

Product states and nonseparable states

Add a worked tensor product with the basis order stated.

Contrast it with a normalized two-system state that cannot factor into a product. Use state vectors without circuit programming.

Physical meaning of a subsystem

Choose a physical two-level example. Identify the preparation and the measured observable for each subsystem.

Explain which assumptions let us model the pair as a tensor product.

Preparation versus statistical mixture

Develop one physical preparation of a superposition and one mixture with the same probabilities in a chosen basis.

Use a second measurement basis to distinguish them.

A complete Born-rule example

Specify a normalized state and a measurement basis. Calculate every outcome probability and the post-measurement state.

Include a student checkpoint with a different basis.

Single-particle interference

Add the experiment, preparation, and detection procedure.

Explain interference between indistinguishable alternatives for a single quantum system.
Avoid describing it as photons needing to collide with one another.

Which-path information and coherence

Compare coherent alternatives with distinguishable paths. Connect the observed distributions to amplitude addition and probability addition.

Distinguish loss of local coherence from conditioning on a measurement outcome.

Stern–Gerlach measurement model

Develop the preparation, magnetic-field gradient, and readout.

Separate the Pauli observable with eigenvalues ± 1 from physical spin angular momentum with eigenvalues $\pm \hbar/2$.

Sequential measurements

Work through two measurement axes and conditional probabilities.

Explain the change of state and the difference between an observable, apparatus setting, and observed value.

Hamiltonian and time evolution

Derive the connection between the Schrödinger equation and $U(t)$ for a time-independent Hermitian Hamiltonian.

State the assumptions and units. Replace the unfinished derivation in original Lecture 12, slides 41–42.

Energy eigenstates and relative phase

Use a two-level energy spectrum to calculate phase accumulation.

Distinguish a shared global phase from a relative phase observable in a suitable basis.

Physics-to-computation boundary

Finish with a worked physical evolution and its unitary matrix.

Q3 will treat selected transformations as allowed computational operations. Leave circuit software for M_Q.

Entanglement and local statistics

Define separability and entanglement with explicit joint states.

Calculate joint probabilities and each subsystem's marginal probabilities. Explain why correlations do not permit faster-than-light messaging.

Bell assumptions and an experimental test

State the assumptions behind the chosen Bell inequality. Give measurement settings, a classical bound, and a quantum prediction.

Explain experimental limitations without claiming that the result proves faster-than-light communication.

Q2 synthesis exercise

Combine state preparation, tensor products, measurement bases, and physical evolution in one problem.

Students should explain the predicted evidence before Q3 introduces computational models.

Density matrices and reduced states

Develop pure states, statistical mixtures, and the partial trace with worked two-level examples.

Show how a pure entangled joint state gives a mixed local state.

Entropy and physical information

Calculate Shannon and von Neumann entropy in small examples.

Connect the eigenvalues of a density matrix to uncertainty, purity, and correlations. Define all conventions.

A physical decoherence mechanism

Develop one system–environment coupling model. Calculate the reduced state and the loss of off-diagonal coherence.

Distinguish decoherence, measurement conditioning, relaxation, and dephasing.

Noise channels and time scales

Introduce T_1 and T_2 with physical preparation and readout procedures.

Work through a simple channel and compare ideal and noisy output probabilities.

Error mitigation and its limits

Choose a mitigation method and state its calibration assumptions.

Compare bias, variance, and sampling overhead. Explain why mitigation alone does not provide fault tolerance.

Current hardware comparison

Update the illustrative platform and vendor examples with dated primary sources.

Compare encoding, control, readout, connectivity, coherence, and native operations.
Separate physical and logical qubits.

Logical qubits and syndrome measurement

Develop one small code, its encoding, and a syndrome table.

Show which errors it corrects and which it cannot. Explain why syndrome measurement can preserve logical information.

Fault tolerance and overhead

Connect physical error rates, code distance, and logical failure probability.

State the assumptions behind a threshold claim and provide a worked resource example.

An evidence-based hardware case study

Choose a dated result from a primary source. Identify the task, classical comparison, accuracy, and total resources.

Distinguish a simulator demonstration, a query advantage, and useful hardware performance.

Final synthesis assessment

Trace one Q3 algorithm through state preparation, compilation, noisy execution, and readout.

Ask students to explain what would have to improve for the demonstration to become useful.