

Composite system and entanglement

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Composite system

- System = Set of states & set of measurements
- **Composite** system = “Product” of systems.
- **Composite** system of a system of a coin (two-dimensional classical system) and a system of a dice (six-dimensional classical system) is twelve-dimensional classical system.
- What is a **composite** system of quantum systems ?

Tensor product of linear spaces

For linear product spaces V and W over a field F (usually \mathbb{R} or \mathbb{C}), a tensor space $V \otimes W$ is a linear space spanned by $v \otimes w$ for all $v \in V$, $w \in W$.

- $\forall c \in F, \forall v \in V, \forall w \in W, c(v \otimes w) = (cv) \otimes w = v \otimes (cw)$.
- $\forall u, v \in V, \forall w \in W, (u + v) \otimes w = u \otimes w + v \otimes w$.
- $\forall v \in V, \forall w, y \in W, v \otimes (w + y) = v \otimes w + v \otimes y$.

Let $(e_i)_i$ be an orthonormal basis of V and $(f_j)_j$ be an orthonormal basis of W . Since $v \otimes w = (\sum_i v_i e_i) \otimes (\sum_j w_j f_j) = \sum_{i,j} v_i w_j (e_i \otimes f_j)$
This implies $\dim(V \otimes W) = \dim(V) \dim(W)$.

If V and W are inner product spaces, $V \otimes W$ is also a inner product space defined by

$$\langle v \otimes w, u \otimes y \rangle = \langle v, u \rangle \langle w, y \rangle.$$

Vector representation in tensor product

Let $V := \mathbb{C}^n$, $W := \mathbb{C}^m$.

$$e_i := \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \begin{matrix} 1 \\ \\ i-1 \\ i \\ i+1 \\ \\ n \end{matrix} \in \mathbb{C}^n, \quad f_j := \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \begin{matrix} 1 \\ \\ j-1 \\ j \\ j+1 \\ \\ m \end{matrix} \in \mathbb{C}^m$$

$$e_i \otimes f_j = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \begin{matrix} (1, 1) \\ \\ (i, j-1) \\ (i, j) \\ (i, j+1) \\ \\ (n, m) \end{matrix} \in \mathbb{C}^n \otimes \mathbb{C}^m$$

Vector representation in tensor product

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$$\begin{aligned} v \otimes w &= \left(\sum_i v_i e_i \right) \otimes \left(\sum_j w_j f_j \right) = \sum_{i,j} v_i w_j (e_i \otimes f_j) \\ &= \begin{bmatrix} \vdots \\ v_i w_j \\ \vdots \end{bmatrix} (i, j) = \begin{bmatrix} v_1 w \\ v_2 w \\ \vdots \\ v_n w \end{bmatrix} \in \mathbb{C}^n \otimes \mathbb{C}^m \end{aligned}$$

Linear spaces

- $\mathcal{L}(V, W)$: A linear space spanned by linear maps from a linear space V to a linear space W .
- $\mathcal{L}(V) := \mathcal{L}(V, V)$.
- $\mathcal{H}(V)$: A real linear space spanned by Hermitian operators acting on a complex linear space V .

Tensor product of linear maps

$$\mathcal{L}(V, X) \otimes \mathcal{L}(W, Y) \cong \mathcal{L}(V \otimes W, X \otimes Y)$$

since the both sides are complex linear spaces with dimension

$$\dim(V) \dim(W) \dim(X) \dim(Y).$$

A natural choice of an isomorphism is

$$\begin{aligned} \mathcal{L}(V, X) \otimes \mathcal{L}(W, Y) &\longrightarrow \mathcal{L}(V \otimes W, X \otimes Y) \\ A \otimes B &\longmapsto (v \otimes w \mapsto A(v) \otimes B(w)). \end{aligned}$$

$$A \otimes B = \begin{bmatrix} A_{11}B & A_{12}B & \dots & A_{1m}B \\ A_{21}B & A_{22}B & \dots & A_{2m}B \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1}B & A_{n2}B & \dots & A_{nm}B \end{bmatrix}$$

Tensor product of Hermitian maps

$$\mathcal{H}(V) \otimes \mathcal{H}(W) \cong \mathcal{H}(V \otimes W)$$

since the both sides are real linear spaces with dimension

$$\dim(V)^2 \dim(W)^2.$$

A natural choice of an isomorphism is

$$\begin{aligned} \mathcal{H}(V) \otimes \mathcal{H}(W) &\longrightarrow \mathcal{H}(V \otimes W) \\ A \otimes B &\longmapsto (v \otimes w \mapsto A(v) \otimes B(w)). \end{aligned}$$

Composite quantum system

A quantum system on a complex linear space V :

- Set of states = $\{\omega \in \mathcal{H}(V) \mid \omega \in C_{\geq 0}, \text{Tr}(\omega) = 1\}$.
- Set of binary measurements = $\{e \in \mathcal{H}(V) \mid e \in C_{\geq 0}, I - e \in C_{\geq 0}\}$.

For a quantum systems on V and W , a composite system is a quantum system on $V \otimes W$.

A useful formula.

$$\begin{aligned}\text{Tr}(A \otimes B) &= \sum_{i,j} (\langle i| \otimes \langle j|)(A \otimes B)(|i\rangle \otimes |j\rangle) \\ &= \sum_{i,j} \langle i| A |i\rangle \langle j| B |j\rangle \\ &= \text{Tr}(A)\text{Tr}(B)\end{aligned}$$

Tensor product of states

$$\begin{aligned} & (|\psi\rangle \langle\psi| \otimes |\phi\rangle \langle\phi|) (|\nu\rangle \otimes |w\rangle) \\ &= (|\psi\rangle \langle\psi| |\nu\rangle) \otimes (|\phi\rangle \langle\phi| |w\rangle) \\ &= \langle\psi|\nu\rangle \langle\phi|w\rangle |\psi\rangle \otimes |\phi\rangle \end{aligned}$$

On the other hand,

$$\begin{aligned} & (|\psi\rangle \otimes |\phi\rangle) (\langle\psi| \otimes \langle\phi|) (|\nu\rangle \otimes |w\rangle) \\ &= \langle\psi|\nu\rangle \langle\phi|w\rangle |\psi\rangle \otimes |\phi\rangle \end{aligned}$$

Hence,

$$|\psi\rangle \langle\psi| \otimes |\phi\rangle \langle\phi| = (|\psi\rangle \otimes |\phi\rangle) (\langle\psi| \otimes \langle\phi|).$$

We use the notations $|\psi\phi\rangle := |\psi\rangle |\phi\rangle := |\psi\rangle \otimes |\phi\rangle$.

For quantum states ρ and σ

$$\begin{aligned} \rho \otimes \sigma &= \left(\sum_j \mu_j |\psi_j\rangle \langle\psi_j| \right) \otimes \left(\sum_k \nu_k |\phi_k\rangle \langle\phi_k| \right) \\ &= \sum_{j,k} \mu_j \nu_k |\psi_j \phi_k\rangle \langle\psi_j \phi_k| \succeq 0 \end{aligned}$$

Examples: two-qubit system

Examples of states

- $|0\rangle\langle 0| \otimes |1\rangle\langle 1| = |01\rangle\langle 01|$
- $\frac{1}{2}(|0\rangle\langle 0| \otimes |0\rangle\langle 0| + |0\rangle\langle 0| \otimes |1\rangle\langle 1|) = |0\rangle\langle 0| \otimes \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|) = |0\rangle\langle 0| \otimes \frac{1}{2}I.$
- $\frac{1}{2}(|1\rangle\langle 1| \otimes |0\rangle\langle 0| + |0\rangle\langle 0| \otimes |1\rangle\langle 1|).$
- $\frac{1}{2}(|0\rangle\langle 0| \otimes |0\rangle\langle 0| + |0\rangle\langle 1| \otimes |0\rangle\langle 1| + |1\rangle\langle 0| \otimes |1\rangle\langle 1| + |1\rangle\langle 1| \otimes |1\rangle\langle 1|) = |\Phi\rangle\langle\Phi|$ for $|\Phi\rangle := \frac{1}{\sqrt{2}}(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle).$

Separable states & entangled states

A quantum state ρ in a composite system is said to be **separable** if

$$\rho = \sum_i p_i \rho_1^i \otimes \rho_2^i$$

for some probability distribution p and quantum states $\{\rho_1^i\}$ and $\{\rho_2^i\}$ for subsystems.

If a quantum state is not separable, the state is said to be **entangled** state.

In general, it is difficult to determine whether given state is separable or entangled.

Pure separable states

Lemma

A pure state $|\psi\rangle \in V \otimes W$ is separable if and only if there exist pure states $|\varphi\rangle \in V$ and $|\phi\rangle \in W$ such that $|\psi\rangle = |\varphi\rangle |\phi\rangle$.

Proof.

$$\begin{aligned} |\psi\rangle \langle \psi| &= \sum_i p_i \rho_i \otimes \sigma_i \\ &= \sum_i p_i \left(\sum_j \lambda_{i,j} |\varphi_{i,j}\rangle \langle \varphi_{i,j}| \right) \otimes \left(\sum_k \gamma_{i,k} |\phi_{i,k}\rangle \langle \phi_{i,k}| \right) \\ &= \sum_{\ell} q_{\ell} |\varphi_{\ell}\rangle \langle \varphi_{\ell}| \otimes |\phi_{\ell}\rangle \langle \phi_{\ell}| \end{aligned}$$

$$\begin{aligned} 1 &= \text{Tr} \left(|\psi\rangle \langle \psi| \left(\sum_i p_i \rho_i \otimes \sigma_i \right) \right) \\ &= \sum_{\ell} q_{\ell} |\langle \psi | (|\varphi_{\ell}\rangle |\phi_{\ell}\rangle)|^2 \iff |\psi\rangle = e^{i\theta_{\ell}} |\varphi_{\ell}\rangle |\phi_{\ell}\rangle \quad \forall \ell \quad \square \end{aligned}$$

Isomorphism between $V \otimes W$ and $\mathcal{L}(W, V)$

We consider isomorphism \mathcal{M} between $V \otimes W$ and $\mathcal{L}(W, V)$ defined by

$$\mathcal{M} : V \otimes W \rightarrow \mathcal{L}(W, V)$$

$$|i\rangle_V |j\rangle_W \mapsto |i\rangle_V \langle j|_W$$

where $(|i\rangle_V)_i$ and $(|j\rangle_W)_j$ are orthonormal basis of V and W , respectively.

$$\begin{aligned} & \mathcal{M}(|\psi\rangle_V |\varphi\rangle_W) \\ &= \mathcal{M}\left(\left(\sum_i \psi_i |i\rangle_V\right) \otimes \left(\sum_j \varphi_j |j\rangle_W\right)\right) \\ &= \sum_{i,j} \psi_i \varphi_j \mathcal{M}(|i\rangle_V |j\rangle_W) \\ &= \sum_{i,j} \psi_i \varphi_j |i\rangle_V \langle j|_W \\ &= \left(\sum_i \psi_i |i\rangle_V\right) \left(\sum_j \varphi_j \langle j|_W\right) = |\psi\rangle_V \langle \varphi|_W^* \end{aligned}$$

Determine the separability of pure state

$$\begin{aligned} |\psi\rangle \in V \otimes W \text{ is separable} &\iff |\psi\rangle = |\varphi\rangle |\phi\rangle \text{ for some } |\varphi\rangle \in V, |\phi\rangle \in W \\ &\iff \mathcal{M}(|\psi\rangle) = |\varphi\rangle \langle\phi| \text{ for some } |\varphi\rangle \in V, |\phi\rangle \in W \\ &\iff \mathcal{M}(|\psi\rangle) \text{ is rank 1} \end{aligned}$$

$$\begin{aligned} &\mathcal{M}\left(\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)\right) \\ &= \frac{1}{\sqrt{2}}(|0\rangle\langle 0| + |1\rangle\langle 1|) = \frac{1}{\sqrt{2}}I \end{aligned}$$

$\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)$ is entangled!

Schmidt decomposition

Theorem (Schmidt decomposition)

For any pure state $|\psi\rangle \in V \otimes W$, there exist *orthonormal systems* $(|v_i\rangle)_i$ of V and $(|w_j\rangle)_j$ of W , and positive real numbers $(\lambda_i)_i$ such that

$$|\psi\rangle = \sum_i \lambda_i |v_i\rangle_V |w_i\rangle_W.$$

Proof.

Let $A := \mathcal{M}(|\psi\rangle)$. By the *singular value decomposition*,

$$A = \sum_i \lambda_i |s_i\rangle_V \langle t_i|_W$$

Since $|\psi\rangle = \mathcal{M}^{-1}(A)$,

$$|\psi\rangle = \sum_i \lambda_i |s_i\rangle_V |t_i\rangle_W^*.$$



The number of the terms in the decomposition is called the *Schmidt rank*.

Measurements on composite system

Set of measurements on the composite system on $V \otimes W$ is

$$\{(e_1, \dots, e_k) \in \mathcal{H}(V \otimes W) \mid e_1 + \dots + e_k = I, e_j \in C_{\succeq 0} \\ i = 1, 2, \dots, k, k = 1, 2, \dots\}.$$

For measurements $(P_a \in \mathcal{H}(V))_a$ and $(Q_b \in \mathcal{H}(W))_b$ for the partial systems, $(P_a \otimes Q_b \in \mathcal{H}(V \otimes W))_{a,b}$ is a measurement since $P_a \otimes Q_b \succeq 0$ and

$$\sum_{a,b} P_a \otimes Q_b = \left(\sum_a P_a \right) \otimes \left(\sum_b Q_b \right) = I_V \otimes I_W = I_{V \otimes W}.$$

Partial trace and reduced density matrix

A probability of outcome of local measurement in a composite system is

$$P_{V \otimes W}(a, b) = \text{Tr}(\rho(P_a \otimes Q_b)).$$

$$\begin{aligned} P_V(a) &= \sum_b P_{V \otimes W}(a, b) = \sum_b \text{Tr}(\rho(P_a \otimes Q_b)) \\ &= \text{Tr} \left(\rho \left(P_a \otimes \sum_b Q_b \right) \right) \\ &= \text{Tr}(\rho(P_a \otimes I)) \\ &= \text{Tr}(\text{Tr}_W(\rho)P_a). \end{aligned}$$

The **partial trace** $\text{Tr}_W(\rho) \in \mathcal{H}(V)$ is defined by

$$\text{Tr}(\text{Tr}_W(\rho)P) = \text{Tr}(\rho(P \otimes I))$$

for any $P \in \mathcal{H}(V)$. Indeed, $\text{Tr}_W(\cdot)$ is a linear operator from $\mathcal{H}(V \otimes W)$ to $\mathcal{H}(V)$ defined by $\text{Tr}_W(\rho_V \otimes \sigma_W) = \text{Tr}(\sigma_W)\rho_V$.

Reduced density matrix from the Schmidt decomposition

For a pure state $|\psi\rangle \in \mathcal{H}(V) \otimes \mathcal{H}(W)$ with the **Schmidt decomposition**

$$|\psi\rangle = \sum_i \lambda_i |v_i\rangle_V |w_i\rangle_W$$

it is easy to derive a **reduced density matrices**.

$$\begin{aligned} |\psi\rangle \langle\psi| &= \sum_{i,j} \lambda_i \lambda_j |v_i\rangle_V |w_i\rangle_W \langle v_j|_V \langle w_j|_W \\ &= \sum_{i,j} \lambda_i \lambda_j |v_i\rangle_V \langle v_j|_V \otimes |w_i\rangle_W \langle w_j|_W \end{aligned}$$

$$\begin{aligned} \text{Tr}_W(|\psi\rangle \langle\psi|) &= \sum_{i,j} \lambda_i \lambda_j |v_i\rangle_V \langle v_j|_V \text{Tr}(|w_i\rangle_W \langle w_j|_W) \\ &= \sum_i \lambda_i^2 |v_i\rangle_V \langle v_i|_V \end{aligned}$$

$$\text{Tr}_V(|\psi\rangle \langle\psi|) = \sum_i \lambda_i^2 |w_i\rangle_W \langle w_i|_W$$

Assignments

- 1 Show the Schmidt decomposition of the following pure states
 - A $\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$
 - B $\frac{1}{2}(|00\rangle - |01\rangle - |10\rangle + |11\rangle)$
 - C $\frac{1}{2}(|00\rangle - i|01\rangle + i|10\rangle + |11\rangle)$
 - D $\frac{1}{\sqrt{2}}(\cos \theta |00\rangle - \sin \theta |01\rangle + \sin \theta |10\rangle + \cos \theta |11\rangle)$
- 2 Show the reduced density matrices for each qubit of the above pure states.