Week 4: Nonstandard Measurements, Heisenberg Uncertainty Principle, EPR Paradox

COMS 4281 (Fall 2025)

Admin

1. Worksheet3 available, Quiz3 on Gradescope tonight.
2. Pset1 out (finally!), due October 10, 11:59pm.

AI Policy

Syllabus has been updated with the AI policy. The gist of it is:

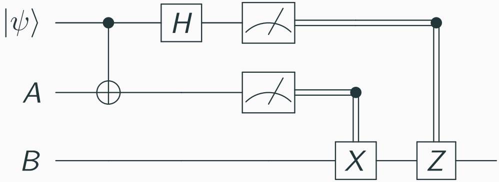
You may use AI/LLMs as a study aid, but not as a substitute for your own work. Quizzes and problem sets are practice for the midterm and final (70% of your grade), which you must do without any external help. Use AI wisely: ask it to explain, critique, or suggest alternatives — not just to give you the answer. Everything you submit must be something you understand and could explain to a peer without notes.

Recap

- Outer products
- Quantum teleportation

Quantum teleportation

Recall: the teleportation circuit.



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Both the preshared entanglement, and the classical communication are necessary for quantum teleportation to work.

Public Service Announcement

Entanglement does not allow for faster-than-light communication!

Nonstandard Measurements

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This is what we call a **standard basis measurement** or a **computational basis measurement**: the outcomes are the standard basis (a.k.a. computational basis) vectors

$$\begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix} \qquad \cdots \qquad \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$$

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Rewrite $|\psi\rangle$ as a linear combination of the $\{|+\rangle\,, |-\rangle\}$ basis:

$$|\psi\rangle = \alpha\frac{\sqrt{2}}{2}\Big(\,|+\rangle + |-\rangle\,\Big) + \beta\frac{\sqrt{2}}{2}\Big(\,|+\rangle - |-\rangle\,\Big)$$

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$$= \frac{\sqrt{2}}{2}\Big(\alpha + \beta\Big)\,|+\rangle + \frac{\sqrt{2}}{2}\Big(\alpha - \beta\Big)\,|-\rangle$$

Measuring in diagonal basis

The probability of getting $|+\rangle$ outcome is thus

$$\left(\frac{\sqrt{2}}{2}\right)^2 \cdot \left|\alpha + \beta\right|^2$$

and similarly the probability of $|-\rangle$ outcome is

$$\left(\frac{\sqrt{2}}{2}\right)^2 \cdot \left|\alpha - \beta\right|^2$$

Another perspective

Geometric perspective: measuring $|\psi\rangle$ in diagonal basis is **projecting** $|\psi\rangle$ along the $|+\rangle, |-\rangle$ axes. The probability of either outcome is the square of the magnitude of the projections.

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Algebraically, we apply the projection matrices $|+\rangle\langle+|$ and $|-\rangle\langle-|$ to $|\psi\rangle$. Projection of $|\psi\rangle$ along $|+\rangle$ is

$$|v\rangle = |+\rangle\langle+|\,|\psi\rangle = \langle+|\psi\rangle\;|+\rangle\;\;.$$

The probability of getting $|+\rangle$ outcome is equal to

$$\Big\|\,|v\rangle\,\Big\|^2 = \Big\|\,\langle+|\psi\rangle\;|+\rangle\,\Big\|^2 = |\,\langle+|\psi\rangle\,|^2\cdot\Big\|\;|+\rangle\;\Big\|^2 = |\,\langle+|\psi\rangle\,|^2$$

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Similarly probability of getting $|-\rangle$ outcome is $|\,\langle-|\psi\rangle\,|^2$.

General formula for measuring in a basis

Let $|\psi\rangle \in \mathbb{C}^d$ be a quantum state. Let $B = \{|b_1\rangle, \ldots, |b_d\rangle\}$ be an **orthonormal basis** for $\mathbb{C}^d$.

Measuring $|\psi\rangle$ with respect to basis B yields outcome $|b_j\rangle$ with probability

$$\left|\left\langle b_j \middle| \psi \right\rangle\right|^2$$

and the post-measurement state is $|b_j\rangle$.

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Measuring $|\psi\rangle$ in a basis B is **equivalent** to

1. Apply a unitary V that maps B to standard basis (i.e. $|b_j\rangle \rightarrow |j\rangle$).
2. Measure $V|\psi\rangle$ in standard basis to get outcome $|j\rangle$.
3. Apply inverse unitary $V^\dagger$ to map $|j\rangle$ back to $|b_j\rangle$ as the post-measurement state.

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After it collapses to $|0\rangle$, we apply $H^\dagger = H$ to get $|+\rangle$, the post-measurement state.

Partial measurements plus nonstandard measurements

Let's combine the two concepts! Let $|\psi\rangle = \sum_{i,j} \alpha_{ij} |i\rangle \otimes |j\rangle$ denote a two-qubit state. Say we measure the first qubit with respect to basis $\{|b_0\rangle, |b_1\rangle\}$.

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Measurement rule: Equivalent to applying the projections

$$|v_0\rangle = \Big(|b_0\rangle \langle b_0| \otimes \mathrm{I} \Big) |\psi\rangle$$
$$|v_1\rangle = \Big(|b_1\rangle \langle b_1| \otimes \mathrm{I} \Big) |\psi\rangle \ .$$

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The probability of getting $|b_0\rangle$ outcome is $\| \, |v_0\rangle \, \|^2$, and the post-measurement state is $|v_0\rangle / \| \, |v_0\rangle \, \|$.

Similarly, probability of getting $|b_1\rangle$ outcome is $\| \, |v_1\rangle \, \|^2$, and post-measurement state is $|v_1\rangle / \| \, |v_1\rangle \, \|$.

Projecting $|\psi\rangle$ along the first projection yields

$$\begin{aligned}\Big(|b_0\rangle\langle b_0|\otimes \mathrm{I}\Big)|\psi\rangle &= \sum_{i,j}\alpha_{ij}\,|b_0\rangle\langle b_0|i\rangle\otimes \mathrm{I}\,|j\rangle \\ &= \sum_{i,j}\alpha_{ij}\,\langle b_0|i\rangle\,|b_0\rangle\otimes|j\rangle \\ &= |b_0\rangle\otimes\Big(\sum_{i,j}\alpha_{ij}\,\langle b_0|i\rangle\,|j\rangle\Big)\,.\end{aligned}$$

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The probability of getting $|b_0\rangle$ outcome is

$$\begin{aligned}\Big\|\,|b_0\rangle\otimes\Big(\sum_{i,j}\alpha_{ij}\langle b_0|i\rangle\,|j\rangle\Big)\Big\|^2 &= \underbrace{\|\,|b_0\rangle\,\|^2}_{1}\cdot\Big\|\sum_{i,j}\alpha_{ij}\langle b_0|i\rangle\,|j\rangle\,\Big\|^2 \\ &= \Big\|\sum_{j}\Big(\sum_{i}\alpha_{ij}\langle b_0|i\rangle\Big)|j\rangle\,\Big\|^2 \\ &= \sum_{j}\Big|\sum_{i}\alpha_{ij}\langle b_0|i\rangle\Big|^2\,.\end{aligned}$$

Partial measurements plus nonstandard measurements

Conditioned on the outcome $|b_0\rangle$ in the first qubit, the post-measurement state of the two qubits is then

$$|b_0\rangle \otimes \frac{\sum_{i,j} \alpha_{ij} \langle b_0|i\rangle |j\rangle}{\left\| \sum_{i,j} \alpha_{ij} \langle b_0|i\rangle |j\rangle \right\|} = |b_0\rangle \otimes \frac{\sum_{i,j} \alpha_{ij} \langle b_0|i\rangle |j\rangle}{\sqrt{\sum_j \left| \sum_i \alpha_{ij} \langle b_0|i\rangle \right|^2}}$$

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Notice that, even though the original state $|\psi\rangle$ could have been entangled, the post-measurement state is **unentangled**! Measurement generally destroy entanglement.

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Let's work through an example:

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \, .$$

Measure the **first** qubit in the **diagonal basis**.

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Measure the **first** qubit in the **diagonal basis**.

- What is the probability the outcome is $|+\rangle$? Or $|-\rangle$?
- What is the post-measurement state in either case?

Next time

Heisenberg's uncertainty principle, EPR paradox, Bell's Theorem.

Heisenberg Uncertainty Principle

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Popular science version: can't exactly know both the position and momentum of a particle simultaneously.

Heisenberg Uncertainty Principle

In quantum information theory terms: it is not possible for a qubit $|\psi\rangle \in \mathbb{C}^2$ to be simultaneously determined in both the **standard** basis and the **diagonal basis**.

Heisenberg Uncertainty Principle

In quantum information theory terms: it is not possible for a qubit $|\psi\rangle \in \mathbb{C}^2$ to be simultaneously determined in both the **standard** basis and the **diagonal basis**.

In other words, if measuring $|\psi\rangle$ in standard basis yields a deterministic outcome, then it **cannot** have a deterministic outcome if measured according to diagonal basis.

Heisenberg Uncertainty Principle

Quantitatively, let:

1. $p_0 = |\langle 0|\psi\rangle|^2$ and $p_1 = |\langle 1|\psi\rangle|^2$ be probability of outcomes in standard basis.

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Then a version of Heisenberg's uncertainty principle says

$$(p_0 - p_1)^2 + (p_+ - p_-)^2 \leq 1$$

.

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Important point: it's not about what happens if you **sequentially** measure the state $|\psi\rangle$ (what happens then?).

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It's reasoning about **counterfactual scenarios**: measuring $|\psi\rangle$ in the standard basis, **or** measuring $|\psi\rangle$ in the diagonal basis.

Heisenberg Uncertainty Principle

We say that the standard basis and diagonal basis are **incompatible** or **complementary**.

In quantum physics, the position and momentum of a particle correspond to incompatible measurements!

EPR Paradox

The EPR Paradox

In 1935, Einstein, Podolsky, and Rosen published a paper called

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

The EPR Paradox

The EPR thesis:

Quantum mechanics may be very good at predicting outcomes of experiments, but it cannot be a **complete** *description of Nature.*

The reason they thought this was because of a thought experiment.

The EPR Paradox

Alice and Bob are in far-away galaxies and share the EPR state

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

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

Consider two possible experiments:

- **Experiment A**: Alice measures her qubit in the standard basis $\{|0\rangle, |1\rangle\}$
- **Experiment B**: Alice measures her qubit in the diagonal basis $\{|+\rangle, |-\rangle\}$

Experiment A

Alice gets outcome

- $|0\rangle$ with probability $1/2$, and the post-measurement state is $|00\rangle$.
- $|1\rangle$ with probability $1/2$, and the post-measurement state is $|11\rangle$.

Experiment B

To calculate the probability of getting outcome $|+\rangle$, we use the partial measurement + nonstandard basis rules: first, compute the vector

$$|v_+\rangle = \Big(|+\rangle\langle+| \otimes I\Big)\,|\Phi\rangle = |+\rangle \otimes \frac{1}{\sqrt{2}}\Big(\langle + \mid 0\rangle\,|0\rangle\ +\ \langle + \mid 1\rangle\,|1\rangle\Big)$$

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$$= |+\rangle \otimes \frac{1}{\sqrt{2}} \Big(\frac{1}{\sqrt{2}} |0\rangle + \frac{1}{\sqrt{2}} |1\rangle \Big) = \frac{1}{\sqrt{2}} |+\rangle \otimes |+\rangle \, .$$

The squared length is $\| \, |v_+\rangle \, \|^2 = \frac{1}{2}$.

Experiment B

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Experiment B

The post-measurement state is then $\sqrt{2}\,|v_+\rangle = |+\rangle \otimes |+\rangle$.

Similarly, the probability of getting outcome $|-\rangle$ is $\frac{1}{2}$ and the post-measurement state is $|-\rangle \otimes |-\rangle$.

The EPR Paradox

Alice and Bob are in far-away galaxies and share the EPR state $|\Phi\rangle = \frac{1}{\sqrt{2}}\Big(|00\rangle + |11\rangle\Big)$. If Alice measures in standard basis, after seeing her result she knows exactly what state Bob's qubit is in – even if Bob's qubit is zillions of lightyears away.

The EPR Paradox

Einstein's (and Podolsky's and Rosen's) reasoning:

1. If Alice did Experiment A and got outcome (say) $|0\rangle$, then it must have been Bob's qubit was really $|0\rangle$ all along.

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3. But Alice's choice of measurement (standard or diagonal) couldn't have made an instantaneous difference in intrinsic the state of Bob's qubit, right?

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3. But Alice's choice of measurement (standard or diagonal) couldn't have made an instantaneous difference in intrinsic the state of Bob's qubit, right?
4. Therefore Bob's qubit must have answers prepared for both Experiments simultaneously – violating Heisenberg's Uncertainty Principle!

The EPR Paradox

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EPR's thesis: There is a **deeper** classical theory – called a **local hiden variable theory** – that

- Reproduces the same statistics as Quantum Mechanics
- But has hidden variables that describes the intrinsic state of particles.
- Respects the speed of light limit.

What do you think of Einstein's reasoning?

It is a paradox?