

Quantum Cyber Security

Lecture 4: Quantum Information Basics II

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The following four lectures

- Understand mathematics of **quantum states**

Most general way to describe quantum systems

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Most general way to describe quantum systems

- **Quantum measurements** and their mathematics
- **Quantum operations** and their mathematics
- Properties and concepts of classical and quantum information theory



Describe



Observe



Evolve



As a carrier of
Information

- Single qubit in Hilbert space of dimension 2: $|\psi\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$

Quantum Systems beyond single qubit

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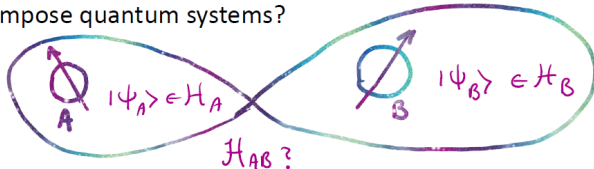
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- Or multiple qubits: n -qubits have states of dimension $d = 2^n$ Hilbert space
- Let's see how to compose quantum systems (e.g. two qubits)

Composite Systems

How to compose quantum systems?



- Two Hilbert spaces $\mathcal{H}_A, \mathcal{H}_B$ can form a new (composite) Hilbert space \mathcal{H}_{AB}

$$\dim \mathcal{H}_{AB} = \dim \mathcal{H}_A \times \dim \mathcal{H}_B$$

- Basis vectors of composite are the “product” of the basis vectors of the individual spaces
- Tensor product $\mathcal{H}_{AB} := \mathcal{H}_A \otimes \mathcal{H}_B$

Tensor Product of Vector Spaces

Let V and W be two vector spaces with $\dim m$ and n . The tensor product $V \otimes W$ of these vector spaces is a vector space of dimension $m \times n$ to which is associated a bilinear map that maps a pair $(v, w), v \in V, w \in W$ to an element of $V \otimes W$ denoted as $v \otimes w$.

- Let $|i\rangle$ and $|j\rangle$ be orthonormal bases for V and W respectively
Then $|i\rangle \otimes |j\rangle$ is orthonormal basis for $V \otimes W$
- General state $|\psi\rangle_{VW} = \sum_{i,j} \psi_{ij} |i\rangle_V \otimes |j\rangle_W$

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- Matrix rep.** of operator tensor products:

Let A_{ij} matrix elements of A and B_{kl} of B :

$$A \otimes B = \sum_{i,j,k,l} A_{ij} B_{kl} |i\rangle \langle j| \otimes |k\rangle \langle l|$$

$$A \otimes B = \begin{bmatrix} A_{11}B & A_{12}B & \cdots & A_{1n}B \\ A_{21}B & A_{22}B & \cdots & A_{2n}B \\ \vdots & \vdots & \vdots & \vdots \\ A_{m1}B & A_{m2}B & \cdots & A_{mn}B \end{bmatrix}$$

- Dirac notation:

$$|0\rangle \otimes |+\rangle, |-\rangle \otimes |-\rangle \otimes |+\rangle, |01\rangle \otimes |-\rangle$$

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$$|0\rangle \otimes |0\rangle = |00\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \times \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ 0 \times \begin{pmatrix} 1 \\ 0 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

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- Operators:

$$\begin{pmatrix} 1 & 2 \\ 0 & 4 \end{pmatrix} \otimes \begin{pmatrix} 2 & 1 \\ 3 & i \end{pmatrix}$$

Properties of Tensor Products

- Properties:

- $c(|v\rangle \otimes |w\rangle) = (c|v\rangle) \otimes |w\rangle = |v\rangle \otimes (c|w\rangle)$ where c is a scalar.
- $(|v_1\rangle + |v_2\rangle) \otimes |w\rangle = |v_1\rangle \otimes |w\rangle + |v_2\rangle \otimes |w\rangle$
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- Tensor product isn't commutative $|v\rangle \otimes |w\rangle \neq |w\rangle \otimes |v\rangle$
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- If A acts on V and B acts on W , then

$$(A \otimes B)(|v\rangle \otimes |w\rangle) = A|v\rangle \otimes B|w\rangle$$

Examples: tensor product operators

- $O_1 |\psi_1\rangle = |\phi_1\rangle$ and $O_2 |\psi_2\rangle = |\phi_2\rangle$

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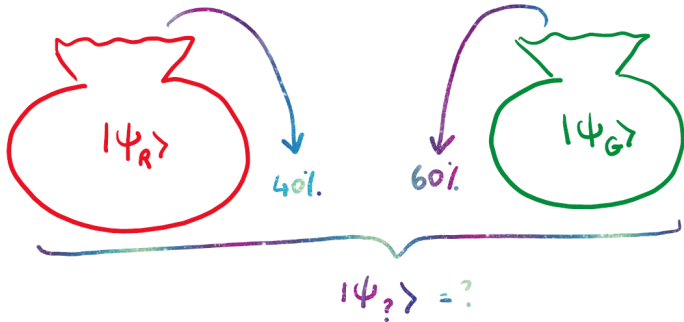
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- $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$, $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

$$H \otimes X = \frac{1}{\sqrt{2}} \begin{pmatrix} X & X \\ X & -X \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 \\ 1 & 0 & -1 & 0 \end{pmatrix}$$

Ensembles of Quantum States



- Examples:

$$\rho = \frac{1}{2} |0\rangle \langle 0| + \frac{1}{2} |+\rangle \langle +|$$

$$\rho = p_1 |\psi_R\rangle \langle \psi_R| + p_2 |\psi_G\rangle \langle \psi_G| \text{ where } p_1 = 0.4, p_2 = 0.6$$

Definition: A **density matrix** is a matrix (or operator) ρ that:

- ① is Hermitian $\rho^\dagger = \rho$
 - ② positive semi-definite (i.e. has non-negative eigenvalues)
 - ③ has unit trace $\text{Tr}(\rho) = 1$
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 - Pure state vector $|\psi\rangle$ goes to pure density matrix:
 $\rho_\psi := |\psi\rangle\langle\psi|$
 - Can incorporate probabilities over quantum states (ensembles)

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- All mixed states can be expressed as ensembles (diagonalise!)

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Mixture of product states: $\rho = \sum_{ij} p_{ij} \rho_i \otimes \rho_j$

- To describe a subsystem of a (pure or mixed) entangled state, we need density matrices!

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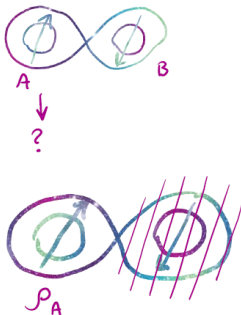
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(i) if $a_0 = 0$ then the term that has $|00\rangle$ vanishes (which it shouldn't)

(ii) if $b_1 = 0$ the term with $|11\rangle$ vanishes \square

Subsystems and partial trace



- Let $\rho_{AB} = |\psi_{AB}\rangle \langle \psi_{AB}|$

Then $\rho_A := \text{Tr}_B(\rho_{AB})$ and $\rho_B := \text{Tr}_A(\rho_{AB})$

- It easy to see that for product states $\rho_{AB} = \rho_A \otimes \rho_B$ this is the case

- Consider $M_{AB} = \sum_{i,j,k,l} c_{ijkl} |i\rangle \langle j|_A \otimes |k\rangle \langle l|_B$
- Partial trace over B:

$$M_A := \text{Tr}_B(M_{AB}) = \sum_{i,j,k,l} c_{ijkl} |i\rangle \langle j|_A \times \text{Tr}(|k\rangle \langle l|_B)$$

(note the trace is number not a matrix)

$$= \sum_{i,j,k,l} c_{ijkl} |i\rangle \langle j|_A \times (\langle l| k \rangle_B) \text{ (using cyclic property)}$$

$$= \sum_{i,j,k,l} c_{ijkl} |i\rangle \langle j|_A \times (\delta_{k,l}) \text{ (using orthogonality)}$$

$$\sum_{i,j} \sum_k c_{ijkk} |i\rangle \langle j|_A$$

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$$\sum_{i,j} \sum_k c_{ijkk} |i\rangle \langle j|_A$$

- Reduced matrix (partial trace over B) is a matrix at space A
- Partial trace over A is defined similarly

- Reduced state for product states $\rho_{AB} = \rho_A \otimes \rho_B$

As expected: ρ_A and ρ_B

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- Reduced state for entangled (Bell) state:

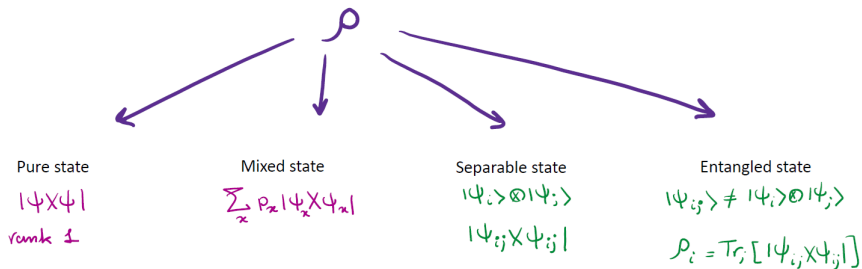
$$\rho_{AB} = |\Phi^+\rangle \langle \Phi^+|$$

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)$$

$$\rho_A = \text{Tr}(\rho_{AB}) = \dots = \frac{1}{2}(|0\rangle \langle 0| + |1\rangle \langle 1|)_A$$

$$\rho_B = \text{Tr}(\rho_{AB}) = \dots = \frac{1}{2}(|0\rangle \langle 0| + |1\rangle \langle 1|)_B$$

One density operator to rule them all!



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Born Rule:

The measured result for an observable O , on a quantum system $|\psi\rangle$ is given by its eigenvalues λ

The probability of getting a specific eigenvalue λ_i is equal to $p(i) = \langle \psi | P_i | \psi \rangle$

or more generally for a density matrix ρ is given by $p(i) = \text{Tr}[P_i \rho P_i^\dagger]$

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- Can define more general measurements (non-projective)

See next lecture!

- Quantum Computation and Quantum Information by Nielsen & Chuang: 2.1.7, 2.4
- Introduction to Quantum Cryptography by Thomas Vidick and Stephanie Wehner: chapter 2
- Quantum Information Theory by Mark M. Wilde: chapter 3