Recent Developments in Quantum Computing

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Outline

- Mathematics of quantum computing
- An application
- Challenges and breakthroughs

The Quantum Bit (qubit)

(Informal) Definition

A state of the qubit is a unit vector with two complex entries.

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix}, \quad \alpha, \beta \in \mathbb{C}, \quad |\alpha|^2 + |\beta|^2 = 1.$$

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To work (that is, compute) with a qubit we first need a frame of reference (that is, basis).
Of course, we can use the standard basis:

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \beta \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

The Quantum Bit (qubit)

In quantum physics it is customary to use Dirac's bra-ket notation, where a vector is denoted with a ket $|\cdot\rangle$

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A qubit is a quantum system that can exists in any superposition of two independent quantum states.

superposition = linear combination

independent = basis

Composite Quantum Systems

Definition

Let A and B be any $m \times n$ and $p \times q$ matrices. The Kronecker/Tensor product of A and B, denote $A \otimes B$, is the $mp \times nq$ block matrix

$$A \otimes B = \begin{bmatrix} a_{11}B & a_{12}B & \cdots & a_{1n}B \\ a_{21}B & a_{22}B & \cdots & a_{2n}B \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}B & a_{n2}B & \cdots & a_{nn}B \end{bmatrix}.$$

Composite Quantum Systems

Suppose that we have two qubit states

$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}, |\varphi\rangle = \begin{bmatrix} \gamma \\ \delta \end{bmatrix}.$$

Then, their composite state gives a 2-qubit state

$$|\psi\rangle \otimes |\varphi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \otimes \begin{bmatrix} \gamma \\ \delta \end{bmatrix} = \begin{bmatrix} \alpha\gamma \\ \alpha\delta \\ \beta\gamma \\ \beta\delta \end{bmatrix}.$$

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Note that, since $\alpha^2 + \beta^2 = 1$ and $\gamma^2 + \delta^2 = 1$, we have that

$$(\alpha\gamma)^2 + (\alpha\delta)^2 + (\beta\gamma)^2 + (\beta\delta)^2 = (\alpha^2 + \beta^2)(\gamma^2 + \delta^2) = 1,$$

and thus $|\psi\rangle \otimes |\varphi\rangle$ is a valid 2-qubit state.

Composite Quantum Systems

The computational basis for a 2-qubit system then becomes

$$|0\rangle \otimes |0\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, |0\rangle \otimes |1\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, |1\rangle \otimes |0\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, |1\rangle \otimes |1\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}.$$

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Definition

A (state of a) 2-qubit (system) is a unit vector in $\mathbb{C}^4$, with computational basis $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$.

A 2-qubit state is called entangled if it **cannot** be decomposed as $|\psi\rangle \otimes |\varphi\rangle$.

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Postulate 1: It is impossible to know the state of a qubit. That is, the α and β in $|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$ are unknown.

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Postulate 3: A measurement will irreversibly destroy the state of the qubit.

Measurements

Let us start with a state

$$|\psi\rangle = \alpha_0 |0\rangle + \alpha_1 |1\rangle, \; \alpha_0^2 + \alpha_1^2 = 1.$$

After the measurement, the following two things will happen simultaneously:

1. $|\psi\rangle$ will collapse to one of the basis states $|i\rangle$ with probability α_i^2, and
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2. i will be outputted.

Since the original state will be irreversibly lost, the only piece (bit) of information that we have to work with is i, which was obtained with probability α_i^2.

Measurements: An Example

Let us consider the state

$$|+\rangle \equiv \frac{|0\rangle + |1\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

If we measure $|+\rangle$, then with equal probability $1/2 = (1/\sqrt{2})^2$ we will either get 0 or 1 and the $|+\rangle$ will collapse to $|0\rangle$ or $|1\rangle$ respectively.

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More advanced things: Measure with respect to different bases and partial measurements.

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Handily:

$$X|a\rangle = |a \oplus 1\rangle \text{ and } Z|a\rangle = (-1)^a |a\rangle.$$

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The Hadamard gate $H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$: $H|0\rangle = |+\rangle$, $H|1\rangle = |-\rangle$.

Quantum Gates: Multi Qubit Gates

Tensoring 1-qubit gates yields 2 qubit gates:

$$X \otimes Z = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} \text{ or } H \otimes Z = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}$$

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The Controlled-Not gate $CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$:

$$CNOT \left|00\right\rangle = \left|00\right\rangle, \; CNOT \left|01\right\rangle = \left|01\right\rangle,$$
$$CNOT \left|10\right\rangle = \left|11\right\rangle, \; CNOT \left|11\right\rangle = \left|10\right\rangle.$$

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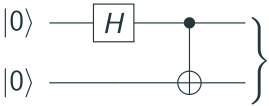
Example:



$$|\beta_{00}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

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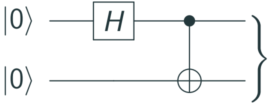

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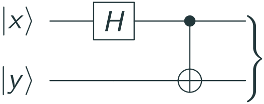
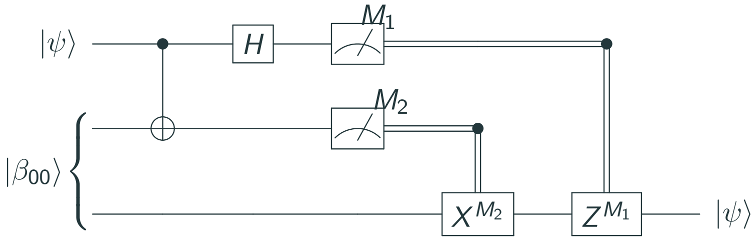
In general



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

Quantum Teleportation



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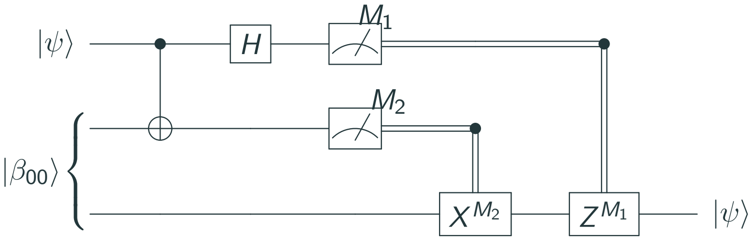

$$
\begin{aligned}
|\psi_0\rangle &= |\psi\rangle \otimes |\beta_{00}\rangle \\
&= \Big[\alpha\,|0\rangle + \beta\,|1\rangle\Big] \otimes \Big[\frac{|00\rangle + |11\rangle}{\sqrt{2}}\Big] \\
&= \frac{1}{\sqrt{2}}\Big[\alpha\,|0\rangle\Big(\,|00\rangle + |11\rangle\,\Big) + \beta\,|1\rangle\Big(\,|00\rangle + |11\rangle\,\Big)\Big].
\end{aligned}
$$

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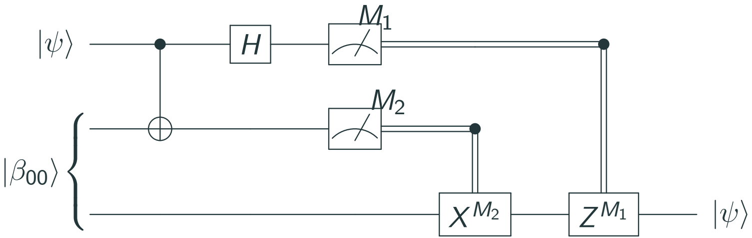

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\Big[\alpha\,|0\rangle\Big(\,|00\rangle + |10\rangle\,\Big) + \beta\,|1\rangle\Big(\,|00\rangle + |10\rangle\,\Big)\Big].$$

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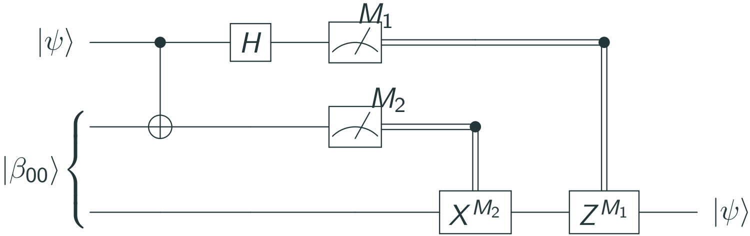

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$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\left[\alpha\left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)\Big(\,|00\rangle + |11\rangle\,\Big) + \beta\left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right)\Big(\,|00\rangle + |11\rangle\,\Big)\right]$$

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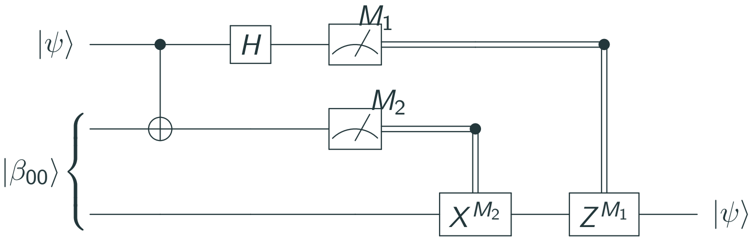

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$$= \frac{1}{2}\Big[\,|00\rangle\,\Big(\alpha\,|0\rangle + \beta\,|1\rangle\Big) + |01\rangle\,\Big(\alpha\,|1\rangle + \beta\,|0\rangle\Big) + |10\rangle\,\Big(\alpha\,|0\rangle - \beta\,|1\rangle\Big) + |11\rangle\,\Big(\alpha\,|1\rangle - \beta\,|0\rangle\Big)\Big].$$

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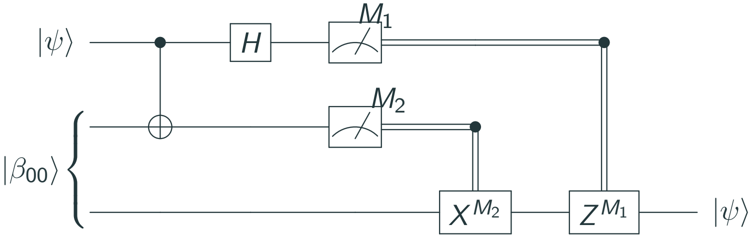

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&= \frac{1}{2}\Big[\,|00\rangle\,\big(\underbrace{\alpha\,|0\rangle + \beta\,|1\rangle}_{|\psi\rangle}\big) + |01\rangle\,\big(\underbrace{\alpha\,|1\rangle + \beta\,|0\rangle}_{X|\psi\rangle}\big) + |10\rangle\,\big(\underbrace{\alpha\,|0\rangle - \beta\,|1\rangle}_{Z|\psi\rangle}\big) + |11\rangle\,\big(\underbrace{\alpha\,|1\rangle - \beta\,|0\rangle}_{XZ|\psi\rangle}\big)\Big].
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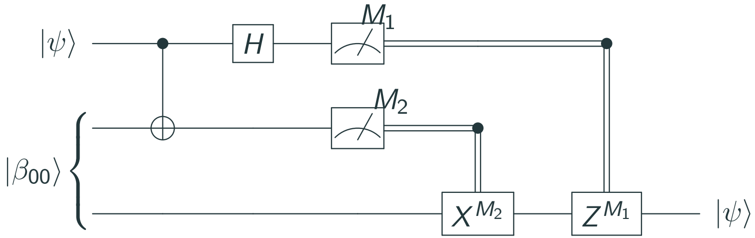

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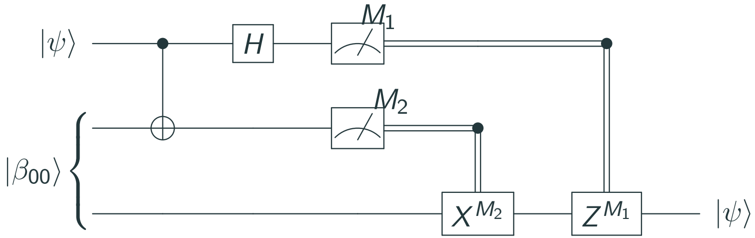

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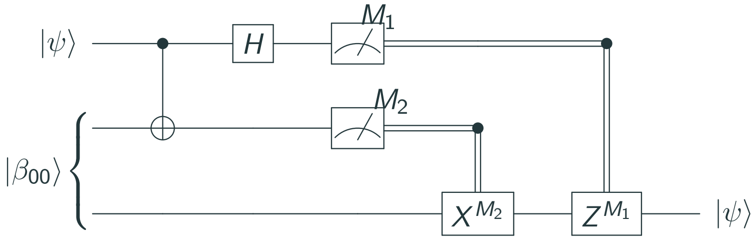

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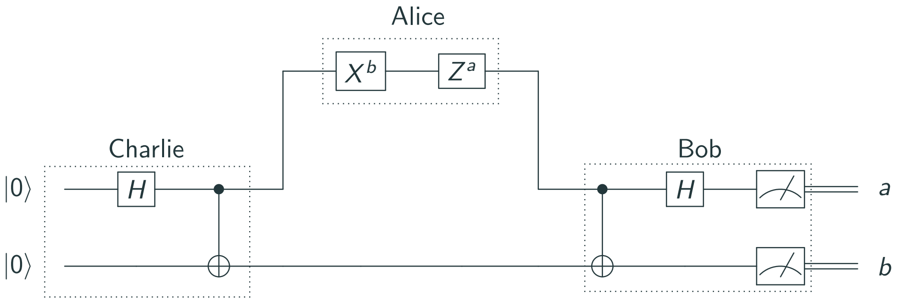
ab &\rightarrow X^b Z^a\,|\psi\rangle
\end{aligned}$$

Superdense Coding

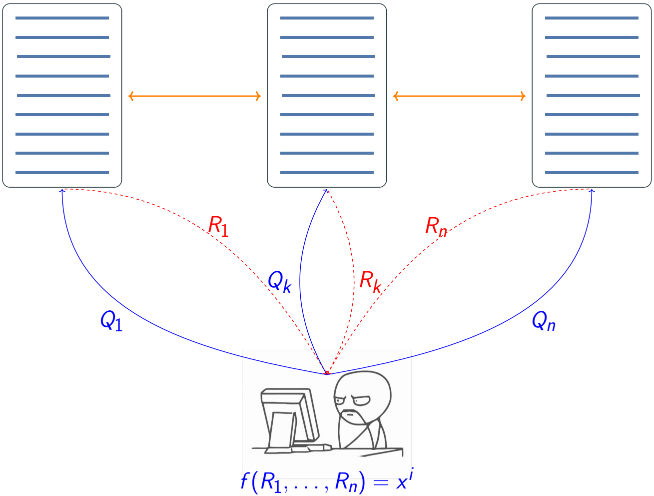


Distributed Computation/Communication

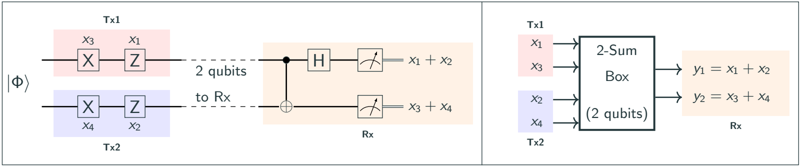
m files $x^1, \ldots, x^m \in \mathbb{F}_q^{\beta \times k}$ are encoded and stored on n servers by a $[n, k]$ storage code $\mathcal{C}$.

$$\begin{array}{c} \\ \text{file } 1 \\ \\ \\ \text{file } m \\ \\ \end{array} \begin{pmatrix} \boxed{\begin{matrix} x^1_{1,1} & \cdots & x^1_{1,k} \\ \vdots & \ddots & \vdots \\ x^1_{\beta,1} & \cdots & x^1_{\beta,k} \end{matrix}} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} \\ \boxed{\begin{matrix} x^m_{1,1} & \cdots & x^m_{1,k} \\ \vdots & \ddots & \vdots \\ x^m_{\beta,1} & \cdots & x^m_{\beta,k} \end{matrix}} \end{pmatrix} \cdot \mathbf{G}_{\mathcal{C}} = \begin{array}{c} \begin{pmatrix} y^1_{1,1} & \cdots & y^1_{1,n} \\ \vdots & \ddots & \vdots \\ y^1_{\beta,1} & \cdots & y^1_{\beta,n} \\ \vdots & \vdots & \vdots \\ y^m_{1,1} & \cdots & y^m_{1,n} \\ \vdots & \ddots & \vdots \\ y^m_{\beta,1} & \cdots & y^m_{\beta,n} \end{pmatrix} \\ \begin{matrix} \text{SERVER}_1 & \qquad & \text{SERVER}_n \end{matrix} \end{array}$$

Distributed Computation/Communication



The Two-Sum Protocol



$$\mathbf{Mx} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} x_1 + x_2 \\ x_3 + x_4 \end{pmatrix}.$$

Challenges

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- Scalability

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- Hardware (and software) development

Breakthroughs

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- Large(ish) scale architectures

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- Large(ish) scale architectures
- Demonstrated quantum advantage

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- Large(ish) scale architectures
- Demonstrated quantum advantage
- Integration with classical systems

Thank You!

email: tpllaha@usf.edu
website: pllahat.github.io