Introduction to Quantum Information and Communication

Theory Assignment-2

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Exercise 4.1.3

Given:

- A is a square operator acting on Hilbert space $\mathcal{H}_S$
- I_R is the identity operator acting on a Hilbert space $\mathcal{H}_R$ isomorphic to $\mathcal{H}_S$
- $|\Gamma\rangle_{RS}$ is the unnormalized maximally entangled vector.

To Prove:

$$\operatorname{Tr}\{A\} = \langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS}$$

Proof:

In the computational basis

$$|\Gamma\rangle_{RS} = \sum_{i=0}^{d-1} |i\rangle_R |i\rangle_S$$

$$\langle\Gamma|_{RS} = \sum_{i=0}^{d-1} \langle i|_R \langle i|_S$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \left(\sum_{i=0}^{d-1} \langle i|_R \langle i|_S\right) (I_R \otimes A_S) \left(\sum_{j=0}^{d-1} |j\rangle_R |j\rangle_S\right)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \left(\sum_{i=0}^{d-1} \langle i|_R \langle i|_S\right) \left(\sum_{j=0}^{d-1} (I_R \otimes A_S)\big(|j\rangle_R \otimes |j\rangle_S\big)\right)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \left(\sum_{i=0}^{d-1} \langle i|_R \langle i|_S\right) \left(\sum_{j=0}^{d-1} \big(I_R |j\rangle_R\big) \otimes \big(A_S |j\rangle_S\big)\right)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \left(\sum_{i=0}^{d-1} \langle i|_R \langle i|_S\right) \left(\sum_{j=0}^{d-1} |j\rangle_R \otimes \big(A_S |j\rangle_S\big)\right)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \sum_{i,j=0}^{d-1} \big(\langle i|_R \otimes \langle i|_S\big)\big(|j\rangle_R \otimes \big(A_S |j\rangle_S\big)\big)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \sum_{i,j=0}^{d-1} \big(\langle i|j\rangle_R \otimes \langle i|_S A_S |j\rangle_S\big)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \sum_{i,j=0}^{d-1} \big(\delta_{i,j} \otimes \langle i|_S A_S |j\rangle_S\big)$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \sum_{i=0}^{d-1} \langle i|_S A_S |i\rangle_S$$

$$\langle\Gamma|_{RS} I_R \otimes A_S |\Gamma\rangle_{RS} = \mathrm{Tr}\{A\}$$

Hence, proven.

Exercise 4.1.16

Given:

- Commutating projectors Π_1 and Π_2
- $0 \leq \Pi_1, \Pi_2 \leq I$

To Prove:

For arbitrary density operator ρ

$$\mathrm{Tr}\{(I - \Pi_1\Pi_2)\rho\} \leq \mathrm{Tr}\{(I - \Pi_1)\rho\} + \mathrm{Tr}\{(I - \Pi_2)\rho\}$$

Proof:

$$I - \Pi_1 \geq 0 \text{ and } I - \Pi_2 \geq 0$$

Since trace of product of semi positive definite matrices is non negative (as discussed in class)

$$\mathrm{Tr}\{(I - \Pi_1)(I - \Pi_2)\rho\} \geq 0$$

$$\mathrm{Tr}\{(I - \Pi_1 - \Pi_2 + \Pi_1\Pi_2)\rho\} \geq 0$$

$$\mathrm{Tr}\{(I - \Pi_1 + I - \Pi_2 + \Pi_1\Pi_2 - I)\rho\} \geq 0$$

$$\mathrm{Tr}\{(I - \Pi_1)\rho\} + \mathrm{Tr}\{(I - \Pi_2)\rho\} - \mathrm{Tr}\{(I - \Pi_1\Pi_2)\rho\} \geq 0$$

$$\mathrm{Tr}\{(I - \Pi_1\Pi_2)\rho\} \leq \mathrm{Tr}\{(I - \Pi_1)\rho\} + \mathrm{Tr}\{(I - \Pi_2)\rho\}$$

Hence, proven.

Exercise 4.2.2

Given:

- Ensemble $\{p_X(x), \rho_x\}$ of density operators
- POVM with elements $\{\Lambda_x\}$
- Operator τ such that $\tau \geq p_X(x)\rho_x$

To Prove:

$$\mathrm{Tr}\{\tau\} \geq \sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\}$$

Proof:

$$\sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\} = \sum_x \mathrm{Tr}\{\Lambda_x p_X(x) \rho_x\}$$

$$\sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\} \leq \sum_x \mathrm{Tr}\{\Lambda_x \tau\}$$

$$\sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\} \leq \mathrm{Tr}\left\{\sum_x \Lambda_x \tau\right\}$$

$$\sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\} \leq \mathrm{Tr}\left\{\tau \sum_x \Lambda_x\right\}$$

$$\sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\} \leq \mathrm{Tr}\{\tau I\}$$

$$\sum_x p_X(x)\ \mathrm{Tr}\{\Lambda_x \rho_x\} \leq \mathrm{Tr}\{\tau\}$$

Hence, proven.

Now for the case of encoding n bits into a d-dimensional subspace.

$$\{2^{-n}, \rho_i\}_{i\in\{0,1\}^n}$$

Consider

$$p_X(x)\rho_x = 2^{-n}\rho_i$$

$$p_X(x)\rho_x = 2^{-n}\sum_j \lambda_j |j\rangle\langle j|$$

$$2^{-n}I - p_X(x)\rho_x = 2^{-n}I - 2^{-n}\sum_j \lambda_j |j\rangle\langle j|$$

$$2^{-n}I - p_X(x)\rho_x = 2^{-n}\sum_j |j\rangle\langle j| - 2^{-n}\sum_j \lambda_j |j\rangle\langle j|$$

$$2^{-n}I - p_X(x)\rho_x = 2^{-n}\sum_j \left(1-\lambda_j\right)|j\rangle\langle j|$$

Since $0 \leq \lambda_j \leq 1\ \forall j$, $1 - \lambda_j \geq 0\ \forall j$. All the eigenvalues of the matrix in LHS are non-negative.

$$2^{-n}I - p_X(x)\rho_x \geq 0$$

$$2^{-n}I \geq p_X(x)\rho_x$$

$\therefore$ We consider $\tau = 2^{-n}I$

Now, we know that the probability of success is upper bounded by $\mathrm{Tr}\{\tau\}$

$$\mathrm{Tr}\{\tau\} = \mathrm{Tr}\{2^{-n}I\}$$

$$\mathrm{Tr}\{\tau\} = 2^{-n}\ \mathrm{Tr}\{I\}$$

Since I is d-dimensional,

$$\mathrm{Tr}\{\tau\} = d2^{-n}$$

Thus, the expected success probability is bounded above by $d2^{-n}$

Exercise 4.3.1

Given:

- A' has a Hilbert space structure isomorphic to that of system A

- $\forall x, y \; F_{AA'}|x\rangle_A|y\rangle_{A'} = |y\rangle_A|x\rangle_{A'}$

To Prove:

$$P(\rho_A) = \mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\}$$

Proof:

$$\rho_A = \sum_i \lambda_i |i\rangle_A \langle i|_A$$

$$\rho_{A'} = \sum_j \lambda_j |j\rangle_{A'} \langle j|_{A'}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\{F_{AA'}(\rho_A \otimes \rho_{A'})\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\left\{F_{AA'}\left(\left(\sum_i \lambda_i |i\rangle_A \langle i|_A\right) \otimes \left(\sum_j \lambda_j |j\rangle_{A'} \langle j|_{A'}\right)\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\left\{F_{AA'}\left(\sum_{i,j} \lambda_i \lambda_j |i\rangle_A \langle i|_A \otimes |j\rangle_{A'} \langle j|_{A'}\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\left\{F_{AA'}\left(\sum_{i,j} \lambda_i \lambda_j |i\rangle_A \langle i|_A \otimes |j\rangle_{A'} \langle j|_{A'}\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\left\{F_{AA'}\left(\sum_{i,j} \lambda_i \lambda_j \left(|i\rangle_A |j\rangle_{A'}\right)\left(\langle i|_A \langle j|_{A'}\right)\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\left\{\left(\sum_{i,j} \lambda_i \lambda_j \left(F_{AA'}|i\rangle_A |j\rangle_{A'}\right)\left(\langle i|_A \langle j|_{A'}\right)\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\left\{\sum_{i,j} \lambda_i \lambda_j \left(|j\rangle_A |i\rangle_{A'}\right)\left(\langle i|_A \langle j|_{A'}\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \sum_{i,j} \lambda_i \lambda_j \mathrm{Tr}\left\{\left(|j\rangle_A |i\rangle_{A'}\right)\left(\langle i|_A \langle j|_{A'}\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \sum_{i,j} \lambda_i \lambda_j \mathrm{Tr}\left\{\left(\langle i|_A \langle j|_{A'}\right)\left(|j\rangle_A |i\rangle_{A'}\right)\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \sum_{i,j} \lambda_i \lambda_j \mathrm{Tr}\left\{\langle i|j\rangle_A \otimes \langle j|i\rangle_{A'}\right\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \sum_{i,j} \lambda_i \lambda_j \langle i|j\rangle_A \langle j|i\rangle_{A'}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \sum_{i,j} \lambda_i \lambda_j \delta_{i,j}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \sum_i \lambda_i^2$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = \mathrm{Tr}\{\rho_A^2\}$$

$$\mathrm{Tr}\{(\rho_A \otimes \rho_{A'})F_{AA'}\} = P(\rho_A)$$

Hence, proven.

Exercise 4.3.6

Given:

$$\Pi_{\text{even}} = \frac{1}{2}(I_A \otimes I_B + Z_A \otimes Z_B) = |00\rangle\langle 00|_{AB} + |11\rangle\langle 11|_{AB}$$

$$\Pi_{\text{odd}} = \frac{1}{2}(I_A \otimes I_B - Z_A \otimes Z_B) = |01\rangle\langle 01|_{AB} + |10\rangle\langle 10|_{AB}$$

$$|\Phi^+\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|00\rangle_{AB} + |11\rangle_{AB}\right)$$

$$\pi_A = \frac{1}{2}\left(|0\rangle\langle 0|_A + |1\rangle\langle 1|_A\right)$$

$$\pi_B = \frac{1}{2}\left(|0\rangle\langle 0|_B + |1\rangle\langle 1|_B\right)$$

To Prove:

- $|\Phi^+\rangle_{AB}$ returns an even parity result with probabilty 1
- $\pi_A \otimes \pi_B$ returns even or odd parity with equal probability

Proof:

First we find the density matrix of the bell state

$$\rho_{AB} = |\Phi^+\rangle_{AB}\langle\Phi^+|_{AB}$$

Now, the probability of the bell state collapsing to Π_{even} is

$$P = \mathrm{Tr}\{\rho_{AB}\Pi_{\text{even}}\}$$

$$P = \mathrm{Tr}\left\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB}\left(|00\rangle\langle 00|_{AB} + |11\rangle\langle 11|_{AB}\right)\right\}$$

$$P = \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||00\rangle\langle 00| + |\Phi^+\rangle\langle\Phi^+||11\rangle\langle 11|\}$$

$$P = \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||00\rangle\langle 00|\} + \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||11\rangle\langle 11|\}$$

$$P = \mathrm{Tr}\{\langle 00|\Phi^+\rangle\langle\Phi^+|00\rangle\} + \mathrm{Tr}\{\langle 11|\Phi^+\rangle\langle\Phi^+|11\rangle\}$$

$$P = \frac{1}{2} + \frac{1}{2}$$

$$P = 1$$

$\therefore |\Phi^+\rangle_{AB}$ returns an even parity result with probabilty 1

Now, we find the probability of $\pi_A \otimes \pi_B$ returning even parity

$$P = \mathrm{Tr}\{(\pi_A \otimes \pi_B)\Pi_{\text{even}}\}$$

$$P = \frac{1}{4}\,\mathrm{Tr}\left\{\left(|0\rangle\langle 0|_A + |1\rangle\langle 1|_A\right) \otimes \left(|0\rangle\langle 0|_B + |1\rangle\langle 1|_B\right)\left(|00\rangle\langle 00|_{AB} + |11\rangle\langle 11|_{AB}\right)\right\}$$

$$P = \frac{1}{4}\ \mathrm{Tr}\Big\{\big(|0\rangle\langle 0|_A \otimes |0\rangle\langle 0|_B + |0\rangle\langle 0|_A \otimes |1\rangle\langle 1|_B + |1\rangle\langle 1|_A \otimes |0\rangle\langle 0|_B + |1\rangle\langle 1|_A \otimes |1\rangle\langle 1|_B\big)\big(|00\rangle\langle 00|_{AB} + |11\rangle\langle 11|_{AB}\big)\Big\}$$

$$P = \frac{1}{4}\ \mathrm{Tr}\{(|00\rangle\langle 00| + |01\rangle\langle 01| + |10\rangle\langle 10| + |11\rangle\langle 11|)(|00\rangle\langle 00| + |11\rangle\langle 11|)\}$$

$$\begin{gathered} P = \frac{1}{4}\ \mathrm{Tr}\{|00\rangle\langle 00||00\rangle\langle 00| + |00\rangle\langle 00||11\rangle\langle 11| + \\ |01\rangle\langle 01||00\rangle\langle 00| + |01\rangle\langle 01||11\rangle\langle 11| + \\ |10\rangle\langle 10||00\rangle\langle 00| + |10\rangle\langle 10||11\rangle\langle 11| + \\ |11\rangle\langle 11||00\rangle\langle 00| + |11\rangle\langle 11||11\rangle\langle 11|\} \end{gathered}$$

$$P = \frac{1}{4}(\mathrm{Tr}\{|00\rangle\langle 00|\} + \mathrm{Tr}\{|11\rangle\langle 11|\})$$

$$P = \frac{1}{4}(1 + 1)$$

$$P = \frac{1}{2}$$

The probability of $\pi_A \otimes \pi_B$ returning an odd parity is $1 - P = 1 - \frac{1}{2} = \frac{1}{2}$ (As the measurements are orthogonal)

$\therefore \pi_A \otimes \pi_B$ returns even or odd parity with equal probability

Now, we perform the same calculations for the phase parity measurement

$$\Pi^X_{\text{even}} = \frac{1}{2}(I_A \otimes I_B + X_A \otimes X_B)$$

$$\Pi^X_{\text{odd}} = \frac{1}{2}(I_A \otimes I_B - X_A \otimes X_B)$$

The probability of the bell state collapsing to Π^X_{even} is

$$P = \mathrm{Tr}\{\rho_{AB}\Pi^X_{\text{even}}\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB}(I_A \otimes I_B + X_A \otimes X_B)\Big\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB} I_A \otimes I_B\Big\} + \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB} X_A \otimes X_B\Big\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB}\Big\} + \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB} X_A \otimes X_B\Big\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\Big\{\langle\Phi^+|_{AB}|\Phi^+\rangle_{AB}\Big\} + \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB} X_A \otimes X_B\Big\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\Big\{\langle\Phi^+|\Phi^+\rangle_{AB}\Big\} + \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB} X_A \otimes X_B\Big\}$$

$$P = \frac{1}{2} + \frac{1}{2}\ \mathrm{Tr}\Big\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB} X_A \otimes X_B\Big\}$$

$$P = \frac{1}{2} + \frac{1}{2}\ \mathrm{Tr}\left\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB}\left(|0\rangle\langle 1|_A + |1\rangle\langle 0|_A\right) \otimes \left(|0\rangle\langle 1|_B + |1\rangle\langle 0|_B\right)\right\}$$

$$P = \frac{1}{2} + \frac{1}{2}\ \mathrm{Tr}\left\{|\Phi^+\rangle_{AB}\langle\Phi^+|_{AB}\left(|0\rangle\langle 1|_A \otimes |0\rangle\langle 1|_B + |0\rangle\langle 1|_A \otimes |1\rangle\langle 0|_B + |1\rangle\langle 0|_A \otimes |0\rangle\langle 1|_B + |1\rangle\langle 0|_A \otimes |1\rangle\langle 0|_B\right)\right\}$$

$$P = \frac{1}{2} + \frac{1}{2}\ \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+|(|00\rangle\langle 11| + |01\rangle\langle 10| + |10\rangle\langle 01| + |11\rangle\langle 00|\}$$

$$P = \frac{1}{2}(1 + \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||00\rangle\langle 11|\} + \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||01\rangle\langle 10|\} + \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||10\rangle\langle 01|\} + \mathrm{Tr}\{|\Phi^+\rangle\langle\Phi^+||11\rangle\langle 00|\})$$

$$P = \frac{1}{2}(1 + \mathrm{Tr}\{\langle 11|\Phi^+\rangle\langle\Phi^+|00\rangle\} + \mathrm{Tr}\{\langle 10|\Phi^+\rangle\langle\Phi^+|01\rangle\} + \mathrm{Tr}\{\langle 01|\Phi^+\rangle\langle\Phi^+|10\rangle\} + \mathrm{Tr}\{\langle 00|\Phi^+\rangle\langle\Phi^+|11\rangle\})$$

$$P = \frac{1}{2}\left(1 + \mathrm{Tr}\left\{\frac{1}{\sqrt{2}} * \frac{1}{\sqrt{2}}\right\} + \mathrm{Tr}\{0 * 0\} + \mathrm{Tr}\{0 * 0\} + \mathrm{Tr}\left\{\frac{1}{\sqrt{2}} * \frac{1}{\sqrt{2}}\right\}\right)$$

$$P = \frac{1}{2}\left(1 + \frac{1}{2} + \frac{1}{2}\right)$$

$$P = \frac{1}{2}(2)$$

$$P = 1$$

$\therefore |\Phi^+\rangle_{AB}$ returns an even phase parity result with probabilty 1

Now, we find the probability of $\pi_A \otimes \pi_B$ returning even phase parity

$$P = \mathrm{Tr}\left\{(\pi_A \otimes \pi_B)\Pi^X_{\text{even}}\right\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\{(\pi_A \otimes \pi_B)(I_A \otimes I_B + X_A \otimes X_B)\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\{(\pi_A \otimes \pi_B)(I_A \otimes I_B)\} + \frac{1}{2}\ \mathrm{Tr}\{(\pi_A \otimes \pi_B)(X_A \otimes X_B)\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\{\pi_A \otimes \pi_B\} + \frac{1}{2}\ \mathrm{Tr}\{(\pi_A \otimes \pi_B)(X_A \otimes X_B)\}$$

$$P = \frac{1}{2}\ \mathrm{Tr}\{\pi_A\}\mathrm{Tr}\{\pi_B\} + \frac{1}{2}\ \mathrm{Tr}\{(\pi_A \otimes \pi_B)(X_A \otimes X_B)\}$$

$$P = \frac{1}{2} + \frac{1}{2}\ \mathrm{Tr}\{(\pi_A \otimes \pi_B)(X_A \otimes X_B)\}$$

$$P = \frac{1}{2}(1 + \mathrm{Tr}\{\pi_A X_A \otimes \pi_B X_B\})$$

$$P = \frac{1}{2}(1 + \mathrm{Tr}\{\pi_A X_A\}\ \mathrm{Tr}\{\pi_B X_B\})$$

$$P = \frac{1}{2}(1 + \mathrm{Tr}\{X_A \pi_A\}\ \mathrm{Tr}\{X_B \pi_B\})$$

$$P = \frac{1}{2}\left(1 + \mathrm{Tr}\{X\pi\}^2\right)$$

$$P = \frac{1}{2}\left(1 + \mathrm{Tr}\{X(|0\rangle\langle 0| + |1\rangle\langle 1|)\}^2\right)$$

$$P = \frac{1}{2}\left(1 + \mathrm{Tr}\{|1\rangle\langle 0| + |0\rangle\langle 1|\}^2\right)$$

$$P = \frac{1}{2}\left(1 + \mathrm{Tr}\left\{\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\right\}^2\right)$$

$$P = \frac{1}{2}(1 + 0)$$

$$P = \frac{1}{2}$$

The probability of $\pi_A \otimes \pi_B$ returning an odd phase parity is $1 - P = 1 - \frac{1}{2} = \frac{1}{2}$ (As the measurements are orthogonal)

$\therefore \pi_A \otimes \pi_B$ returns even or odd phase parity with equal probability

The same is true for the phase parity measurement. Hence, proven.

Exercise 4.3.18

Given:

$$\rho_A = \sum_{x \in X} p_X(x) \rho_A^x$$

$$\rho_{XA} = \sum_{x \in X} p_X(x) |x\rangle\langle x| \otimes \rho_A^x$$

$$\text{Measurement operators } \left\{\Lambda_A^j\right\}$$

To Prove:

$$\mathrm{Tr}\left\{\rho_A \Lambda_A^j\right\} = \mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\}$$

Proof:

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \mathrm{Tr}\left\{\left(\sum_{x \in X} p_X(x)|x\rangle\langle x| \otimes \rho_A^x\right)\left(I_X \otimes \Lambda_A^j\right)\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \mathrm{Tr}\left\{\sum_{x \in X}\left(p_X(x)(|x\rangle\langle x| \otimes \rho_A^x)\left(I_X \otimes \Lambda_A^j\right)\right)\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \mathrm{Tr}\left\{\sum_{x \in X}\left(p_X(x)\left(|x\rangle\langle x| I_X \otimes \rho_A^x \Lambda_A^j\right)\right)\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \mathrm{Tr}\left\{\sum_{x \in X}\left(p_X(x)\left(|x\rangle\langle x|_X \otimes \rho_A^x \Lambda_A^j\right)\right)\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \sum_{x \in X} p_X(x) \mathrm{Tr}\left\{|x\rangle\langle x|_X \otimes \rho_A^x \Lambda_A^j\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \sum_{x\in X} p_X(x)\mathrm{Tr}\left\{|x\rangle\langle x|_X\right\}\ \mathrm{Tr}\left\{\rho_A^x \Lambda_A^j\right\}$$

Since trace of a density operator is 1,

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \sum_{x\in X} p_X(x)\mathrm{Tr}\left\{\rho_A^x \Lambda_A^j\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \mathrm{Tr}\left\{\sum_{x\in X} p_X(x)\rho_A^x \Lambda_A^j\right\}$$

$$\mathrm{Tr}\left\{\rho_{XA}\left(I_X \otimes \Lambda_A^j\right)\right\} = \mathrm{Tr}\left\{\rho_A \Lambda_A^j\right\}$$

Hence, proven.

Exercise 4.4.1

Given:

- Linear Map $\mathcal{N}$
- Choi operator $\mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(|\Gamma\rangle\langle\Gamma|_{RA}\right) = \sum_{i,j=0}^{d-1} |i\rangle\langle j|_R \otimes \mathcal{N}_{A\to B}\left(|i\rangle\langle j|_A\right)$ is PSD

To Prove:

- $\mathcal{N}$ is completely positive

Proof:

To prove that $\mathcal{N}$ is completely positive, we need to show that $\mathrm{id}_R \otimes \mathcal{N}_{A\to B}(X_{RA})$ is PSD for all X_{RA} that are PSD

$$\mathrm{id}_R \otimes \mathcal{N}_{A\to B}(X_{RA}) = \mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(\sum |\varphi_i\rangle\langle\varphi_i|_{RA}\right)$$

$$\mathrm{id}_R \otimes \mathcal{N}_{A\to B}(X_{RA}) = \sum_i \mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(|\varphi_i\rangle\langle\varphi_i|_{RA}\right)$$

Consider $M_i = \mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(|\varphi_i\rangle\langle\varphi_i|_{RA}\right)$

We have $|\varphi_i\rangle = \sum_{j,k=0}^{d-1} \alpha_{jk} |j\rangle_R |k\rangle_A$

$$M_i = \mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(\sum_{j_1,k_1=0}^{d-1} \alpha_{j_1k_1} |j_1\rangle_R |k_1\rangle_A \sum_{j_2,k_2=0}^{d-1} \alpha_{j_2k_2}^* \langle j_2|_R \langle k_2|_A\right)$$

$$M_i = \mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(\sum_{j_1,k_1,j_2,k_2=0}^{d-1} \alpha_{j_1k_1}\alpha_{j_2k_2}^* |j_1\rangle_R |k_1\rangle_A \langle j_2|_R \langle k_2|_A\right)$$

$$M_i = \mathrm{id}_R \otimes \mathcal{N}_{A\to B}\left(\sum_{j_1,k_1,j_2,k_2=0}^{d-1} \alpha_{j_1k_1}\alpha_{j_2k_2}^* |j_1\rangle\langle j_2|_R \otimes |k_1\rangle\langle k_2|_A\right)$$

$$M_i = \sum_{j_1,k_1,j_2,k_2=0}^{d-1} \alpha_{j_1k_1}\alpha_{j_2k_2}^* (\mathrm{id}_R \otimes \mathcal{N}_{A\to B})\left(|j_1\rangle\langle j_2|_R \otimes |k_1\rangle\langle k_2|_A\right)$$

$$M_i = \sum_{j_1,k_1,j_2,k_2=0}^{d-1} \alpha_{j_1k_1}\alpha_{j_2k_2}^* \left(\mathrm{id}_R |j_1\rangle\langle j_2|_R\right) \otimes \left(\mathcal{N}_{A\to B} |k_1\rangle\langle k_2|_A\right)$$

$$M_i = \sum_{j_1, k_1, j_2, k_2 = 0}^{d-1} \alpha_{j_1 k_1} \alpha^*_{j_2 k_2} |j_1\rangle\langle j_2|_R \otimes \mathcal{N}_{A\to B} |k_1\rangle\langle k_2|_A$$

Now, using 4.198-4.212 of the book, we have

$$M_i = \sum_{j_1, k_1, j_2, k_2 = 0}^{d-1} \alpha_{j_1 k_1} \alpha^*_{j_2 k_2} |j_1\rangle\langle j_2|_R \otimes \sum_{l=0}^{d-1} V_l |k_1\rangle\langle k_2| V_l^\dagger$$

$$M_i = \sum_{l=0}^{d-1} \sum_{j_1, k_1, j_2, k_2 = 0}^{d-1} \alpha_{j_1 k_1} \alpha^*_{j_2 k_2} |j_1\rangle\langle j_2|_R \otimes V_l |k_1\rangle\langle k_2| V_l^\dagger$$

$$M_i = \sum_{l=0}^{d-1} \sum_{j_1, k_1, j_2, k_2 = 0}^{d-1} \alpha_{j_1 k_1} \alpha^*_{j_2 k_2} I_R |j_1\rangle\langle j_2|_R I_R \otimes V_l |k_1\rangle\langle k_2| V_l^\dagger$$

$$M_i = \sum_{l=0}^{d-1} I_R \otimes V_l \left(\sum_{j_1, k_1, j_2, k_2 = 0}^{d-1} \alpha_{j_1 k_1} \alpha^*_{j_2 k_2} |j_1\rangle\langle j_2|_R \otimes |k_1\rangle\langle k_2| \right) I_R \otimes V_l^\dagger$$

$$M_i = \sum_{l=0}^{d-1} I_R \otimes V_l \big(|\varphi_l\rangle\langle\varphi_l|_{RA} \big) I_R \otimes V_l^\dagger$$

Now, from the Choi-Kraus theorem, M_i is completely positive.

$$\mathrm{id}_R \otimes \mathcal{N}_{A\to B}(X_{RA}) = \sum_i M_i$$

Since sum of completely positive maps is also completely positive, $\mathcal{N}$ is completely positive.

Hence, proven

Exercise 4.6.3

Given:

- Hilbert spaces $\mathcal{H}_A, \mathcal{H}_B, \mathcal{H}_X$
- A Classical-Quantum channel $\mathcal{N}^1_{A\to B}$ that transforms $\rho_A \to \sum_k \langle k|_A \rho_A |k\rangle_A \sigma^k_B$
- A Quantum-Classical channel $\mathcal{N}^2_{A\to B}$ that transforms $\rho_A \to \sum_x \mathrm{Tr}\{\Lambda^x_A \rho_A\} |x\rangle\langle x|_X$

To Prove:

- $N^1_{A\to B}$ is Entanglement-Breaking
- $N^2_{A\to B}$ is Entanglement-Breaking

Proof:

$$\Phi_{RA} = \frac{1}{d} \sum_{i,j=0}^{d_A - 1} |i\rangle\langle j|_R \otimes |i\rangle\langle j|_A$$

For $N^1_{A\to B}$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = I_R \otimes N^1_{A\to B} \frac{1}{d} \sum_{i,j=0}^{d_A - 1} |i\rangle\langle j|_R \otimes |i\rangle\langle j|_A$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d} \sum_{i,j=0}^{d_A - 1} \big(I_R \otimes N^1_{A\to B}\big) \big(|i\rangle\langle j|_R \otimes |i\rangle\langle j|_A\big)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(I_R|i\rangle\langle j|_R \otimes N^1_{A\to B}|i\rangle\langle j|_A\right)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes N^1_{A\to B}|i\rangle\langle j|_A\right)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_k \langle k|_A|i\rangle_A\langle j|_A|k\rangle_A\sigma^k_B\right)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_k \langle k|i\rangle_A\langle j|k\rangle_A\sigma^k_B\right)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_k \delta_{i,k}\delta_{k,j}\sigma^k_B\right)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j,k=0}^{d_A-1}\delta_{i,k}\delta_{k,j}\left(|i\rangle\langle j|_R \otimes \sigma^k_B\right)$$

$$I_R \otimes N^1_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{k=0}^{d_A-1}|i\rangle\langle j|_R \otimes \sigma^k_B$$

Since this is a convex combination of product states, $I_R \otimes N^1_{A\to B}(\Phi_{RA})$ is separable.

Therefore, from Exercise 4.6.2, $N^1_{A\to B}$ is Entanglement-Breaking.

For $N^2_{A\to B}$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = I_R \otimes N^2_{A\to B}\frac{1}{d}\sum_{i,j=0}^{d_A-1}|i\rangle\langle j|_R \otimes |i\rangle\langle j|_A$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(I_R \otimes N^2_{A\to B}\right)\left(|i\rangle\langle j|_R \otimes |i\rangle\langle j|_A\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(I_R|i\rangle\langle j|_R \otimes N^2_{A\to B}|i\rangle\langle j|_A\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes N^2_{A\to B}|i\rangle\langle j|_A\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_x \mathrm{Tr}\left\{\Lambda^x_A|i\rangle_A\langle j|_A\right\}|x\rangle\langle x|_X\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_x \mathrm{Tr}\left\{\Lambda^x_A|i\rangle_A\langle j|_A\right\}|x\rangle\langle x|_X\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_x \mathrm{Tr}\left\{|x\rangle_A\langle x|_A|i\rangle_A\langle j|_A\right\}|x\rangle\langle x|_X\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j=0}^{d_A-1}\left(|i\rangle\langle j|_R \otimes \sum_x \mathrm{Tr}\left\{\langle j|x\rangle_A\langle x|i\rangle_A\right\}|x\rangle\langle x|_X\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{i,j,x=0}^{d_A-1}\delta_{i,x}\delta_{j,x}\left(|i\rangle\langle j|_R \otimes |x\rangle\langle x|_X\right)$$

$$I_R \otimes N^2_{A\to B}(\Phi_{RA}) = \frac{1}{d}\sum_{x=0}^{d_A-1}|x\rangle\langle x|_R \otimes |x\rangle\langle x|_X$$

Since this is a convex combination of product states, $I_R \otimes N^2_{A\to B}(\Phi_{RA})$ is separable.

Therefore, from Exercise 4.6.2, $N^2_{A\to B}$ is Entanglement-Breaking.

Hence, proven.