# Introduction to Quantum Computing for Folks

## Joint Advanced Student School 2009

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# A (qu)bit of General Culture I

Figure 1: Sombrero vueltiao (Hat with laps)

# A (qu)bit of General Culture II

Figure 2: Botero's Painting

# Recommendations

- Forget the idea of common sense
- Einstein: "God does not play dice"
- Bohr: "Stop telling God what to do with his dice"
- Keep as skeptical as you can
- Find out the intended bugs

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# Introduction

- Certain quantum mechanical effects cannot be simulated efficiently on a classical computer [2]
- Building quantum computers proved tricky, and no one was sure how to use the quantum effects to speed up computation
- Applications of interest:
  - Quantum key distribution
  - Quantum teleportation
  - A three-bit quantum computer
- In quantum systems the amount of parallelism increases exponentially with the size of the system
- Physical implementation:
  - Ion traps
  - Nuclear Magnetic Resonance (NMR)
  - Optical and solid state techniques

# Ion traps


Figure 3: 4 Magnets

# Ion traps

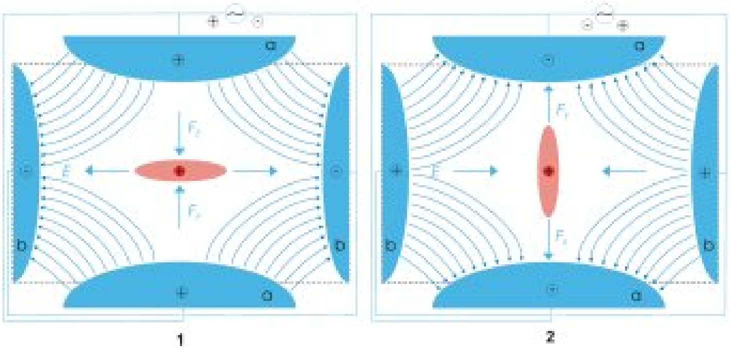


Figure 4: Paul trap

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# Quantum Mechanics

- Quantum mechanics describes physical systems at the atomic level
- Quantum mechanical phenomena are difficult to understand since most of everyday experiences are not applicable
- By definition Quantum mechanics leads to several apparent paradoxes:
  - Compton effect: an action precedes its cause
  - Schrödinger's cat: the cat is simultaneously alive and dead
  - Einstein, Podolsky, and Rosen paradox: spooky action at a distance

# Experiment I

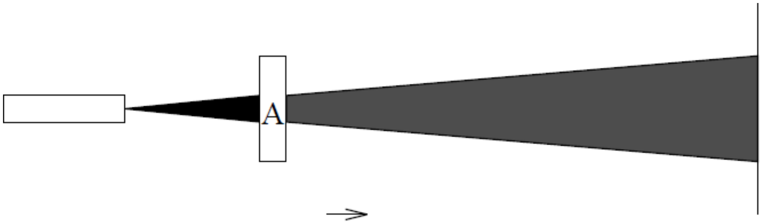


Figure 5: Photon Polarization Experiment

# Experiment II

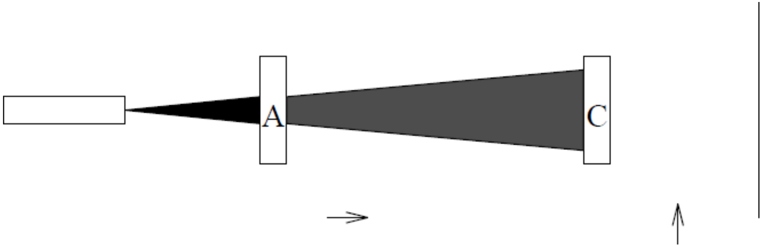


Figure 6: Photon Polarization Experiment

# Experiment III

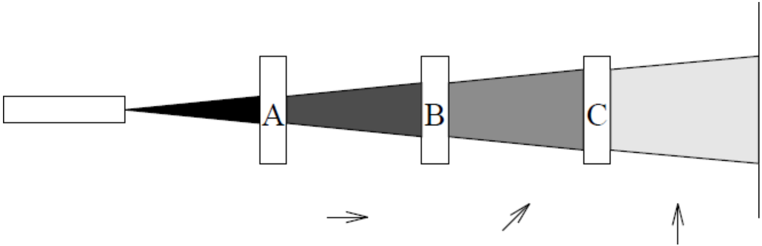


Figure 7: Photon Polarization Experiment

# State Spaces and Bra/Ket Notation

- Ket $|x\rangle$ denotes column vectors and are typically used to describe quantum states
- Bra $\langle x|$ denotes the conjugate transpose of $|x\rangle$
- Combining $\langle x|$ and $|y\rangle$ as in $\langle x||y\rangle$, also written as $\langle x|y\rangle$
- Remarkable results:
  - Inner Product $\langle 0|0\rangle = 1$ (Normality)
  - $\langle 0|1\rangle = 0$ (Orthogonality)
  - $|0\rangle\langle 1||1\rangle = |0\rangle\langle 1|1\rangle = |0\rangle$
  - $|0\rangle\langle 1||0\rangle = |0\rangle\langle 1|0\rangle = 0|0\rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
  - Outer Product $|0\rangle\langle 1| = \begin{pmatrix} 1 \\ 0 \end{pmatrix} (0, 1) = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$

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# Quantum Bits

- A qubit is a unit vector in a two dimensional complex vector space with fixed basis
- Orthonormal basis $|0\rangle$ and $|1\rangle$ may correspond to $|\uparrow\rangle$ and $|\rightarrow\rangle$
- The basis states $|0\rangle$ and $|1\rangle$ are taken to represent the classical bit values 0 and 1 respectively
- Qubits can be in a superposition of $|0\rangle$ and $|1\rangle$ such as $a|0\rangle + b|1\rangle$
- $|a|^2$ and $|b|^2$ are the probabilities that the measured value are $|0\rangle$ and $|1\rangle$ respectively

# Quantum Key Distribution I

- Sequences of single qubits can be used to transmit private keys on insecure channels
- Classically, public key encryption techniques are used for key distribution
- For example, Alice and Bob want to agree on a secret key so that they can communicate privately. They are connected by an ordinary bi-directional open channel and a uni-directional quantum channel both of which can be observed by Eve, who wishes to eavesdrop on their conversation

# Quantum Key Distribution II

Figure 8: Alice

# Quantum Key Distribution III

Figure 9: Bob

# Quantum Key Distribution IV


Figure 10: Eve

# Quantum Key Distribution V

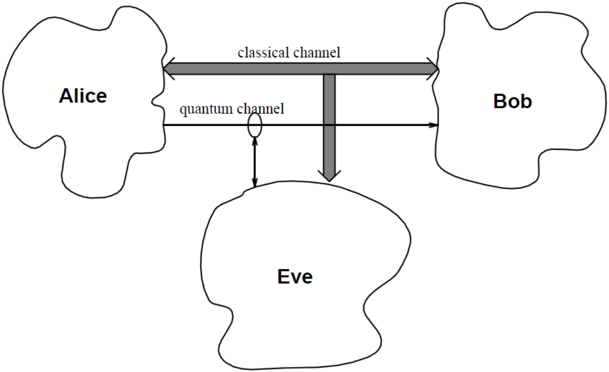


Figure 11: Key Distribution Scenario

# Quantum Key Distribution VI

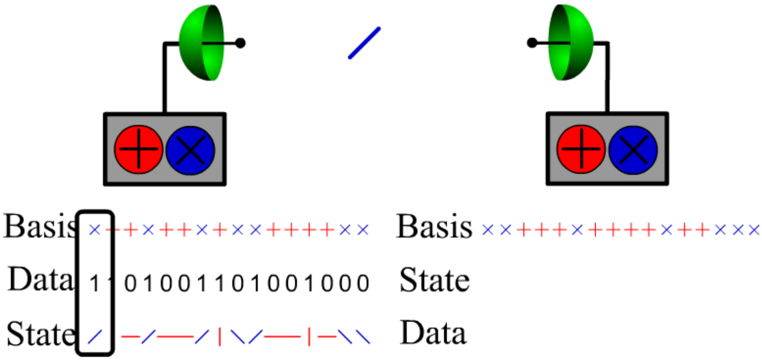


Figure 12: Transmition of the first state

# Quantum Key Distribution VII

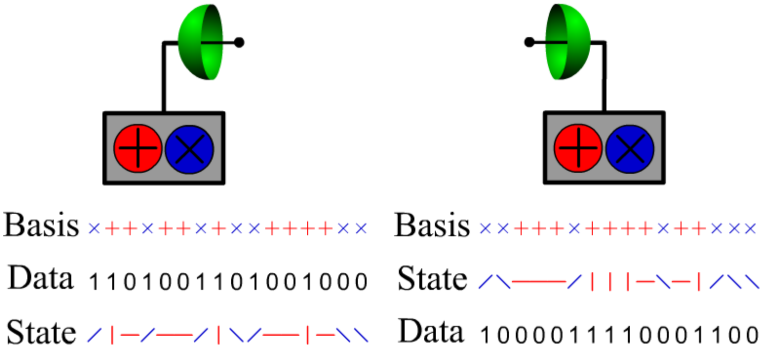


Figure 13: Transmition of the last state

# Quantum Key Distribution VIII

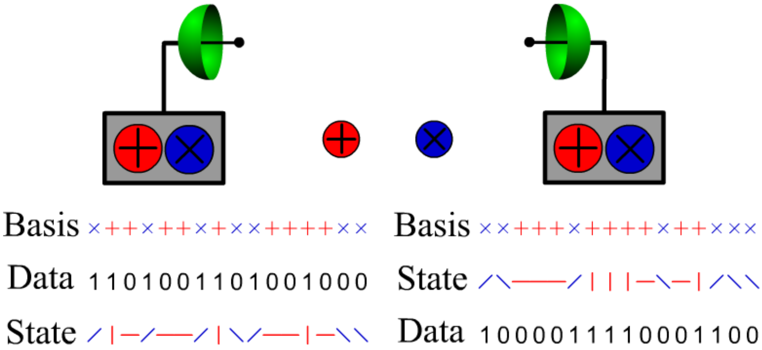


Figure 14: Exchange of the basis

# Quantum Key Distribution IX

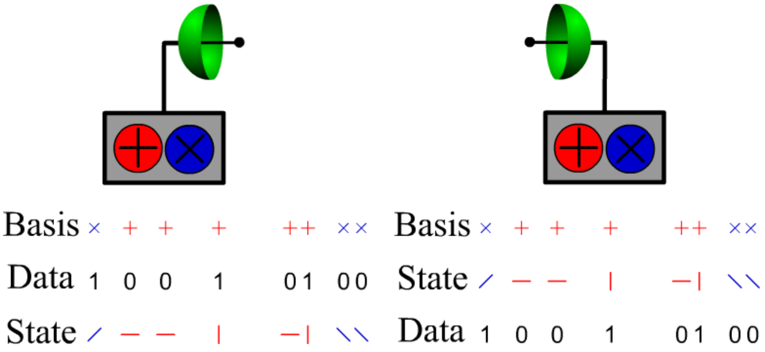


Figure 15: Final agreement between Alice and Bob

# Quantum Key Distribution X

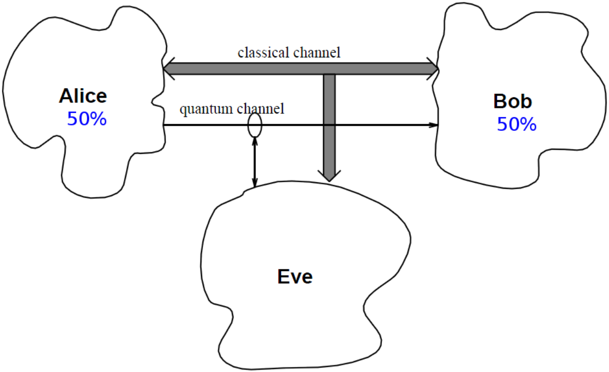


Figure 16: Agreement between Alice and Bob

# Quantum Key Distribution XI

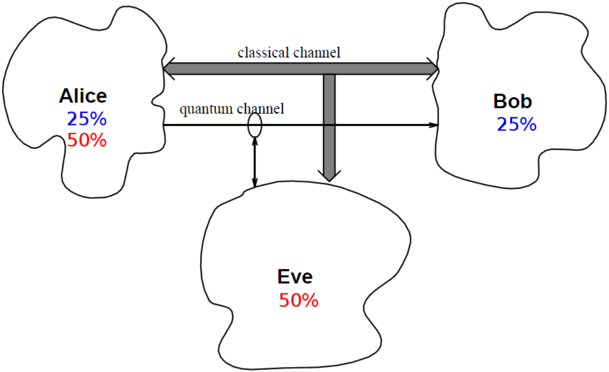


Figure 17: Agreement between Alice, Bob, and Eve

# Multiple Qubits

- The state of a qubit can be represented by a vector in the two dimensional complex vector space spanned by $|0\rangle$ and $|1\rangle$
- The state space for two qubits, each with basis $\{|0\rangle, |1\rangle\}$, has basis $\{|0\rangle \otimes |0\rangle, |0\rangle \otimes |1\rangle, |1\rangle \otimes |0\rangle, |1\rangle \otimes |1\rangle\}$, briefly, $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$

## Example: Entangled States

The state $|00\rangle + |11\rangle$ cannot be described in terms of the state of each of its qubits separately. In other words, we cannot find $a_1, a_2, b_1, b_2$ such that $(a_1|0\rangle + b_1|1\rangle) \otimes (a_2|0\rangle + b_2|1\rangle) = |00\rangle + |11\rangle$ since

$$(a_1|0\rangle + b_1|1\rangle) \otimes (a_2|0\rangle + b_2|1\rangle) = \\ a_1 a_2|00\rangle + a_1 b_2|01\rangle + b_1 a_2|10\rangle + b_1 b_2|11\rangle$$

and $a_1 b_2 = 0$ implies that either $a_1 a_2 = 0$ or $b_1 b_2 = 0$

# Measurement I

- **The result of a measurement is probabilistic and the process of measurement changes the state to that measured**

## Example: Measurement of a 2-qubit system

- Any 2-qubit state can be expressed as $a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$. Where $a, b, c$, and $d$ are complex numbers such that $|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$
- Suppose we wish to measure the first qubit with respect $\{|0\rangle, |1\rangle\}$

$$
\begin{aligned}
a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle = \\
|0\rangle \otimes (a|0\rangle + b|1\rangle) + |1\rangle \otimes (c|0\rangle + d|1\rangle) \\
u|0\rangle \otimes (\frac{a}{u}|0\rangle + \frac{b}{u}|1\rangle) + v|1\rangle \otimes (\frac{c}{v}|0\rangle + \frac{d}{v}|1\rangle)
\end{aligned}
$$

- For quantum computation, multi-bit measurement can be treated as a series of single-bit measurements in the standard basis

# Measurement II

- Particles are not entangled if the measurement of one has no effect on the other

## Example: Measurement Entangled States

- The state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ is entangled since the probability that the first bit is measured to be $|0\rangle$ is $1/2$ if the second bit has not been measured
- The state $\frac{1}{\sqrt{2}}(|00\rangle + |01\rangle)$ is not entangled since: $\frac{1}{\sqrt{2}}(|00\rangle + |01\rangle) = |0\rangle \otimes \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

# The EPR Paradox I

- Einstein, Podolsky, and Rosen proposed a gedanken experiment that seemed to violate fundamental principles relativity
- Imagine a source that generates two maximally entangled particles $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, called an EPR pair, and sends one to Alice and one Bob
- Suppose that Alice measures her particle and observes state $|0\rangle$
- Now Bob measures his particle he will also observe $|0\rangle$
- Similarly, if Alice measures $|1\rangle$, so will Bob

# The EPR Paradox II

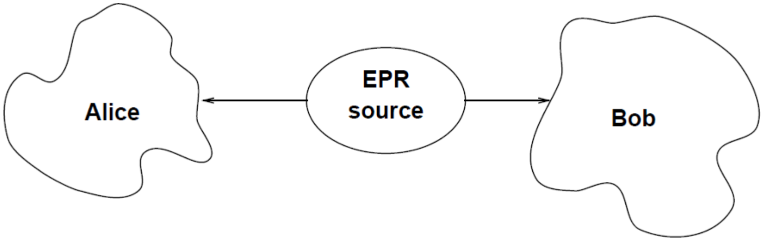


Figure 18: EPR Paradox Setup

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# Quantum Gates

- Any linear transformation on a complex vector space can be described by a matrix
- One can think of unitary transformations as being rotations of a complex vector space

# Simple Quantum Gates

- The transformations are specified by their effect on the basis vectors
- It can be verified that these gates are unitary. For example $YY^* = I$
- Transformations on basis vectors:
  - Identity $I$ : $\begin{array}{lcl} |0\rangle & \to & |0\rangle \\ |1\rangle & \to & |1\rangle \end{array} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
  - Negation $X$ : $\begin{array}{lcl} |0\rangle & \to & |1\rangle \\ |1\rangle & \to & |0\rangle \end{array} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
  - Phase shift negation $Y$ : $\begin{array}{lcr} |0\rangle & \to & -|1\rangle \\ |1\rangle & \to & |0\rangle \end{array} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$
  - Phase shift $Z$ : $\begin{array}{lcr} |0\rangle & \to & |0\rangle \\ |1\rangle & \to & -|1\rangle \end{array} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
  - Controlled-NOT $C_{\text{NOT}}$ : $\begin{array}{lcl} |00\rangle & \to & |00\rangle \\ |01\rangle & \to & |01\rangle \\ |10\rangle & \to & |11\rangle \\ |11\rangle & \to & |10\rangle \end{array} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$
  - Walsh-Hadamard $H$ : $\begin{array}{lcl} |0\rangle & \to & \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \\ |1\rangle & \to & \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \end{array} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

# Examples

- The use of simple quantum gates can be studied with two examples:
    - Dense coding
    - Teleportation
- The key to both dense coding and teleportation is the use of entangled particles

$$\psi_0 = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

# Dense Coding I

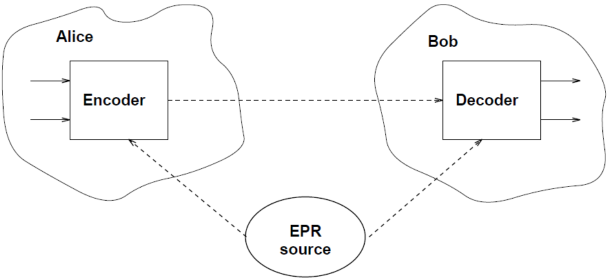


Figure 19: Dense Coding

- The idea is to send 2 bits of classical information using only 1 qubit
- Alice receives two classical bits, encoding the numbers 0 through 3

# Dense Coding II

- Depending on this number Alice performs one of the transformations $\{I, X, Y, Z\}$

| Value | Transformation | New State |
|---|---|---|
| 0 | $\psi_0 = (I \otimes I)\psi_0$ | $\frac{1}{\sqrt{2}}(\|00\rangle + \|11\rangle)$ |
| 1 | $\psi_1 = (X \otimes I)\psi_0$ | $\frac{1}{\sqrt{2}}(\|10\rangle + \|01\rangle)$ |
| 2 | $\psi_2 = (Y \otimes I)\psi_0$ | $\frac{1}{\sqrt{2}}(-\|10\rangle + \|01\rangle)$ |
| 3 | $\psi_3 = (Z \otimes I)\psi_0$ | $\frac{1}{\sqrt{2}}(\|00\rangle - \|11\rangle)$ |

Table 1: Resulting States Alice

- Bob applies a Controlled-NOT to the two qubits of the entangled pair
- He can measure the second qubit without disturbing the quantum state

# Dense Coding III

| Initial State | Controlled-NOT | bit 1 | bit 2 |
|---|---|---|---|
| $\psi_0 = \frac{1}{\sqrt{2}}(\|00\rangle + \|11\rangle)$ | $\frac{1}{\sqrt{2}}(\|00\rangle + \|10\rangle)$ | $\frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)$ | $\|0\rangle$ |
| $\psi_1 = \frac{1}{\sqrt{2}}(\|10\rangle + \|01\rangle)$ | $\frac{1}{\sqrt{2}}(\|11\rangle + \|01\rangle)$ | $\frac{1}{\sqrt{2}}(\|1\rangle + \|0\rangle)$ | $\|1\rangle$ |
| $\psi_2 = \frac{1}{\sqrt{2}}(-\|10\rangle + \|01\rangle)$ | $\frac{1}{\sqrt{2}}(-\|11\rangle + \|01\rangle)$ | $\frac{1}{\sqrt{2}}(-\|1\rangle + \|0\rangle)$ | $\|1\rangle$ |
| $\psi_3 = \frac{1}{\sqrt{2}}(\|00\rangle - \|11\rangle)$ | $\frac{1}{\sqrt{2}}(\|00\rangle - \|10\rangle)$ | $\frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle)$ | $\|0\rangle$ |

Table 2: Resulting States Bob

- Now, Bob applies $H$ to the first qubit

# Dense Coding IV

| State | First bit | $H$ (First bit) |
|---|---|---|
| $\psi_0$ | $\frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)$ | $\frac{1}{\sqrt{2}}(\frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle) + \frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle)) = \|0\rangle$ |
| $\psi_1$ | $\frac{1}{\sqrt{2}}(\|1\rangle + \|0\rangle)$ | $\frac{1}{\sqrt{2}}(\frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle) + \frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)) = \|0\rangle$ |
| $\psi_2$ | $\frac{1}{\sqrt{2}}(-\|1\rangle + \|0\rangle)$ | $\frac{1}{\sqrt{2}}(-\frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle) + \frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle)) = \|1\rangle$ |
| $\psi_3$ | $\frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle)$ | $\frac{1}{\sqrt{2}}(\frac{1}{\sqrt{2}}(\|0\rangle + \|1\rangle) - \frac{1}{\sqrt{2}}(\|0\rangle - \|1\rangle)) = \|1\rangle$ |

Table 3: Applying $H$ to the first bit

- Finally, Bob measures the resulting bit which allows him to distinguish between 0 and 3, and 1 and 2

# Teleportation I

Figure 20: Evidence of Teleportation in the Past

# Teleportation II

- The objective is to transmit the quantum state of a particle using classical bits and reconstruct the exact quantum state at the receiver
- **Since quantum state cannot be copied, the quantum state of the given particle will necessarily be destroyed**

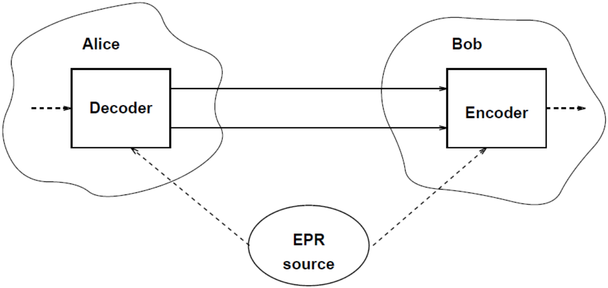


Figure 21: Teleportation

# Teleportation III

- Alice has a qubit whose state she doesn't know. She wants to send the state of this qubit

  $$\phi = a|0\rangle + b|1\rangle$$

  to Bob through classical channels. As with dense coding, Alice and Bob each possess one qubit of an entangled pair

  $$\psi_0 = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

# Teleportation IV

- Alice applies the decoding step of dense coding to the qubit $\phi$ to be transmitted and her half of the entangled pair

$$
\begin{aligned}
&\psi \otimes \psi_0 = \\
&\qquad \frac{1}{\sqrt{2}}(a|0\rangle \otimes (|00\rangle + |11\rangle) + b|1\rangle \otimes (|00\rangle + |11\rangle)) \\
&\qquad \frac{1}{\sqrt{2}}(a|000\rangle + a|011\rangle + b|100\rangle + b|111\rangle)
\end{aligned}
$$

of which Alice controls the first two bits and Bob controls the last one

# Teleportation V

- Alice now applies $C_{\mathrm{NOT}} \otimes I$ and $H \otimes I \otimes I$ to this state:

$$
\begin{aligned}
&(H \otimes I \otimes I)(C_{\mathrm{NOT}} \otimes I)(\psi \otimes \psi_0) = \\
&\quad (H \otimes I \otimes I)(C_{\mathrm{NOT}} \otimes I)\frac{1}{\sqrt{2}}(a|000\rangle + a|011\rangle + b|100\rangle + b|111\rangle) \\
&\quad (H \otimes I \otimes I)\frac{1}{\sqrt{2}}(a|000\rangle + a|011\rangle + b|110\rangle + b|101\rangle) \\
&\quad \frac{1}{2}(a(|000\rangle + |011\rangle + |100\rangle + |111\rangle) \\
&\quad + b(|010\rangle + |001\rangle - |110\rangle - |101\rangle) \\
&\quad \frac{1}{2}(|00\rangle(a|0\rangle + b|1\rangle) + |01\rangle(a|1\rangle + b|0\rangle) \\
&\quad + |10\rangle(a|0\rangle - b|1\rangle) + |11\rangle(a|1\rangle - b|0\rangle))
\end{aligned}
$$

- Alice measures the first two qubits to get one of $|00\rangle$, $|01\rangle$, $|10\rangle$, or $|11\rangle$ with equal probability

# Teleportation VI

- Depending on the result of the measurement, the quantum state of Bob's qubit is projected to $a|0\rangle + b|1\rangle$, $a|1\rangle + b|0\rangle$, $a|0\rangle - b|1\rangle$, $a|1\rangle - b|0\rangle$ respectively
- When Bob receives the two classical bits from Alice he knows how the state of his half of the entangled pair compares to the original state of Alice's qubit

| Bits recieved | State | Decoding |
|---|---|---|
| 00 | $a\|0\rangle + b\|1\rangle$ | $I$ |
| 01 | $a\|1\rangle + b\|0\rangle$ | $X$ |
| 10 | $a\|0\rangle - b\|1\rangle$ | $Z$ |
| 11 | $a\|1\rangle - b\|0\rangle$ | $Y$ |

Table 4: Decoding Transformation

# Teleportation VII

- Bob can reconstruct the original state of Alice's qubit, $\phi$, by applying the appropriate decoding transformation to his part of the entangled pair

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# Quantum Computers

- Quantum mechanics can be used to perform computations
- Computations done via quantum mechanics are qualitatively different from those performed by a conventional computer
- All quantum state transformations have to be reversible

# Quantum Gate Arrays

- The Toffoli gate $T$ can be used to construct complete set of boolean connectives

$$\begin{aligned} T|1,1,x\rangle &= |1,1,\neg x\rangle \ (\textsc{not}) \\ T|x,y,0\rangle &= |x,y,x \wedge y\rangle \ (\textsc{and}) \end{aligned}$$

- Complex Unitary Operations:
  - Controlled-NOT $C_{\textsc{not}} = |0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes X$
  - Toffoli $T = |0\rangle\langle 0| \otimes I \otimes I + |1\rangle\langle 1| \otimes C_{\textsc{not}}$
  - Fredkin "Controled Swap" $F = |0\rangle\langle 0| \otimes I \otimes I + |1\rangle\langle 1| \otimes S$ where $S$ is the swap operation $S = |00\rangle\langle 00| + |01\rangle\langle 10| + |10\rangle\langle 01| + |11\rangle\langle 11|$

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# Shor's Algorithm

- In 1994 Peter Shor found a bounded probability polynomial time algorithm for factoring $n$-digit numbers on a quantum computer
- The most efficient classical algorithm known today is exponential in the size of the input
- Shor's Algorithm uses a standard reduction of the factoring problem to the problem of finding the period of a function

# The Quantum Fourier Transform I

- Fourier transforms in general map from the time domain to the frequency domain
- Discrete Fourier transform (DFT) operates on $N$ equally spaced samples in the interval $[0, 2\pi)$
- The fast Fourier transform (FFT) is a version of DFT where $N$ is a power of 2
- The quantum Fourier transform (QFT) is a variant of the DFT which uses powers of 2. The QFT operates on the amplitude of the quantum state, by sending

$$\sum_x g(x)|x\rangle \rightarrow \sum_c G(c)|c\rangle$$

where $G(c)$ is the DFT of $g(x)$, and $|x\rangle$ and $|c\rangle$ both range over the binary representations for the integers between 0 and $N-1$

# The Quantum Fourier Transform II

- The QFT $U_{QFT}$ with base $N = 2^m$ is defined by:

$$U_{QFT} : |x\rangle \rightarrow \frac{1}{\sqrt{2^m}} \sum_{c=0}^{2^m-1} e^{\frac{2\pi icx}{2^m}} |c\rangle$$

# Outline of Shor's Algorithm

## Shor's Algorithm

1. Quantum parallelism
2. State whose amplitude has the same period as $f$
3. Applying a QFT
4. Extracting the period
5. Finding a factor of $M$
6. Repeating the algorithm, if necessary

# Search Problems

- A large class of problems can be specified as search problems of the form "find some $x$ in a set of possible solutions such that statement $P(x)$ is true."
- Such problems range from database search to sorting to graph coloring
- An unstructured search problem is one where nothing is known about the structure of the solution space and the statement $P$. For example, determining $P(x_0)$ provides no information about the possible value of $P(x_1)$ for $x_0 \neq x_1$
- A structured search problem is one where information about the search space and statement $P$ can be exploited. For instance, searching an alphabetized list

# Grover's Algorithm I

## Grover's Algorithm

1. Prepare a register containing a superposition of all possible values $x_i \in [0, \ldots, 2^n - 1]$
2. Compute $P(x_i)$ on this register
3. Change amplitude $a_j$ to $-a_j$ for $x_j$ such that $P(x_j) = 1$
4. Apply inversion about the average to increase amplitude of $x_j$ with $P(x_j) = 1$
5. Repeat steps 2 through 4 $\frac{\pi}{4}\sqrt{2^n}$-times
6. Read the result

# Grover's Algorithm II

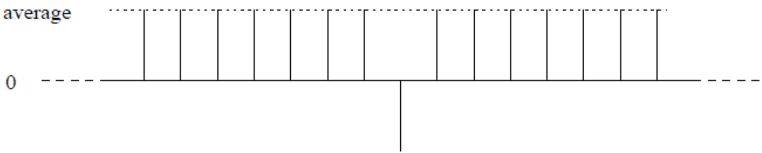


Figure 22: Amplitudes after Step 3

# Grover's Algorithm III

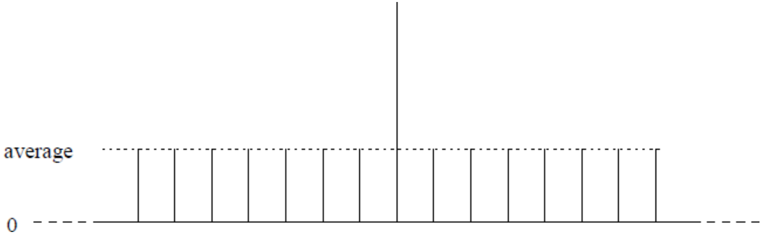


Figure 23: The resulting amplitudes

# Quantum Error Correction

- One fundamental problem in building quantum computers is the need to isolate the quantum state
- An interaction of particles representing qubits with the external environment disturbs the quantum state, and causes it to decohere, or transform in an unintended and often non-unitary fashion
- Quantum error correction must reconstruct the exact encoded quantum state
- Reconstruction appears harder than in the classical case since the impossibility of cloning or copying the quantum state

# Characterization of Errors

- The possible errors for each single qubit considered are linear combinations of no errors $I$, bit flip errors $X$, phase errors $Z$, and bit flip phase errors $Y$

$$|\psi\rangle \rightarrow (e_1 I + e_2 X + e_3 X + e_4 Z)|\psi\rangle = \sum_i e_i E_i |\psi\rangle$$

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# Conclusions

- Quantum computations must be linear and reversible, any classical algorithm can be implemented on a quantum computer
- Given a practical quantum computer, Shor's algorithm would make many present cryptographic methods obsolete
- Grover's search algorithm proves that quantum computers are strictly more powerful than classical ones
- It is an open question whether we can find quantum algorithms that provide exponential speed-up for other problems
- A big breakthrough for dealing with decoherence came from the development of quantum error correction techniques

# Further Reading

- Andrew Steane's Quantum computing [3]
- Richard Feynman's Lectures on Computation [1]
- Williams and Clearwater's book Explorations in Quantum Computing [5]
- SIAM Journal of Computing issue of October 1997
- Leonard Susskind's lecture on Modern Physics: Quantum Mechanics [4]

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# Questions

Please, do not hesitate in asking academic stuff, or contact me through
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"That's all Folks!"