

Bell's Inequality

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CHSH and Tsirelson's Inequalities

Alice: Q, R Bob: S, T

Classical observables distributed according to $P(Q, R, S, T)$. Combination of correlations between Alice and Bobs measurements are bounded according to the CHSH inequality

$$|E(QS) + E(RS) + E(RT) - E(QT)| \leq 2$$

For the quantum version, define 4 spin operators along arbitrary directions

$$Q = \vec{q} \cdot \sigma, R = \vec{r} \cdot \sigma, S = \vec{s} \cdot \sigma, T = \vec{t} \cdot \sigma.$$

The book uses $\vec{q} = (0, 0, 1), \vec{r} = (1, 0, 0), \vec{s} = (-\frac{1}{\sqrt{2}}, 0, -\frac{1}{\sqrt{2}}), \vec{t} = (-\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}})$

$$|\langle Q \otimes S \rangle + \langle R \otimes S \rangle + \langle R \otimes T \rangle - \langle Q \otimes T \rangle| \leq 2\sqrt{2}$$

Questions

We can change (1) measurement axes or (2) the two-qubit state we prepare $|\psi\rangle$

- ▶ How does changing measurement axes change the LHS for a given $|\psi\rangle$
- ▶ What does it have to do with the state $|\psi\rangle$ we prepare?
- ▶ Do more highly entangled states saturate the bound? How do we quantify entanglement?

Choosing Alice and Bob's measurement axes

Problem 2.3 in the book

$$(Q \otimes S + R \otimes S + R \otimes T - Q \otimes T)^2 = 4I + [Q, R] \otimes [S, T]$$

Choosing Alice and Bob's measurement axes

Using that $(\sigma \cdot a)(\sigma \cdot b) = a \cdot b + i\sigma \cdot (a \times b)$

$$\begin{aligned}[Q, R] &= i\sigma \cdot (\vec{q} \times \vec{r} - \vec{r} \times \vec{q}) \\ &= 2i\sigma \cdot (\vec{q} \times \vec{r})\end{aligned}$$

$$\begin{aligned}[S, T] &= i\sigma \cdot (\vec{s} \times \vec{t} - \vec{t} \times \vec{s}) \\ &= 2i\sigma \cdot (\vec{s} \times \vec{t})\end{aligned}$$

Calculating expectations

$$\vec{q} \cdot \sigma \otimes \vec{s} \cdot \sigma = \begin{pmatrix} \vec{s} \cdot \sigma & 0 \\ 0 & -\vec{s} \cdot \sigma \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \end{pmatrix}$$

$$\vec{r} \cdot \sigma \otimes \vec{s} \cdot \sigma = \begin{pmatrix} 0 & \vec{s} \cdot \sigma \\ \vec{s} \cdot \sigma & 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & -1 & -1 \\ 0 & 0 & -1 & 1 \\ -1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \end{pmatrix}$$

$$\vec{r} \cdot \sigma \otimes \vec{t} \cdot \sigma = \begin{pmatrix} 0 & \vec{t} \cdot \sigma \\ \vec{t} \cdot \sigma & 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & -1 & -1 \\ 1 & -1 & 0 & 0 \\ -1 & -1 & 0 & 0 \end{pmatrix}$$

Calculating expectations

$$\vec{q} \cdot \sigma \otimes \vec{t} \cdot \sigma = \begin{pmatrix} \vec{t} \cdot \sigma & 0 \\ 0 & -\vec{t} \cdot \sigma \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & 1 \end{pmatrix}$$

$$\langle \vec{q} \cdot \sigma \otimes \vec{s} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (-\alpha^*(\alpha + \beta) + \beta^*(\beta - \alpha) + \gamma^*(\gamma + \delta) + \delta^*(\gamma - \delta))$$

$$\langle \vec{r} \cdot \sigma \otimes \vec{s} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (-\alpha^*(\gamma + \delta) + \beta^*(\delta - \gamma) - \gamma^*(\alpha + \beta) + \delta^*(\beta - \alpha))$$

$$\langle \vec{r} \cdot \sigma \otimes \vec{t} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (\alpha^*(\gamma - \delta) - \beta^*(\delta + \gamma) + \gamma^*(\alpha - \beta) - \delta^*(\beta + \alpha))$$

$$\langle \vec{q} \cdot \sigma \otimes \vec{t} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (\alpha^*(\alpha - \beta) - \beta^*(\beta + \alpha) + \gamma^*(\delta - \delta) + \delta^*(\gamma + \delta))$$

Full density matrix

$$\rho_{AB} = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* & \alpha\gamma^* & \alpha\delta^* \\ \beta\alpha^* & |\beta|^2 & \beta\gamma^* & \beta\delta^* \\ \gamma\alpha^* & \gamma\beta^* & |\gamma|^2 & \gamma\delta^* \\ \delta\alpha^* & \delta\beta^* & \delta\gamma^* & |\delta|^2 \end{pmatrix}$$

Partial traces

$$\begin{aligned}\mathrm{Tr}_A(\rho_{AB}) &= \sum_{ijkl} \rho_{ij}^{kl} \mathrm{Tr}_A(|i\rangle \langle k|) \otimes |j\rangle \langle l| \\ &= \sum_i \left(\sum_{jl} \rho_{ij}^{il} |j\rangle \langle l| \right) \\ &= (\rho_{00}^{00} + \rho_{10}^{10}) |0\rangle \langle 0| + (\rho_{00}^{01} + \rho_{10}^{11}) |0\rangle \langle 1| + (\rho_{01}^{00} + \rho_{11}^{10}) |1\rangle \langle 0| + (\rho_{01}^{01} + \rho_{11}^{11}) |1\rangle \langle 1|\end{aligned}$$

$$\begin{aligned}\mathrm{Tr}_B(\rho_{AB}) &= \sum_{ijkl} \rho_{ij}^{kl} |i\rangle \langle k| \otimes \mathrm{Tr}_B(|j\rangle \langle l|) \\ &= \sum_j \left(\sum_{ik} \rho_{ij}^{kj} |i\rangle \langle k| \right) \\ &= (\rho_{00}^{00} + \rho_{01}^{01}) |0\rangle \langle 0| + (\rho_{00}^{10} + \rho_{01}^{11}) |0\rangle \langle 1| + (\rho_{10}^{00} + \rho_{11}^{01}) |1\rangle \langle 0| + (\rho_{10}^{10} + \rho_{11}^{11}) |1\rangle \langle 1|\end{aligned}$$

Reduced density matrices for an arbitrary state

$$\text{Tr}_A(\rho_{AB}) = \begin{pmatrix} \rho_{00}^{00} + \rho_{10}^{10} & \rho_{00}^{01} + \rho_{10}^{11} \\ \rho_{01}^{00} + \rho_{11}^{10} & \rho_{01}^{01} + \rho_{11}^{11} \end{pmatrix} = \begin{pmatrix} |\alpha|^2 + |\gamma|^2 & \alpha\beta^* + \gamma\delta^* \\ \beta\alpha^* + \delta\gamma^* & |\beta|^2 + |\delta|^2 \end{pmatrix}$$

$$\text{Tr}_B(\rho_{AB}) = \begin{pmatrix} \rho_{00}^{00} + \rho_{01}^{01} & \rho_{00}^{10} + \rho_{01}^{11} \\ \rho_{10}^{00} + \rho_{11}^{01} & \rho_{10}^{10} + \rho_{11}^{11} \end{pmatrix} = \begin{pmatrix} |\alpha|^2 + |\beta|^2 & \alpha\gamma^* + \beta\delta^* \\ \gamma\alpha^* + \delta\beta^* & |\gamma|^2 + |\delta|^2 \end{pmatrix}$$

Definition of entanglement entropy

The Von Neumann entropy is

$$S(\rho) = -\text{Tr}(\rho \log \rho) = -\sum_x \lambda_x \log \lambda_x$$

for eigenvalues λ_x of ρ . This tells us: do the reduced states ρ_A and ρ_B contain all the information in ρ_{AB} ? Maybe analogous to the mutual information

$$I(X; Y) = H(X) + H(Y) - H(X, Y) \geq 0$$

So a possible measurement of entanglement is

$$\Delta S = S(\rho) - S(\rho_A) - S(\rho_B)$$

Entanglement entropy of $|\phi^+\rangle$

$$S(\rho) = -\text{Tr}(\rho \log \rho) = -\sum_x \lambda_x \log \lambda_x$$

where λ_x are the eigenvalues of ρ . Let $|\phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$

$$\rho_{AB} = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix}$$

which only has one nonzero eigenvalue $\lambda = 2$. Therefore $S(\rho) = 1$.

$$\rho_A = \rho_B = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad S(\rho_A) = S(\rho_B) = 0 \quad \Delta S = 1$$

Entanglement entropy of $|00\rangle$

Let $\psi = |00\rangle$

$$\rho_{AB} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

which only has one nonzero eigenvalue $\lambda = 1$. Therefore $S(\rho) = 0$.

$$\rho_A = \rho_B = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad \lambda = 1$$

Therefore,

$$S(\rho_A) = S(\rho_B) = 0 \quad \Delta S = 0$$

Correlation functions for $|\phi^+\rangle$

$$|\phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

$$\langle \vec{q} \cdot \sigma \otimes \vec{s} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (-\alpha^*(\alpha + \beta) + \beta^*(\beta - \alpha) + \gamma^*(\gamma + \delta) + \delta^*(\gamma - \delta)) = -\frac{1}{\sqrt{2}}$$

$$\langle \vec{r} \cdot \sigma \otimes \vec{s} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (-\alpha^*(\gamma + \delta) + \beta^*(\delta - \gamma) - \gamma^*(\alpha + \beta) + \delta^*(\beta - \alpha)) = -\frac{1}{\sqrt{2}}$$

$$\langle \vec{r} \cdot \sigma \otimes \vec{t} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (\alpha^*(\gamma - \delta) - \beta^*(\delta + \gamma) + \gamma^*(\alpha - \beta) - \delta^*(\beta + \alpha)) = -\frac{1}{\sqrt{2}}$$

$$\langle \vec{q} \cdot \sigma \otimes \vec{t} \cdot \sigma \rangle = \frac{1}{\sqrt{2}} (\alpha^*(\alpha - \beta) - \beta^*(\beta + \alpha) + \gamma^*(\delta - \delta) + \delta^*(\gamma + \delta)) = \frac{1}{\sqrt{2}}$$

$$|\langle Q \otimes S \rangle + \langle R \otimes S \rangle + \langle R \otimes T \rangle - \langle Q \otimes T \rangle| = 2\sqrt{2}$$