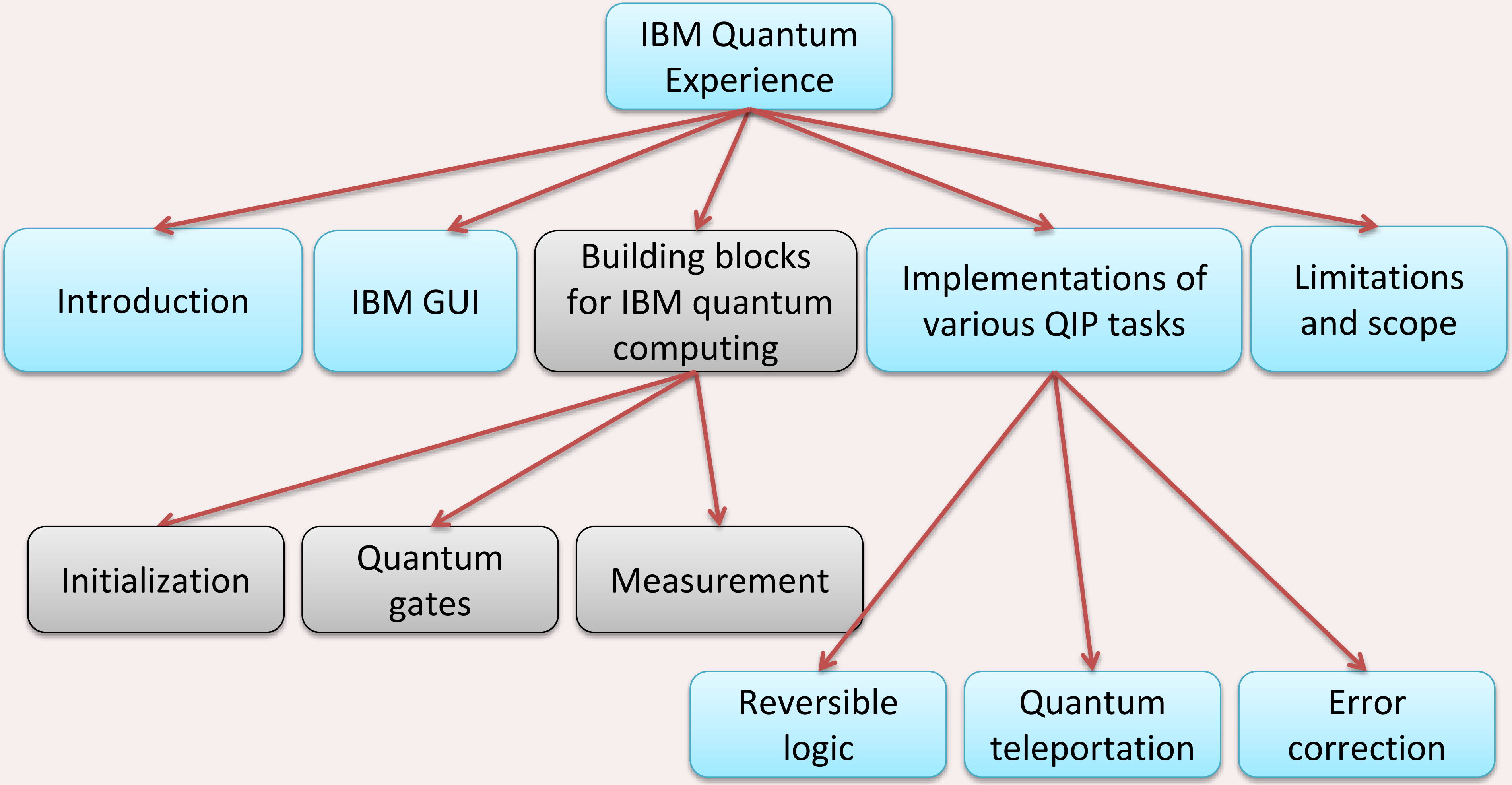
Schematic diagram of architecture



Q0	Q1	Q2	Q3	Q4
f: 5.27 GHz	f: 5.21 GHz	f: 5.03 GHz	f: 5.30 GHz	f: 5.06 GHz
T_1: 44.3 μs	T_1: 31.6 μs	T_1: 41.3 μs	T_1: 46.1 μs	T_1: 63.7 μs
T_2: 28.9 μs	T_2: 31 μs	T_2: 59.8 μs	T_2: 56.8 μs	T_2: 132.5 μs

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

Plan of the talk

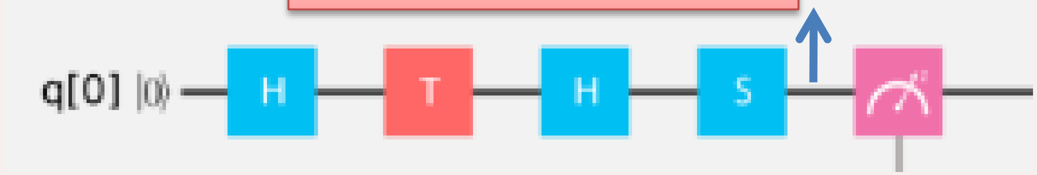


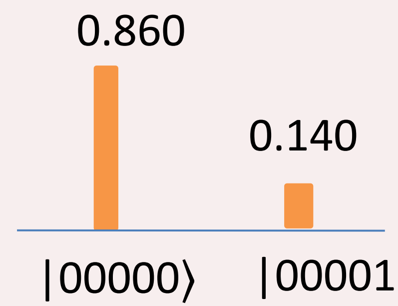
Initialization

Single qubit state

$\alpha = 0.923, \beta = 0.383$

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

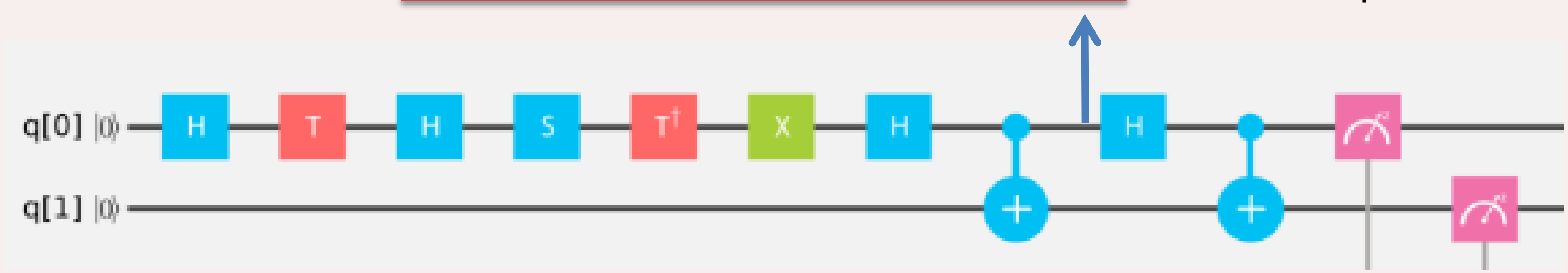


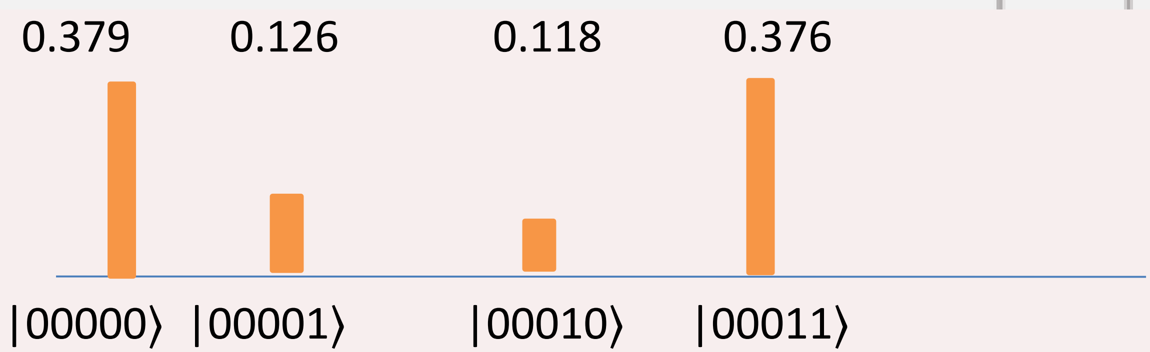


Entangled state

$|\psi\rangle = \alpha\,(|00\rangle + |11\rangle) + \beta\,(|00\rangle + |11\rangle)$

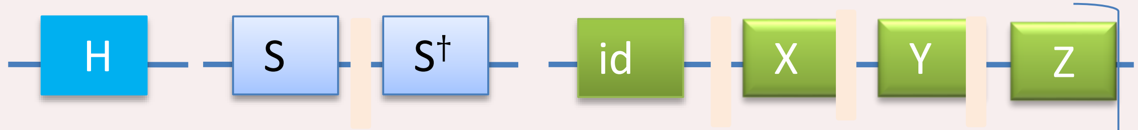
$\alpha = 0.612, \beta = 0.354$





Quantum Gates

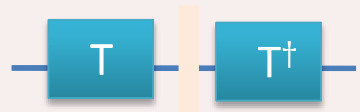
Clifford Gate library



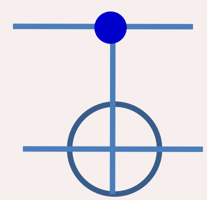
Hadamard Phase gate (π/2) Pauli Gates

Universal Gate library

Phase Gate (π/8)

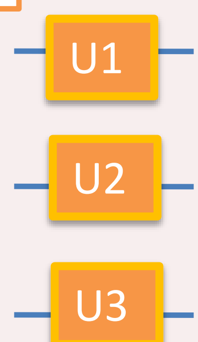


C-NOT



Some more physical Gates

(Helps in preparation of complex states)



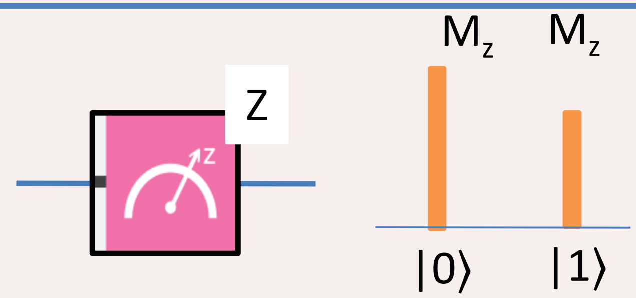
$|0\rangle + |1\rangle / \sqrt{2}$ ----> $(|0\rangle + e^{i\phi}|1\rangle)/\sqrt{2}$

$(|0\rangle + |1\rangle)/\sqrt{2}$ ----> $\alpha|0\rangle + \beta e^{(i\phi)}|1\rangle$

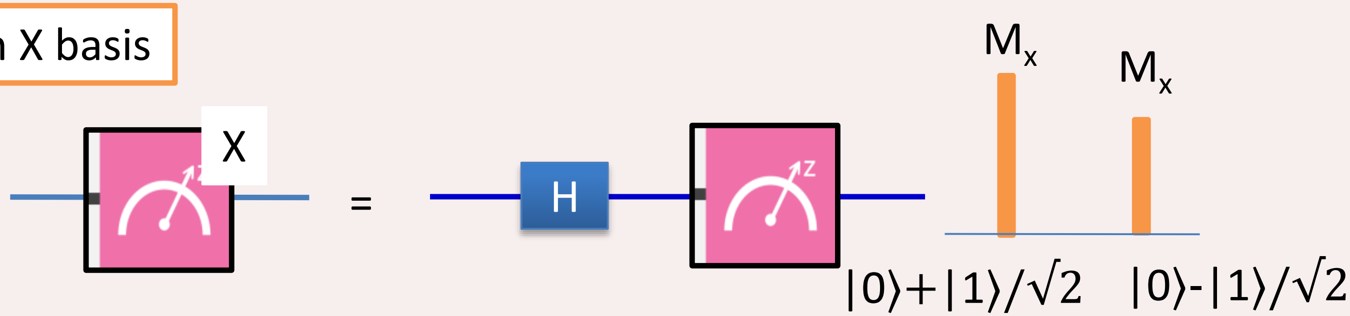
here $\alpha = \cos(\lambda/2)e^{(i\lambda/2)}$, $\beta = \sin(\lambda/2)e^{(-i\lambda/2)}$

Measurement in IBM quantum computer

Measurement in Z basis

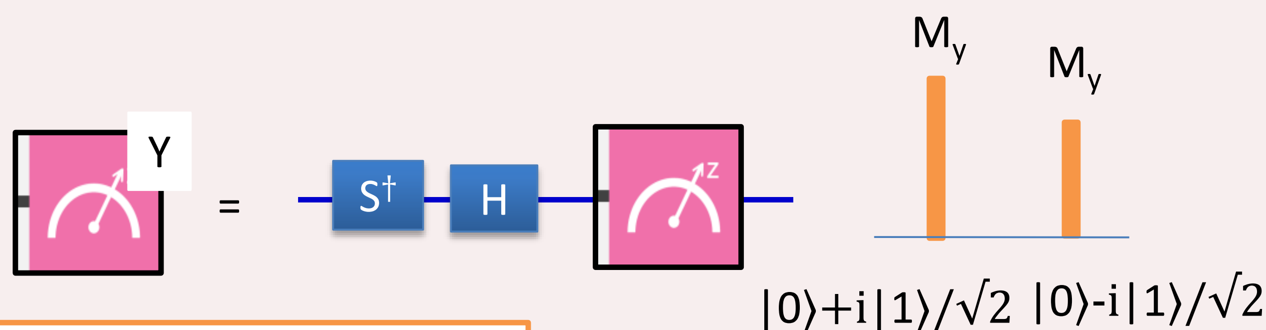


Measurement in X basis



Measurement in Y basis

$$\langle P_i \rangle = M_1 E_1 + M_2 E_2$$

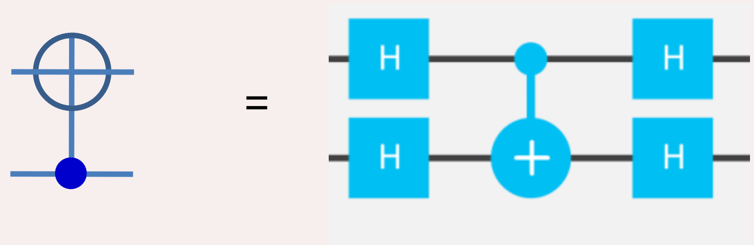


$$\rho = \frac{1}{2} \left[\mathbb{1} + (\langle x \rangle \sigma_x + \langle Y \rangle \sigma_y + \langle Z \rangle \sigma_z) \right]$$

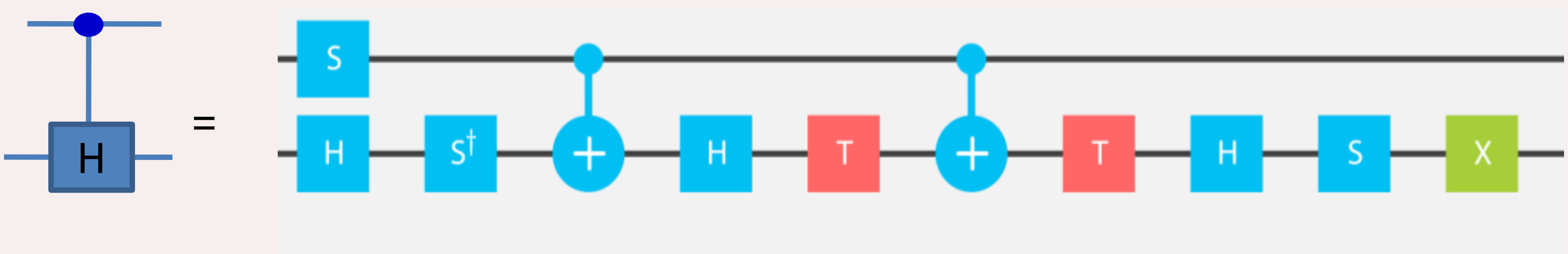
Density matrix tomography (single qubit)

Some useful control operations

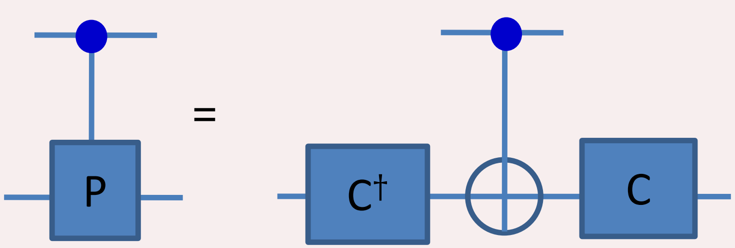
Reverse C-NOT



Control-H



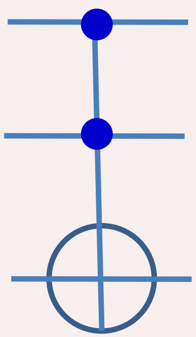
Control-P



P- Pauli Operator
C- Clifford Gate

Some more Gates

Toffoli



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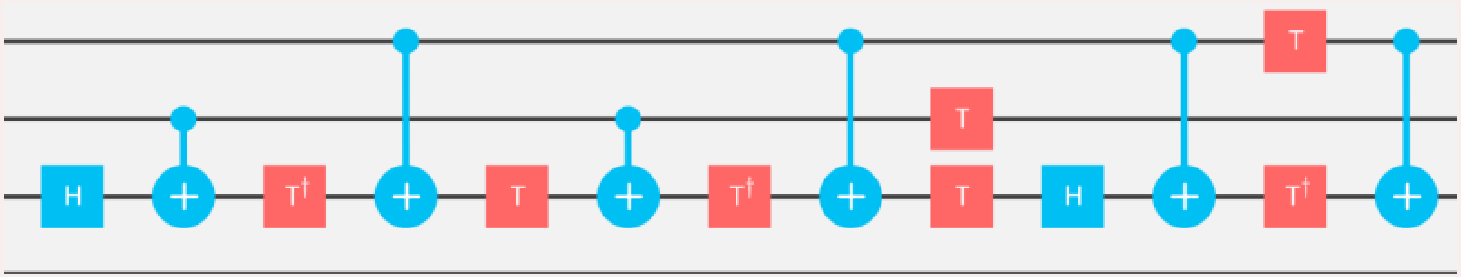
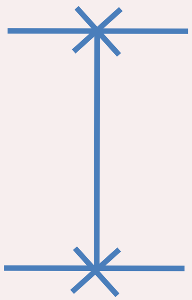


Swap Gates



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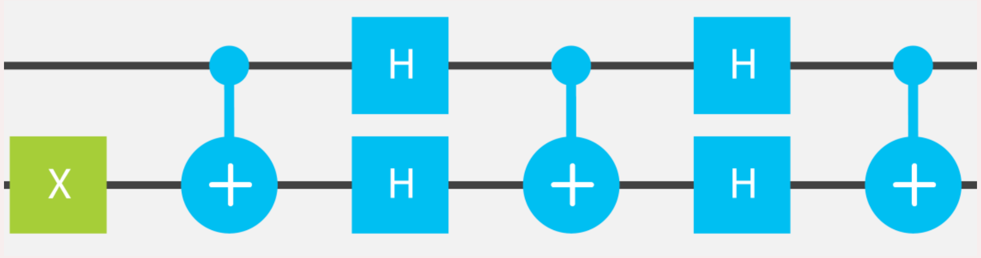
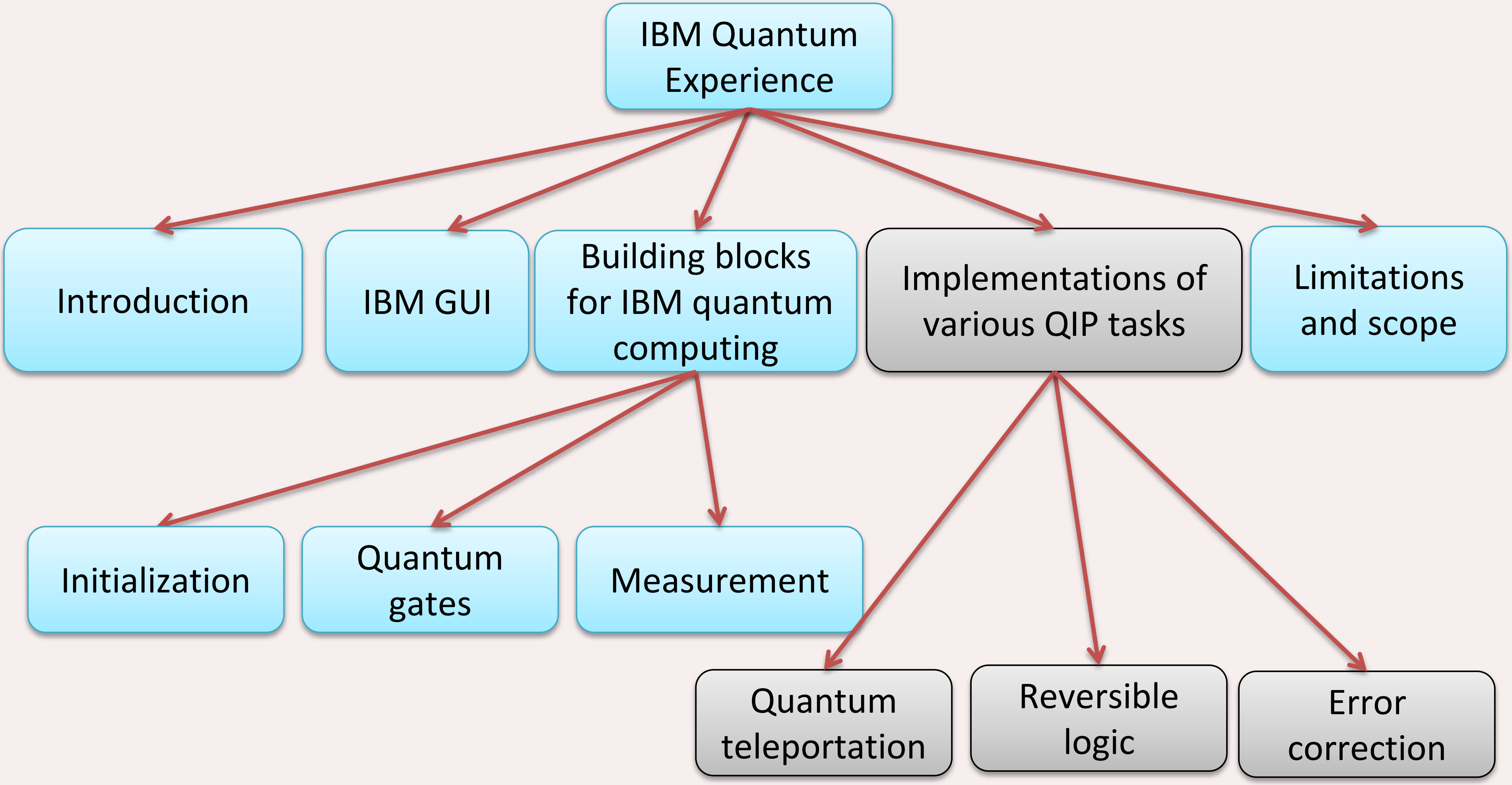


Plan of the talk



Quantum teleportation

Single qubit state teleportation

Reconstructed single qubit state

$|\psi\rangle$

Quantum channel $|\phi^{+}\rangle$

$|\psi\rangle$

Measurement by Alice on her qubits

Classical communication

Application of unitaries by Bob on his qubit

Multi-qubit state teleportation

$|\psi\rangle = \sum_i \alpha_i |x_i\rangle$ where $|x_i\rangle$ is a basis element of N-qubit basis $\{X_i\}$.

$|\psi\rangle$

- Arbitrary N qubit state : N pair of Bell state are required
- Possibility of optimizing channel size: Size depends on Number of unknowns

Teleporting a m-unknown N qubit state of type $|\psi\rangle = \sum_i \alpha_i |x_i\rangle$ by using optimal channel size

$\alpha|000\rangle + \beta|011\rangle + \gamma|100\rangle + \delta|111\rangle$ Choudhury et al., IJTP (2016): 1-7; 4-qubit cluster state;

$\alpha(|0000\rangle + |0111\rangle + \beta(|1101\rangle + |1010\rangle)$ Li et. al, IJTP 55 (2016): 1820-1823 ; Four qubit cluster state;

Quantum teleportation

Example: Teleporting an N qubit state with two unknowns.

Step1:

$$|\psi\rangle = \alpha|x_i\rangle + \beta|x_j\rangle \longrightarrow |\psi'\rangle = \alpha|y_i\rangle + \beta|y_j\rangle$$

$$U = \sum_{i=1}^{N} |y_i\rangle\langle x_j|$$

$$y_i = |0\rangle^{n-1} \otimes |0\rangle$$

$$y_j = |0\rangle^{n-1} \otimes |\bar{0}\rangle$$

Step2:

$|\psi'\rangle$ Standard method for teleporting a single qubit arbitrary state $\longrightarrow$

$|\psi'\rangle$

Step3:

$$|\psi'\rangle \xrightarrow{U^\dagger} |\psi\rangle$$

N qubit state with two unknowns!!

$$\alpha|000\rangle + \beta|011\rangle + \gamma|100\rangle + \delta|111\rangle$$

Two Bell states

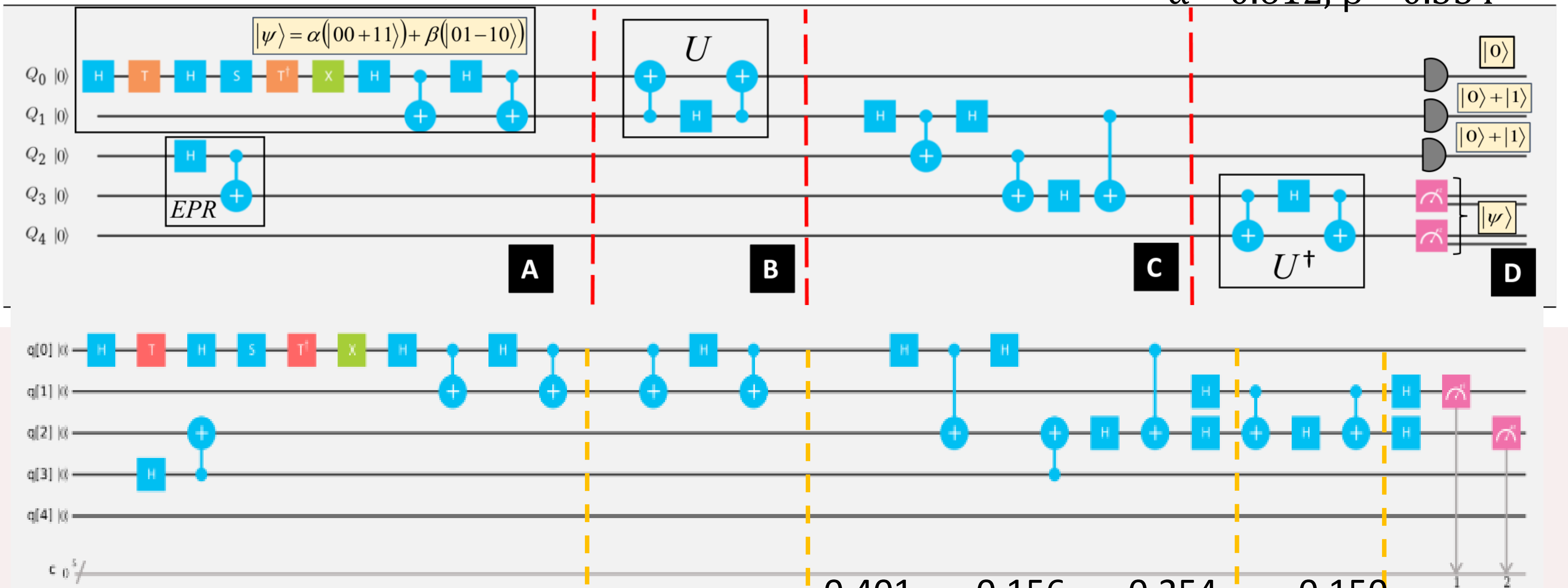
$$\alpha(|0000\rangle + |0111\rangle + \beta(|1101\rangle + |1010\rangle))$$

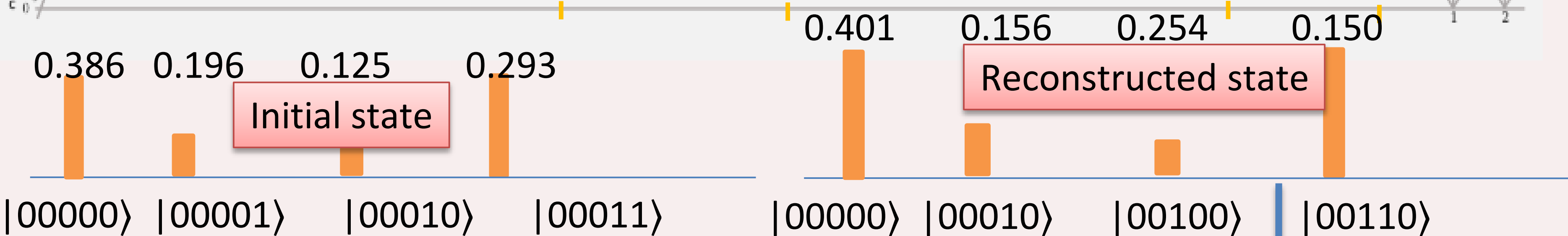
One Bell states

Quantum teleportation

Circuit for Implementation of protocol on IBM quantum computer

α = 0.612, β= 0.354



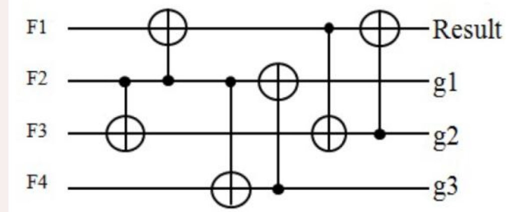


$|\psi\rangle = 0.621(|00\rangle+0.541|11\rangle)+0.443\ (|01\rangle\text{-}0.354|10\rangle)$

$|\psi\rangle = 0.633(|00\rangle+0.387|11\rangle)+0.395\ (|01\rangle\text{-}0.540|10\rangle)$

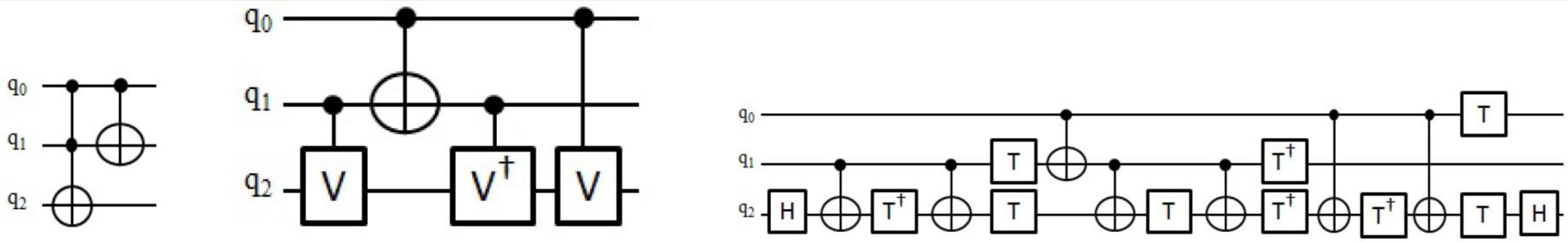
Implementation of reversible circuit on IBM quantum computer

(1) Arithmetic 4:1 reversible multiplexer

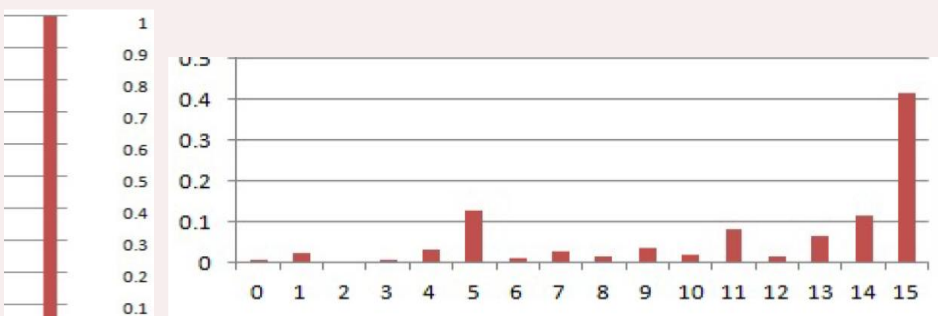


(a) NCT circuit

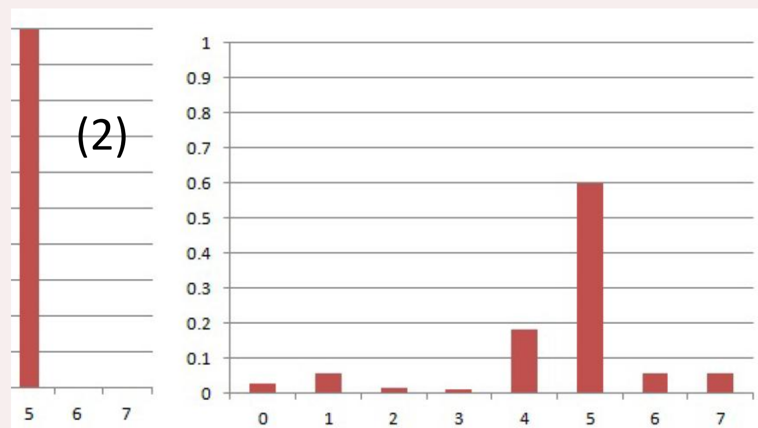
(2) Half adder



(a) NCT circuit (b) NCV circuit (c) Clifford+T circuit



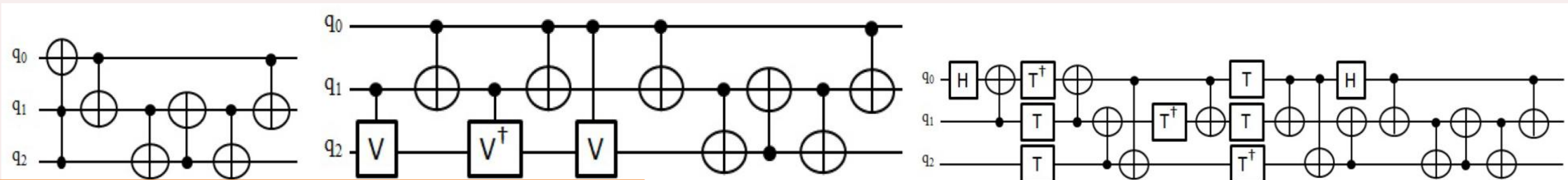
(c) Experimental output



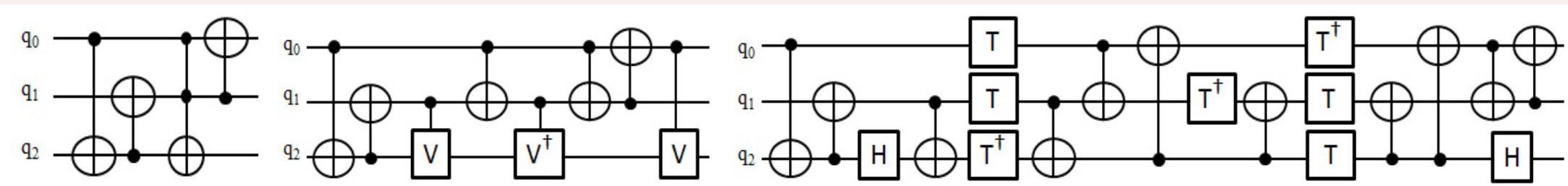
Retrived from: reversible logic benchmark pagehttp://webhome.cs.uvic.ca/dmaslov/

Implementation of reversible circuit on IBM quantum computer

(1) Hamming optimal coding function



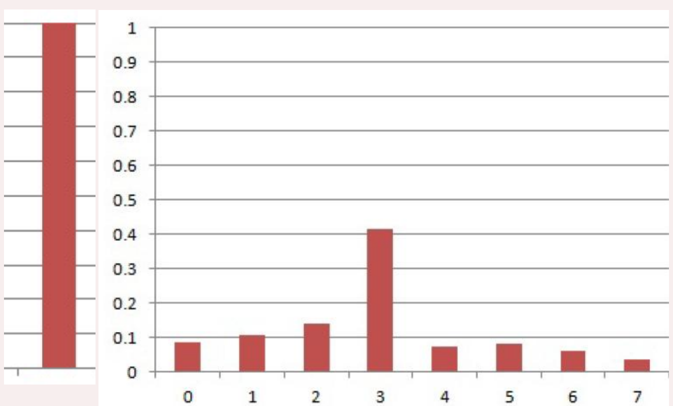
(2) To find primes upto 3 binary digits

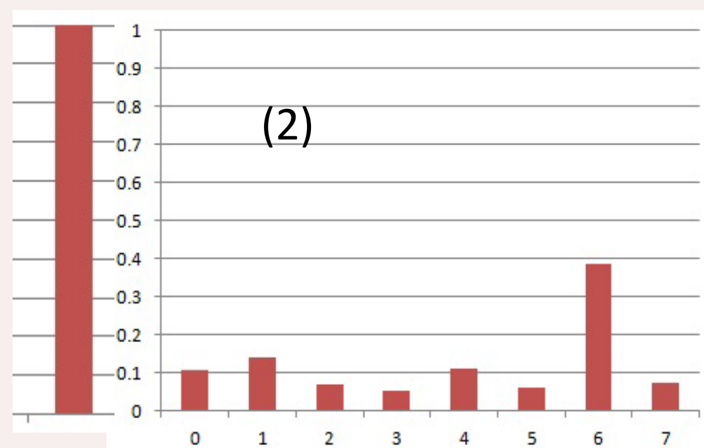


(a) NCT circuit

(b) NCV circuit

(c) Clifford+T circuit

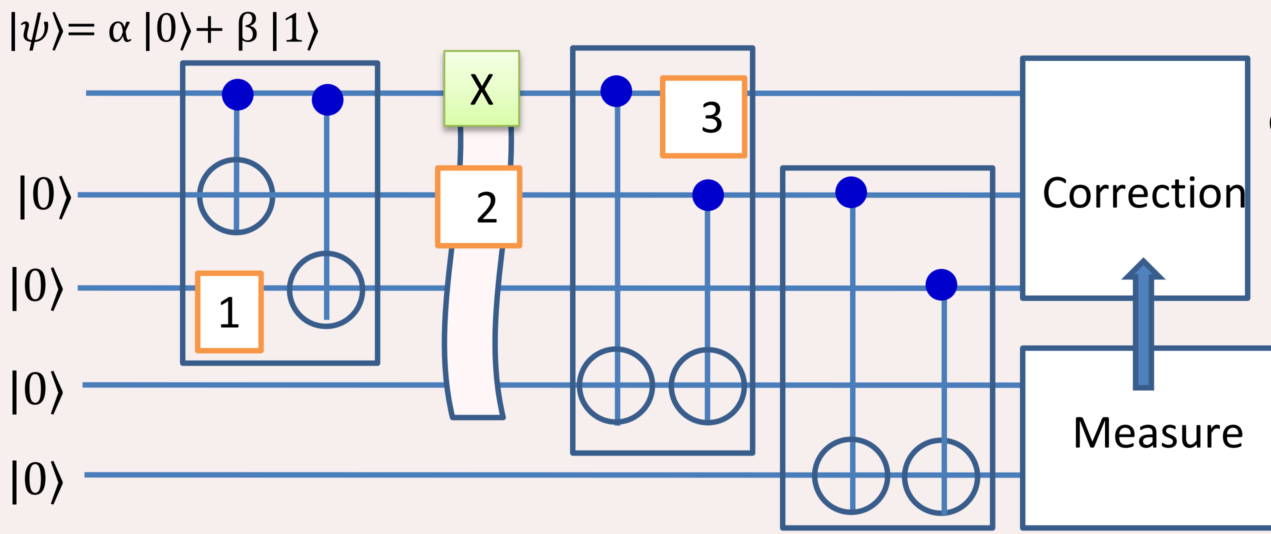




Retrived from: Reversible logic benchmark page, http://webhome.cs.uvic.ca/dmaslov/

Error correction

A simple code for detecting bit-flip error



$\alpha|0\rangle + \beta|1\rangle\ |00\rangle\ |0\rangle_{a1}|0\rangle_{a2}$

1

$\alpha|000\rangle + \beta|111\rangle\ |0\rangle_{a1}|0\rangle_{a2}$

2

$\alpha|100\rangle + \beta\ |011\rangle\ |0\rangle_{a1}|0\rangle_{a}$

3

$\alpha|100\rangle + \beta|011\rangle\ |1\rangle_{a1}|0\rangle_{a2}$

4

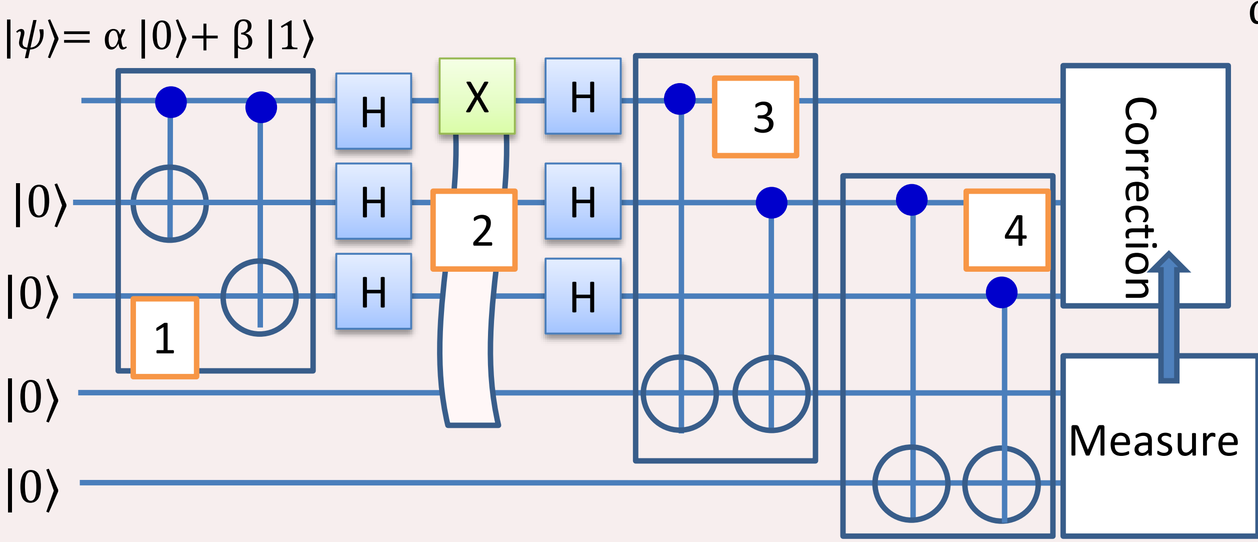
$\alpha|100\rangle + \beta|011\rangle)\ |10\rangle_{a}$

S qubit 1	S qubit 2	S qubit 3	A1	A2
F	N	N	F	N
N	F	N	F	F
N	N	F	N	F

Elements of quantum information and quantum communication, Anirban Pathak, Taylor & Francis (2013).

Error correction

A simple code for detecting phase-flip error



$$\alpha|000\rangle + \beta|111\rangle$$

H^{123}

$$\alpha|+++\rangle + \beta|---\rangle\ |0\rangle_{a1}|0\rangle_{a2}$$

2

$$\alpha|-++\rangle + \beta|+--\rangle\ |0\rangle_{a1}|0\rangle_{a2}$$

H^{123}

$$\alpha|100\rangle + \beta|011\rangle\ |0\rangle_{a1}|0\rangle_{a2}$$

3 4

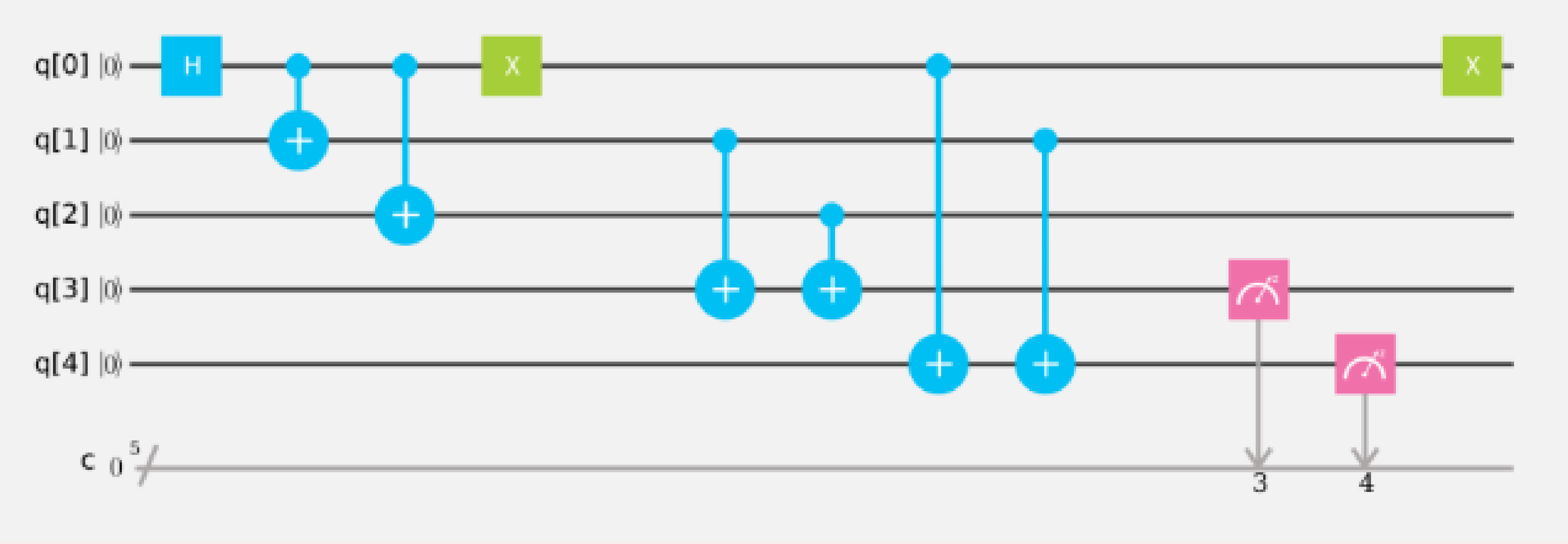
$$\alpha|100\rangle + \beta|011\rangle\ |10\rangle_{a}$$

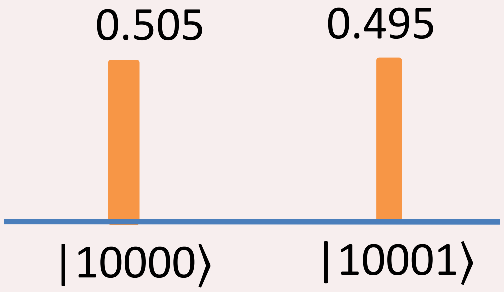
Phase flip error can be encoded in diagonal basis as bit flip error.

Elements of quantum information and quantum communication, Anirban Pathak, Taylor & Francis (2013)

Error correction

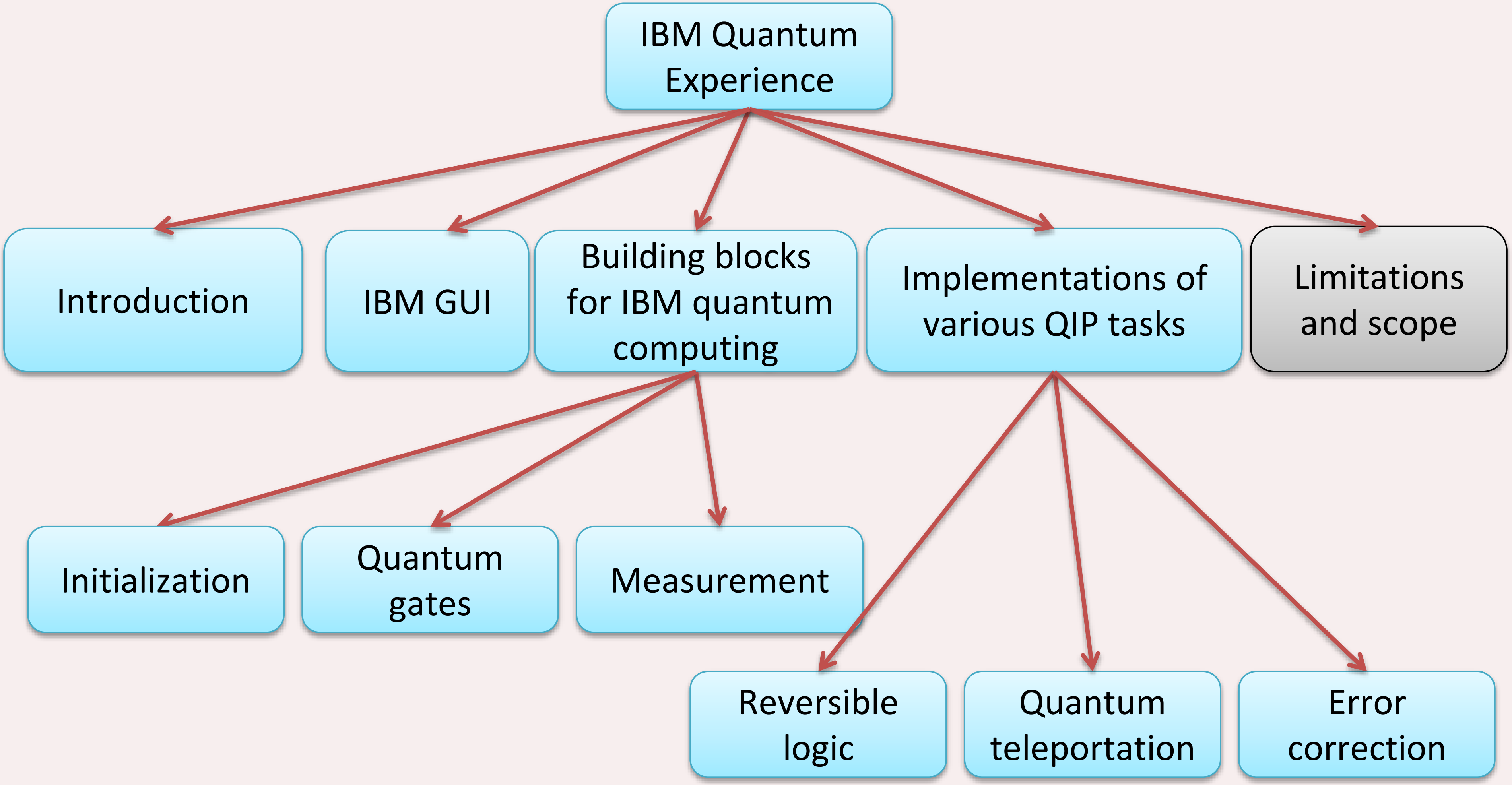
IBM experiment for detecting bit-flip error





Bit flip detected and corrected!!

Plan of the talk

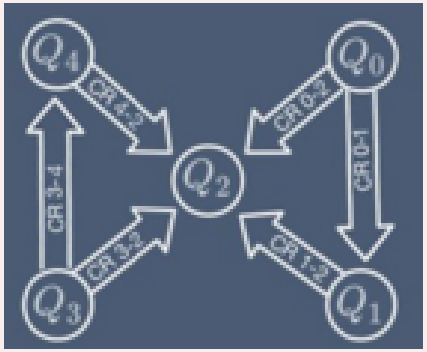


Limitations and scope

- Decoherence and Gate errors: T1, T2 relaxation times are very short compare to already reported qubit systems in same architecture. A brief detail is following.

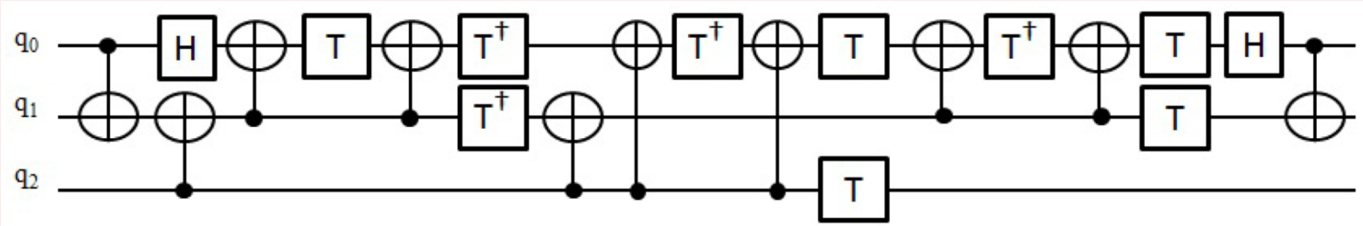
Low fidelity of gates: 0.965 for C-NOT

- Unavailability of all coupled qubits: Restricts direct application of C-NOT gate between arbitrary qubits.



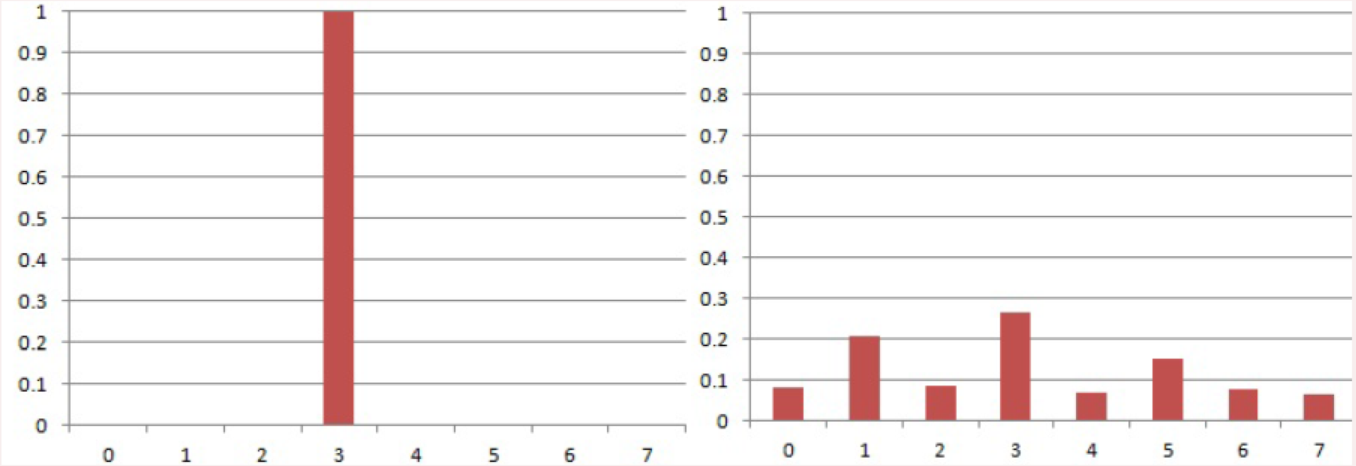
- Swap operations: This limitation can be handled up to an extent only if circuit to be implemented has less complexity. Otherwise results in a drastic loss of fidelity.

Example: Fredkin gate



Limitations and scope

Results

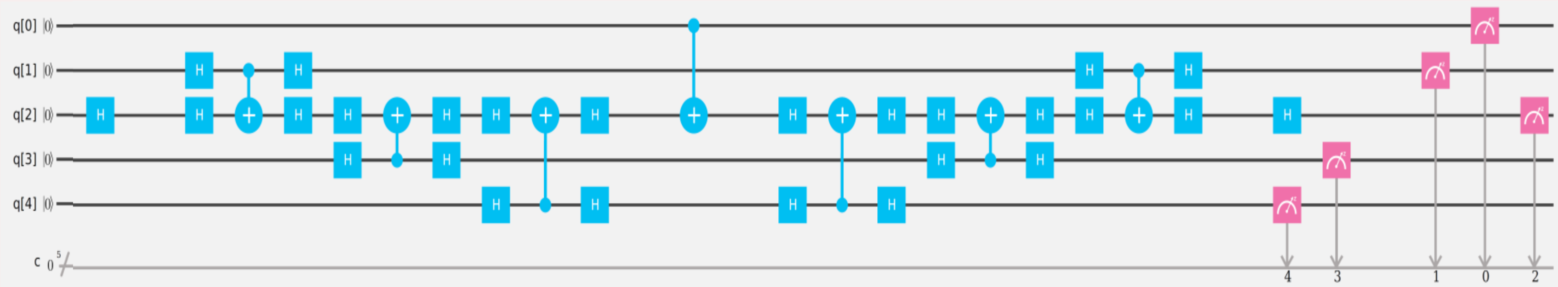


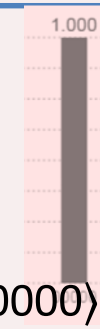
- Restricted number of gates: Currently we can not apply more than forty gates in each line.
- Dead end after measurement: Limits feed back applications.
- Unavailability of shaped pulses.

- It provides a decent platform for application of various QIP tasks on small scale registers and hence provides a chance to test theoretical models.
- Its open access to the young minds will speed-up evolution of quantum technologies.

Entanglement assisted metrology

Detecting state of single spin with the help of an ensemble of spins.





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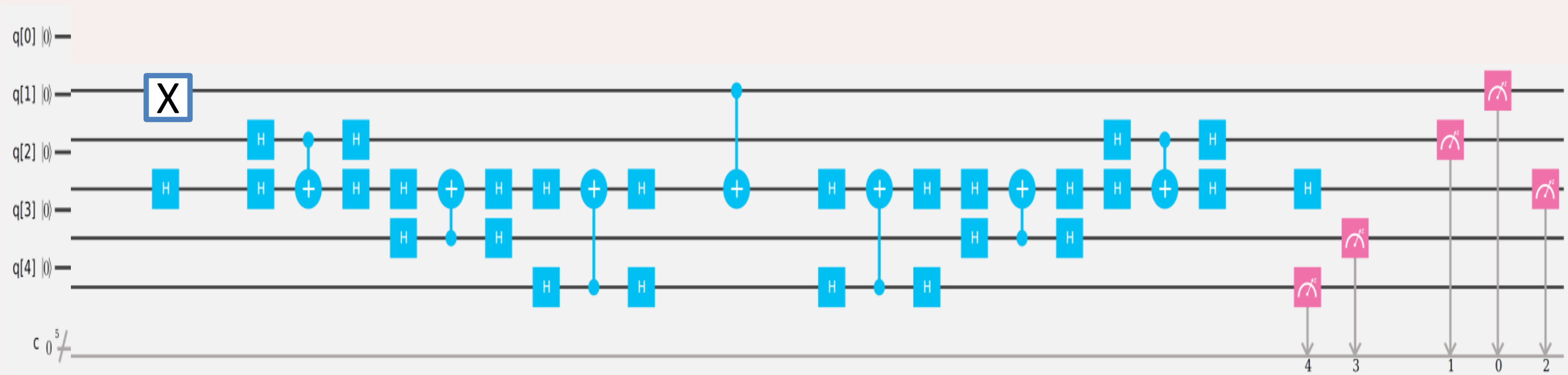

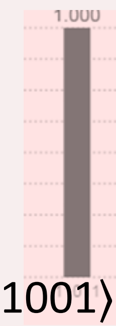

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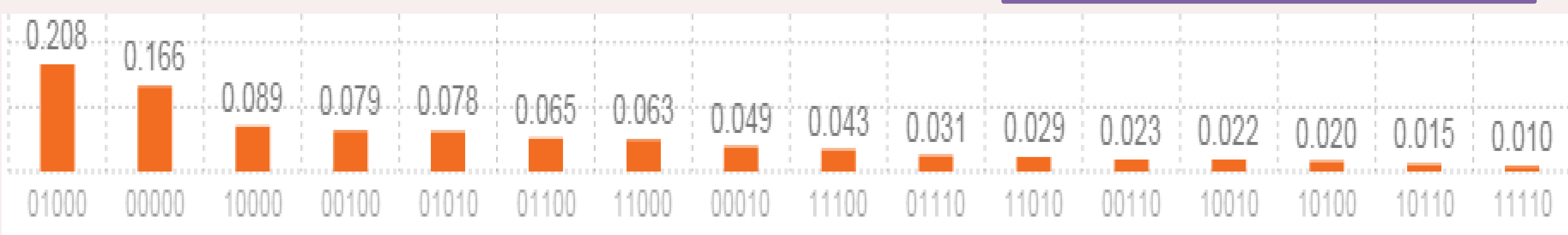
P. Cappellaro et al., PRL, 2005



Group members and project collaborators

Principal investigator

To all of you for your attention and time.