Sending quantum information

- Say Alice wants to send Bob a qubit (i.e., quantum information rather than classical)

- Quantum ‘channels’ are hard to make and maintain!

- Can Alice send the qubit over a classical channel (i.e., the telephone)?

- Option 1: - measure the qubit
  - send the measurement results to Bob
Sending quantum information

- If Alice has complete information about the qubit:
  - Alice tells Bob all of this information
  - Bob performs a preparation to create this state

- If Alice has NO information about the qubit:
  - For instance, the qubit is prepared by a third party
  - Could perform a measurement, e.g., in basis $|0\rangle, |1\rangle$
  - If the qubit were in $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, no information is gained and the qubit is “destroyed” in the process

Without knowledge of the preparation procedure of a qubit, no measurement can determine its state
Quantum teleportation

- Entanglement provides a solution
- Let Alice and Bob share a Bell state

Alice takes the qubit to send (1) and the qubit from the Bell state (2) and measures them in the Bell basis
  - One of four possible outcomes $\rightarrow$ two bits of information
  - Send these bits to Bob, who operates on his qubit (3)

\[ |\psi^\rightarrow\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle) \]
Quantum teleportation

- Result of Alice’s measurements:

<table>
<thead>
<tr>
<th>result</th>
<th>bits</th>
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<tbody>
<tr>
<td>$</td>
<td>\Psi^-\rangle$</td>
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<tr>
<td>$</td>
<td>\Psi^+\rangle$</td>
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<tr>
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<td>\Phi^-\rangle$</td>
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<td>\Phi^+\rangle$</td>
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</tbody>
</table>

Send bits to Bob, who must apply $\rightarrow b_1, b_2$

<table>
<thead>
<tr>
<th>bits</th>
<th>apply</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>$I$</td>
</tr>
<tr>
<td>01</td>
<td>$Z$</td>
</tr>
<tr>
<td>10</td>
<td>$X$</td>
</tr>
<tr>
<td>11</td>
<td>$ZX$</td>
</tr>
</tbody>
</table>

- Result: any measurement predictions involving the original qubit (1) now apply to Bob’s qubit (3)
- The qubit has been *quantum teleported* to Bob
Interpreting quantum teleportation

- The quantum system has not been teleported, only the *state* of the system
- The two bits contain no information about the qubit
- If qubit (1) was entangled with another system before quantum teleportation, qubit (3) is entangled after
- After teleportation, qubit (1) contains no information
Quantum teleportation: reality

- Quantum teleportation has been performed in the lab!

1997: Innsbrook, Austria

- **Qubit**: polarization state of a single photon
- **Bell state**: generated through parametric down conversion

1998: Caltech, USA

- “**Qubit**”: coherent state of electromagnetic field mode
- “**Bell state**”: generated through two-mode squeezing
Quantum teleportation in Oz

2002: Ping-Koy Lam’s group at ANU

- Similar to Caltech exp.
- “Hi-Fi” QT
- Demonstrates:
  - Entanglement was used
  - Alice gains no info about the system