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1 Overview - Quantum States as Computational Resources.

In the last lectures, we saw that quantum states can be considered as resources. In particular, we saw that shared **EPR** pair ($\mathbf{Bell}_{00}$) enables one:

1. Transmit two classical bits by sending a single qubit, via the superdense-coding.
2. 'Teleoperate' a qubit by sending two classical bits. From an engineering point of view, it means that for having a complete quantum internet, it's enough to provide a mechanism to distribute **EPR** pairs.

2 Dense Encoding.

)

3 Quantum Teleportation.

$|\psi\rangle$ 1 H 2
$|0\rangle$ H 1 1
$|0\rangle$ Z

Figure 1: Measuring the single-qubit state $|\psi\rangle$ at the $\{|+\rangle, |-\rangle\}$ base.

4 Gate Teleportation.

Gate teleportation is a method to 'encode' operations by states. At the high level, given a precomputed state, it allows one to apply an operation (gate) by using (probably) simpler gates. The precomputed states are called **Magic States**.

4.1 Leading Example: T-Teleportation.

Recall that the Clifford[1] + T is a universal quantum gate set. The Clifford group alone is considered from the computer science point of view a simple/weak computational class since it can be classically simulated [2]. Yet, we will see that given access to the magic $|T\rangle = T|+\rangle$, one can simulate the T gate using only Clifford gates and measurements.

$|\psi\rangle$ 1 S
$|T\rangle$ [u][1]c

Figure 2: Measuring the single-qubit state $|\psi\rangle$ at the $\{|+\rangle, |-\rangle\}$ base.

$$\begin{aligned}
\left(\sum_x \alpha_x |x\rangle\right) \otimes \frac{1}{\sqrt{2}}\left(|0\rangle + e^{i\frac{\pi}{4}}|1\rangle\right) &\overbrace{\mapsto}^{\textbf{CX}} \sum_{x,y} \frac{1}{\sqrt{2}}\alpha_x |x\rangle |x \oplus y\rangle e^{i\frac{\pi}{4}y} \\
&\mapsto \begin{cases} \sum_x \alpha_x |x\rangle e^{i\frac{\pi}{4}x} = T|\psi\rangle & \text{measured } 0 \\ \sum_x \alpha_x |x\rangle e^{i\frac{\pi}{4}\bar{x}} & \text{measured } 1 \end{cases} \\
&\overbrace{\mapsto}^{\textbf{CS}} \begin{cases} T|\psi\rangle \\ \sum_x \alpha_x |x\rangle e^{i\left(\frac{\pi}{4}\bar{x} + \frac{\pi}{2}x\right)} = \sum_x \alpha_x |x\rangle e^{i\frac{\pi}{4}} e^{i\left(\frac{\pi}{4}\bar{x} + \frac{\pi}{4}x\right)} \end{cases} \\
&= \begin{cases} T|\psi\rangle \\ e^{i\frac{\pi}{4}} \sum_x \alpha_x |x\rangle e^{i\frac{\pi}{4}} = e^{i\frac{\pi}{4}} T|\psi\rangle \end{cases}
\end{aligned}$$

4.2 Extends it.

Let's extends it to a general gate. First create $|\mathbf{GHZ}_{2n}\rangle$ state, then

Let's split upon the measurement result.

1. If we measured 0, means the states 'agreed' in the computational base.

$$|\psi\rangle \otimes \left(\sum_x |x\rangle \otimes U|x\rangle\right)$$

5 Magic State Distillation.

Question. Can we purify noisy magic states into high-fidelity ones, using only Clifford operations?

Magic state distillation is a procedure that uses many copies of noisy magic states, plus only Clifford gates and measurements, to produce fewer, higher-fidelity magic states.

[1] Generated by H, S and CX

[2] And conjectured to be strictly weaker than **P**

6 Uhlmann's theorem

$$\sum_{ij} \langle i;i|AB|j;j\rangle = \sum_{ij} \langle i|A|j\rangle \langle i|B|j\rangle = \sum_{ij} \langle i|A|j\rangle \langle j|B^\top|i\rangle = \sum_{i} \langle i|AB^\top|i\rangle = \mathbf{Tr} AB^\top$$

$$|\psi_\rho\rangle = \sum_i \left(\rho^{\frac{1}{2}} |\psi_i\rangle\right) |i\rangle$$

$$|\psi_\sigma\rangle = \sum_i \left(\sigma^{\frac{1}{2}} |\psi_i'\rangle\right) |i'\rangle = \sum_i \left(\sigma^{\frac{1}{2}} U_1 |\psi_i\rangle\right) U_2 |i\rangle$$

$$\begin{aligned}
\max |\langle\psi_\rho|\psi_\sigma\rangle|^2 &= \max |\sum_i \left(\langle\psi_i| \rho^{\frac{1}{2}}\right) \langle i| \left(\sigma^{\frac{1}{2}} U_1 |\psi_j\rangle\right) U_2 |j\rangle|^2 \\
&= \max |\sum_i \mathbf{Tr} \left[\left(\langle\psi_i| \rho^{\frac{1}{2}}\right) \langle i| \left(\sigma^{\frac{1}{2}} U_1 |\psi_j\rangle\right) U_2 |j\rangle\right] |^2 \\
&= \max |\sum_i \mathbf{Tr} \left[\left(\sigma^{\frac{1}{2}} U_1 |\psi_j\rangle \langle\psi_i| \rho^{\frac{1}{2}}\right) (U_2 |j\rangle \langle i|)\right] |^2 \\
&= \max |\sum_i \mathbf{Tr} \left[\left(\sigma^{\frac{1}{2}} \rho^{\frac{1}{2}} U_1 |\psi_j\rangle \langle\psi_i|\right) (U_2 |j\rangle \langle i|)\right] |^2 \\
&= \max \left|\mathbf{Tr} \left[\left(\sigma^{\frac{1}{2}} \rho^{\frac{1}{2}} U_1\right) \otimes U_2\right]\right|^2 \\
&\leq \left|\mathbf{Tr}\sqrt{\rho^{\frac{1}{2}}\sigma^{\frac{1}{2}}\sigma^{\frac{1}{2}}\rho^{\frac{1}{2}}}\right|^2 = \left|\mathbf{Tr}\sqrt{\rho^{\frac{1}{2}}\sigma\rho^{\frac{1}{2}}}\right|^2
\end{aligned}$$

Notice that $|i\rangle \langle j|$ is unitray since.