Quantum Information Fundamentals

Illustrated-by-Examples Study Q&A Handbook

Based on the EITC/QI/QIF self-learning curriculum

Clear explanations • Key ideas • Worked mini-examples

An independently written study companion organized around the topics and review questions in the supplied 476-page preparatory text. This is not an official examination answer key.

November 7, 2026

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How to use this handbook

Read each question, try answering it before looking below, then review the short example or formula. The handbook follows the subject sequence of the supplied textbook. Its explanations are newly written and intentionally shorter than the original book's detailed review answers. For full coverage, consult the original chapter and its review section.

Source: European IT Certification Institute, *EITC/QI/QIF Quantum Information Fundamentals*, self-learning preparatory materials (2023), supplied PDF.

Getting started

Q1. What is the goal of quantum computation?

Answer. Quantum computing uses controllable quantum states to solve selected problems more efficiently. It does not make every calculation faster: speedups depend on a suitable algorithm, coherent hardware, and a useful measurement outcome.

Remember / example. A quantum processor is not simply a classical processor running many independent calculations at once.

Q2. Why does a system of n qubits have 2^n basis states?

Answer. Each qubit has two computational basis labels. Combining n qubits gives every binary string of length n, so the state vector contains 2^n complex amplitudes. For three qubits the labels run from 000 to 111.

Remember / example. The dimension is 2^n, but measurement does not reveal all 2^n amplitudes.

Introduction to Quantum Mechanics

Q3. What does the double-slit experiment demonstrate?

Answer. When which-path information is unavailable, the amplitudes associated with the two slits interfere. Many individual detections gradually build up bright and dark fringes. Obtaining distinguishable path information removes the interference between alternatives.

Remember / example. The detector registers localized events, while their statistics follow a wave-like pattern.

Q4. Why do probabilities not simply add in the double-slit experiment?

Answer. For indistinguishable alternatives, first add complex probability amplitudes and then take the squared magnitude. The cross term can increase or decrease the final probability. If the paths become distinguishable, interference is lost and ordinary probability addition applies.

Remember / example. P = |a+b|^2, which generally differs from |a|^2+|b|^2.

Introduction to Quantum Information

Q5. What is a qubit and how is it measured?

Answer. A pure qubit is a normalized superposition of two orthogonal basis states. Measurement in the computational basis produces 0 or 1, with probabilities equal to the squared magnitudes of their amplitudes.

Remember / example. |psi> = alpha|0> + beta|1>, with |alpha|^2+|beta|^2=1.

Q6. What does the Bloch sphere represent?

Answer. The Bloch sphere represents pure single-qubit states as points on a unit sphere. Polar angle controls the relative weights of |0> and |1>; azimuthal angle describes relative phase. Mixed states lie inside the sphere.

Remember / example. Global phase does not change the physical state.

Q7. How does photon polarization encode a qubit?

Answer. Horizontal and vertical polarizations can serve as an orthonormal basis. Diagonal polarization is a coherent superposition of the two. A polarizer aligned with a measurement basis gives probabilistic transmission according to the state overlap.

Remember / example. A diagonally polarized photon has equal probabilities for horizontal and vertical outcomes.

Q8. What does the uncertainty principle say?

Answer. For two observables that do not commute, their spreads in a quantum state cannot both be made arbitrarily small. Position and momentum are the standard example. The principle concerns intrinsic state statistics, not merely faulty instruments.

Remember / example. Delta x Delta p >= hbar/2.

Quantum Entanglement

Q9. What is bra-ket notation?

Answer. A ket represents a state vector and a bra its conjugate transpose. Their inner product is a complex amplitude; the squared magnitude gives a transition probability for normalized states. Outer products describe operators.

Remember / example. <phi|psi> is an inner product; |psi><psi| is a projector.

Q10. When is a two-qubit state entangled?

Answer. A pure two-qubit state is entangled when it cannot be written as a tensor product of two individual qubit states. Its correlations cannot be reproduced by assigning an independent pure state to each qubit.

Remember / example. (|00>+|11>)/sqrt(2) is entangled; |0>|+> is not.

Q11. What is the EPR paradox?

Answer. The Einstein–Podolsky–Rosen argument questioned whether quantum mechanics gives a complete description of physical reality. Entangled systems exhibit strong correlations even when measured far apart, challenging simple local hidden-variable explanations.

Remember / example. Entanglement does not allow faster-than-light messaging.

Q12. What does a Bell inequality test?

Answer. Bell inequalities bound correlations predicted by local hidden-variable models under stated assumptions. Certain entangled quantum states and measurement settings violate those bounds, ruling out that class of explanations.

Remember / example. For the CHSH expression, local models obey |S| <= 2; quantum theory allows up to 2 sqrt(2).

Quantum Information Processing

Q13. What is unitary evolution?

Answer. An isolated quantum state evolves by a unitary transformation, which preserves inner products and total probability. A gate is a controlled unitary acting on one or more qubits.

Remember / example. U^dagger U = I.

Q14. What do X, Z, and H gates do?

Answer. X exchanges the computational basis states. Z changes the sign of |1> relative to |0>. Hadamard maps basis states into equal superpositions, making it useful for interference-based circuits.

Remember / example. H|0> = (|0>+|1>)/sqrt(2).

Q15. How does a CNOT gate operate?

Answer. CNOT flips its target qubit only when its control qubit is |1>. Applied to a control in superposition and a target initialized to |0>, it can create entanglement.

Remember / example. CNOT[(|0>+|1>)|0>/sqrt(2)] = (|00>+|11>)/sqrt(2).

Quantum Information Properties

Q16. Why is an unknown quantum state impossible to clone perfectly?

Answer. A universal perfect cloner would have to preserve the inner products of all possible input states under unitary evolution. Requiring two copies instead forces incompatible overlap conditions for arbitrary nonorthogonal states.

Remember / example. Known orthogonal basis states can be copied; arbitrary unknown states cannot.

Q17. How does quantum teleportation work?

Answer. Alice and Bob share an entangled pair. Alice jointly measures her unknown input and her half of the pair, then sends two classical bits to Bob. Bob applies the indicated correction and recovers the original state.

Remember / example. Teleportation transfers a state, not matter, and requires classical communication.

Q18. What does quantum measurement do?

Answer. A projective measurement produces an outcome according to the Born rule and updates the state conditional on that outcome. The chosen basis matters: a state certain in one basis can be random in another.

Remember / example. Measuring |+> in the Z basis gives 0 and 1 with probability 1/2 each.

Introduction to Quantum Computation

Q19. Why are reversible gates important?

Answer. Unitary quantum operations are reversible, whereas ordinary AND and OR discard input information. Classical reversible computation can retain inputs and use auxiliary registers to implement logic without losing information.

Remember / example. The Toffoli gate is a standard reversible three-bit gate.

Q20. What does universal quantum gate set mean?

Answer. A gate family is universal if circuits built from it can approximate any desired unitary operation to arbitrary accuracy. Universality does not imply a short circuit for every unitary.

Remember / example. Single-qubit rotations together with an entangling two-qubit gate form a common universal approach.

Quantum Algorithms

Q21. What is the idea behind Fourier sampling?

Answer. An algorithm prepares amplitudes containing hidden periodic or algebraic structure, applies a Fourier transform, and measures frequency information. The distribution of outcomes reveals constraints on the hidden structure.

Remember / example. Interference boosts informative frequencies and suppresses others.

Q22. What problem does Simon's algorithm solve?

Answer. Simon's algorithm finds a hidden nonzero bit string s satisfying a promise that f(x)=f(y) precisely when y=x xor s for distinct inputs. Quantum measurements provide linear equations modulo two that determine s.

Remember / example. Each useful sample y satisfies y dot s = 0 modulo 2.

Q23. What is the extended Church–Turing thesis?

Answer. Informally, it proposes that physically reasonable computation can be simulated efficiently by a probabilistic classical machine. Quantum speedups motivate examining the limits of this efficiency claim.

Remember / example. This is a claim about efficient simulation, not about which functions are computable.

Quantum Fourier Transform

Q24. What is the quantum Fourier transform?

Answer. The QFT is a unitary transformation on computational-basis amplitudes analogous to the discrete Fourier transform. It converts phase and periodicity patterns into amplitudes that can be measured.

Remember / example. QFT|x> = (1/sqrt(N)) sum_k exp(2 pi i xk/N)|k>.

Q25. Why are roots of unity useful in the QFT?

Answer. Complex Nth roots of unity lie evenly spaced on the unit circle. Their phases cancel when summed over mismatched frequencies, giving the orthogonality that makes Fourier analysis work.

Remember / example. sum_k exp(2 pi i jk/N) = 0 unless j is a multiple of N.

Shor's Quantum Factoring Algorithm

Q26. How does period finding help factor integers?

Answer. For an integer a coprime to N, quantum period finding estimates the order r such that a^r is 1 modulo N. When r is even and a^(r/2) is not -1 modulo N, gcd calculations can reveal nontrivial factors.

Remember / example. Shor combines quantum period finding with classical arithmetic.

Q27. Does Shor's algorithm always succeed on the first try?

Answer. No. Some randomly chosen values of a lead to unsuitable periods, and measured phase estimates can be imperfect. Repetition and classical verification are part of the algorithm.

Remember / example. A valid factor is checked by ordinary multiplication.

Grover's Quantum Search Algorithm

Q28. What speedup does Grover's algorithm provide?

Answer. For an unstructured search with N candidates and one marked item, Grover's algorithm needs on the order of sqrt(N) oracle queries, compared with order N classical queries. The gain is quadratic rather than exponential.

Remember / example. The method relies on repeated amplitude amplification.

Q29. What are the oracle and diffusion steps?

Answer. The oracle changes the phase of marked states. The diffusion operator reflects amplitudes about their mean, increasing marked-state amplitude after each iteration. Too many iterations can reduce success probability again.

Remember / example. With one marked item, about (pi/4)sqrt(N) iterations is a useful approximation.

Observables and Schrodinger's Equation

Q30. What is a quantum observable?

Answer. An observable is represented by a Hermitian operator. Its eigenvalues are possible measurement outcomes, and the state determines their probabilities. Its expectation value is the statistical mean over many identical preparations.

Remember / example. Expectation: <A> = <psi|A|psi>.

Q31. What does the Schrodinger equation describe?

Answer. The Schrodinger equation governs the time evolution of a quantum state under a Hamiltonian. For a time-independent Hamiltonian, energy eigenstates acquire phase factors during evolution.

Remember / example. i hbar d|psi>/dt = H|psi>.

Implementing Qubits

Q32. Why is a particle in a box useful?

Answer. A particle confined to an ideal one-dimensional box has discrete stationary energy levels and sinusoidal wavefunctions. It illustrates how boundary conditions produce quantization and how selected levels could encode information.

Remember / example. For an infinite well of length L, E_n = n^2 pi^2 hbar^2/(2mL^2).

Q33. What makes a physical system a useful qubit?

Answer. A practical qubit needs two addressable levels, preparation, coherent control, readout, and sufficiently low errors. Isolation protects coherence, while controlled coupling enables gates; engineering must balance both.

Remember / example. Examples include spin states, trapped ions, photons, and superconducting circuits.

Quantum Complexity Theory

Q34. What is BQP?

Answer. BQP is the class of decision problems solvable by a uniform family of polynomial-size quantum circuits with bounded error. It formalizes efficient quantum computation and does not mean every hard problem becomes easy.

Remember / example. Shor's factoring-related decision tasks illustrate quantum efficiency.

Q35. What is adiabatic quantum computation?

Answer. Adiabatic computation begins in an easy-to-prepare ground state and slowly changes the Hamiltonian toward one encoding the answer. Its performance depends on the energy gap and how slowly the evolution proceeds.

Remember / example. A very small minimum gap can demand a long runtime.

Introduction to Spin

Q36. Why can spin one-half represent a qubit?

Answer. A spin-one-half particle has two outcomes along any chosen measurement axis. These can encode |0> and |1>, while magnetic fields rotate the spin state.

Remember / example. Stern–Gerlach measurements illustrate discrete spin projections.

Q37. What are the Pauli matrices used for?

Answer. The three Pauli matrices represent spin components up to a factor of hbar/2 and generate single-qubit rotations. Their noncommutation captures the incompatibility of spin measurements along different axes.

Remember / example. [sigma_x,sigma_y] = 2i sigma_z.

Manipulating Spin

Q38. What is Larmor precession?

Answer. A spin in a static magnetic field precesses around the field direction. Its angular frequency is proportional to magnetic-field strength and the gyromagnetic ratio.

Remember / example. omega_L = |gamma| B.

Q39. How does magnetic resonance control a spin qubit?

Answer. A transverse oscillating field near the spin transition frequency drives coherent rotations. Pulse amplitude, duration, phase, and detuning determine the rotation axis and angle.

Remember / example. A calibrated pi pulse can exchange the populations of the two spin levels.

Rapid revision checklist

- Explain superposition, interference, and the Born rule without confusing amplitudes with probabilities.
- Identify separable versus entangled two-qubit states and state what Bell inequalities test.
- Apply basic single-qubit gates and CNOT to computational basis states.
- Explain no-cloning, teleportation, and the role of classical communication.
- Distinguish QFT, Simon, Shor, and Grover by the problem each solves.
- State the meaning of Hermitian observables, unitary evolution, BQP, and adiabatic computation.
- Describe spin, Stern–Gerlach measurement, Larmor precession, and resonance control.

Study note: Some explanatory statements in the supplied preparatory book simplify complex subjects. This companion uses standard quantum-mechanical qualifications where needed (for example, a large Hilbert space does not imply access to exponentially many classical outputs).