

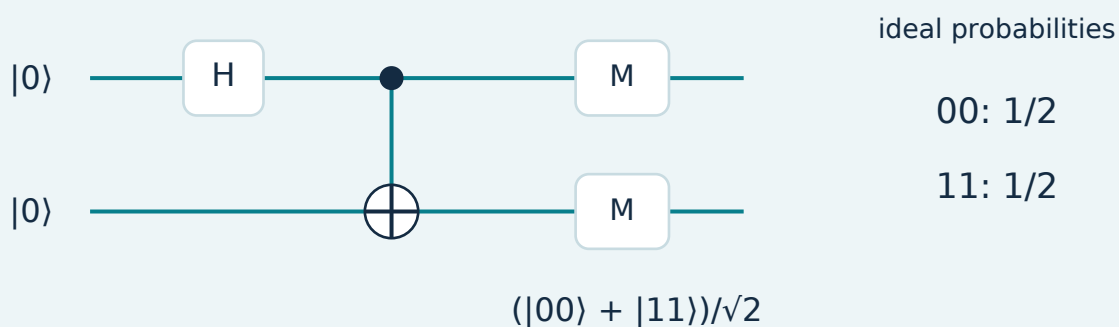
Quantum technology

From physical principles to processors, networks and sensors

Educational master edition

26.09.2026 | v1.0 | EN

An original, structured guide for curious readers, students and technology teams. This is a broad educational synthesis, not an exhaustive inventory of every experiment or a laboratory construction manual. Mathematics is introduced where it clarifies the mechanism. Schematics are conceptual and not to scale. Research status checked on 26 September 2026; individual evidence dates are given in the references.



Contents

01 The quantum technology landscape	3
02 A century of ideas and experiments	3
03 States, amplitudes and measurement	4
04 Superposition is not a bag of answers	4
05 Entanglement, correlations and no-cloning	5
06 Gates, circuits and a first experiment	5
07 Algorithms and the conditions behind speedup	6
08 How hardware encodes a qubit	6
09 The processor is only one part of the machine	7
10 Control electronics, optics and cryogenics	7
11 Noise and error correction	8
12 Logical qubits and fault tolerance	8
13 The quantum software stack	9
14 Benchmarks that answer meaningful questions	9
15 Communication and the quantum internet	10
16 Sensors and precision measurement	10
17 Post-quantum cryptography versus QKD	11
18 Evidence at the 2026 review date	11
19 Future directions: conditional, not inevitable	12
20 Learning path and exercises	12
21 Reading the library responsibly	13
Bibliography and further reading / 14+	

01 The quantum technology landscape

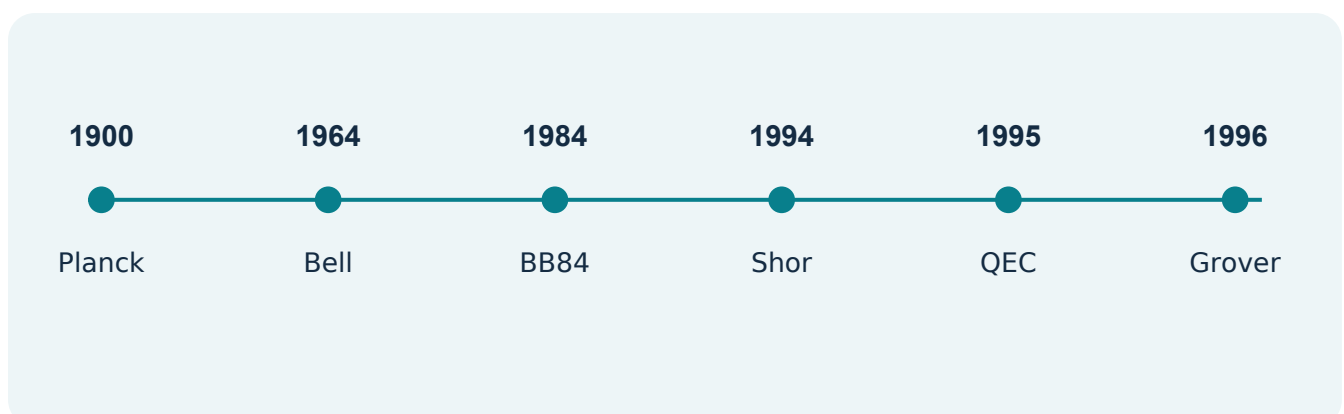
Quantum technology uses controlled physical systems whose behaviour requires quantum mechanics. Computing manipulates information; communication distributes quantum states or keys; sensing measures physical quantities. Lasers, transistors and magnetic resonance already rely on quantum physics. Newer approaches exploit individual quantum systems, coherence and sometimes entanglement as engineered resources.

A quantum computer is normally an accelerator connected to classical computers. It does not replace every processor, and it is not faster for every task. Useful advantage means a better solution at an acceptable total cost, including preparation, control, repetitions and verification. There is no experimentally established technology simply ranked above all quantum technologies. Different architectures solve different problems. [R1, R2]

02 A century of ideas and experiments

Planck introduced energy quantization in 1900; Einstein connected light quanta to the photoelectric effect in 1905. Matrix and wave mechanics emerged in 1925-1926. The 1935 EPR argument and Bell's 1964 theorem clarified the significance of correlations that classical local models cannot reproduce under the relevant assumptions.

In the 1980s, Feynman motivated quantum simulation and Deutsch formalized universal quantum computation. BB84 proposed quantum key distribution in 1984. Shor's 1994 algorithm and Grover's 1996 search algorithm established important computational possibilities; quantum error correction emerged in 1995. Later milestones include controlled gates, cloud-accessible processors, increasingly capable simulators and logical-qubit demonstrations. These are distinct achievements, not evidence that every useful application is already practical. [R1, R2, R10]



Original educational diagram 01. Selected historical landmarks; dates mark ideas, not product readiness.

03 States, amplitudes and measurement

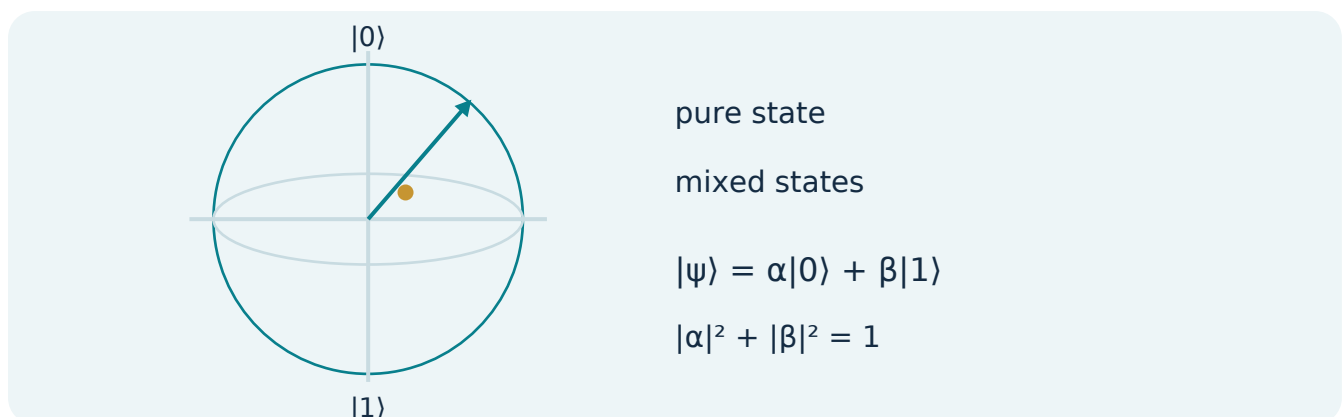
A qubit is a controllable two-level quantum system. In a chosen basis its pure state is $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, with complex amplitudes and $|\alpha|^2 + |\beta|^2 = 1$. Measuring in that basis returns 0 or 1 with those squared magnitudes. A single measurement does not reveal both amplitudes; estimating a state requires many identically prepared samples and several measurement settings.

Relative phase changes interference. A global phase does not change measurement predictions. For an isolated system, coherent evolution is unitary; a Hamiltonian describes its energy and dynamics. Mixed states describe uncertainty or entanglement with an unobserved environment and require a density matrix. The Bloch sphere represents pure single-qubit states on its surface and mixed states inside, but is not a picture of an electron's trajectory. [R10, R11]

04 Superposition is not a bag of answers

The states $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$ both give equal 0/1 probabilities in the computational basis. Applying a Hadamard gate H before measurement distinguishes them: $H|+\rangle = |0\rangle$ and $H|-\rangle = |1\rangle$. Interference therefore turns phase information into observable probability differences.

An n -qubit pure state has 2^n amplitudes, but reading it does not deliver 2^n classical answers. Algorithms must arrange interference to make useful outputs likely. Even the enormous state space does not prove a speedup: some large quantum circuits have efficient classical simulations. The central engineering challenge is to preserve the right interference while suppressing unwanted interactions. [R2, R10]



Original educational diagram 02. Bloch sphere: a geometric representation of one qubit, not an electron orbit.

05 Entanglement, correlations and no-cloning

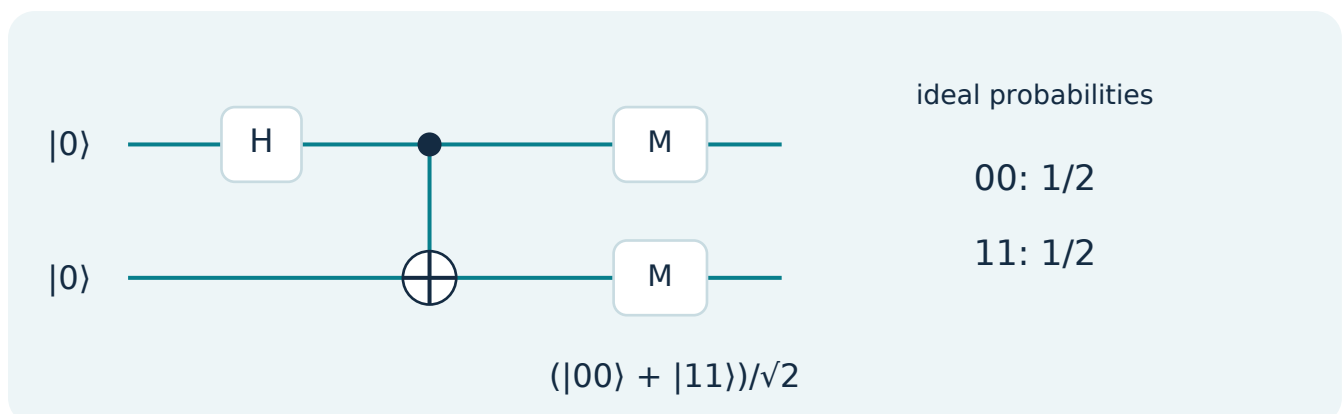
Starting from $|00\rangle$, apply H to the first qubit and then a controlled-NOT with the first as control. The result is the Bell state $(|00\rangle + |11\rangle)/\sqrt{2}$. Ideal computational-basis outcomes are 00 and 11 with equal probability. Each subsystem alone looks random. Correlation in one basis alone does not certify entanglement: a classical mixture of 00 and 11 has the same distribution in that basis.

Entanglement is a property of a joint state that cannot be written as a mixture of product states. Appropriate measurements or witnesses distinguish it from classical correlations. It cannot transmit a controllable message faster than light. No-cloning forbids a universal perfect copier of an unknown quantum state; this is compatible with copying known orthogonal classical states. Teleportation consumes shared entanglement and classical communication. [R3, R10]

06 Gates, circuits and a first experiment

X exchanges $|0\rangle$ and $|1\rangle$. Z changes the sign of the $|1\rangle$ amplitude. H changes between computational and superposition bases. Phase gates S and T apply specific relative phases; continuous rotations provide another useful description. CNOT flips its target only when the control is $|1\rangle$ in the computational basis. A universal gate set can approximate arbitrary unitary computation to a chosen precision.

Circuit wires label qubits and the horizontal direction indicates operation order, not physical distance. Prepare $|00\rangle$, apply H(0), apply CNOT(0,1), measure both, and repeat 1,000 times. Ideally about 500 results are 00 and 500 are 11, with ordinary sampling fluctuations. Noise adds other outcomes. Record the simulator or device, circuit, bit order, repetitions and calibration time. This example illustrates preparation and correlation, not computational advantage. [R10, R11]



Original educational diagram 03. Bell-pair circuit: ideal Z-basis counts do not alone certify entanglement.

07 Algorithms and the conditions behind speedup

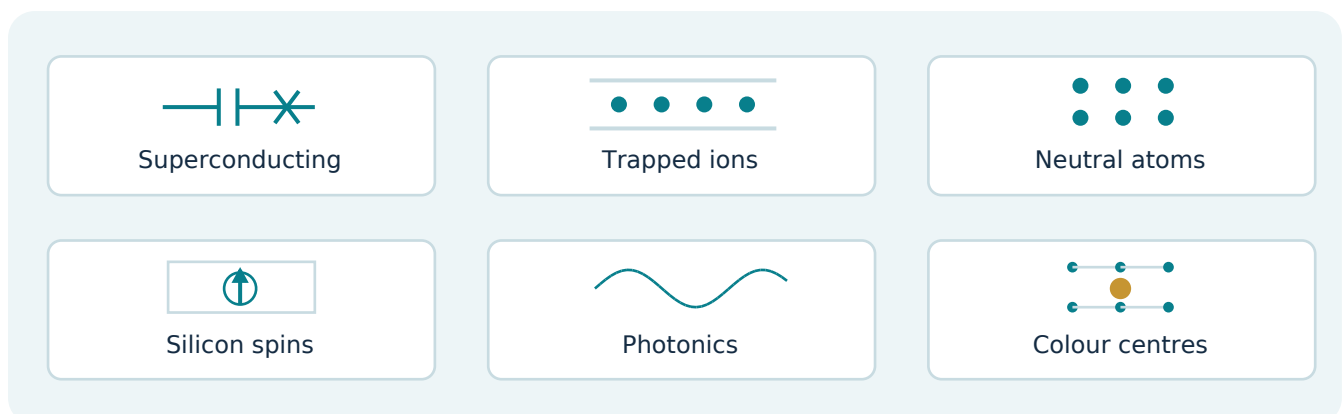
Shor's algorithm reduces factoring and discrete logarithms to period-related quantum computations, threatening widely used public-key schemes on sufficiently capable fault-tolerant hardware. Grover search needs $O(\sqrt{N})$ oracle calls for one marked item among N candidates, compared with $O(N)$ classical queries. The oracle, data access and error correction also cost resources.

Phase estimation extracts information about eigenvalues when suitable controlled evolutions and input states are available. Quantum simulation targets molecular and material dynamics. VQE and QAOA combine parameterized circuits with classical optimization, but generic practical superiority is unproven. Linear-system and machine-learning proposals often assume efficient data loading, favourable conditioning or restricted outputs. Compare complete workflows with strong classical methods, not only an idealized quantum subroutine. [R2, R1]

08 How hardware encodes a qubit

Superconducting circuits use nonlinear electrical oscillators, commonly transmons, with microwave control and millikelvin cooling. Trapped ions use internal atomic states held by electromagnetic fields, with optical or microwave gates. Neutral atoms are arranged with optical tweezers or lattices; Rydberg interactions can generate entanglement.

Semiconductor spin qubits use electron or nuclear spin states and promise dense fabrication, while uniform control and interconnects remain challenges. Photonic platforms encode information in light, for example in modes or polarization; loss, sources, detection and entangling operations matter. Colour centres combine solid-state spins with optical interfaces. Topological approaches seek protected encodings, but claims require independent verification and scalable gate demonstrations. Qubit count alone cannot rank these platforms. [R3, R8, R21]



Original educational diagram 04. Six physical approaches; boxes indicate categories, not a performance ranking.

09 The processor is only one part of the machine

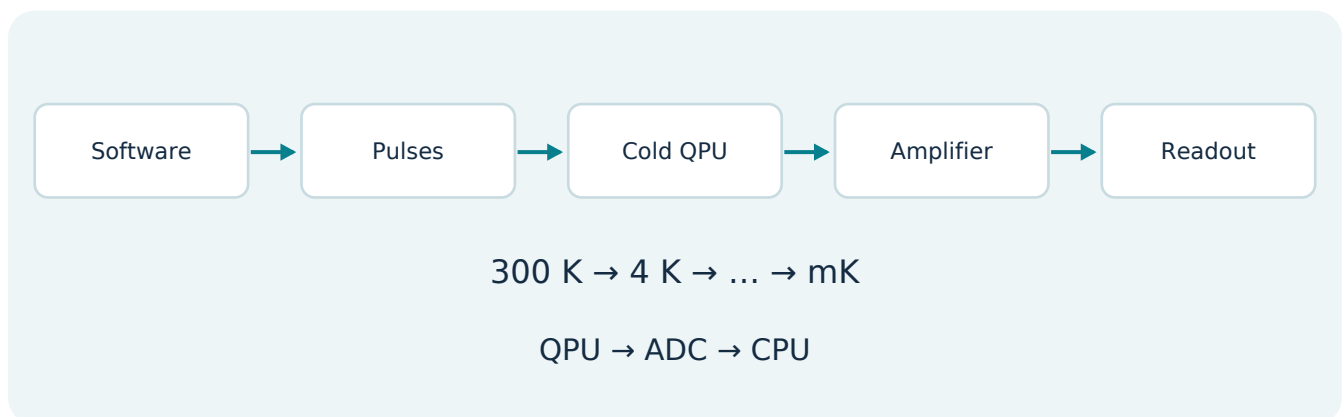
A working system needs preparation, addressing, entangling interactions, readout, reset and calibration. Connectivity determines which qubits can interact directly. Routing may insert SWAP operations and increase both runtime and error. Leakage moves a system outside its intended two-level subspace; crosstalk allows one control operation to disturb another qubit.

Fabrication yield, packaging, optical alignment, vacuum systems and wiring can matter as much as a record gate fidelity. Modular processors need fast, reliable links and protocols that account for failed entanglement attempts. Analog simulation and annealing use different control models from universal gate circuits, so their qubit counts and performance figures are not directly interchangeable. [R1, R3, R8]

10 Control electronics, optics and cryogenics

For a superconducting processor, classical software requests pulses; waveform generators and microwave components shape them; filtered and attenuated lines deliver them to a cold chip. Readout signals return through amplification and digitization. A decoder or feedback controller may need to respond within the timing constraints of error correction.

A dilution refrigerator supplies a sequence of temperature stages; millikelvin operation does not mean absolute zero. More wires introduce heat, noise and packaging constraints. Cryogenic CMOS and multiplexing aim to reduce this burden, but power dissipation and fidelity must be measured. Ion and neutral-atom systems depend strongly on lasers, vacuum and optical control, rather than sharing the same refrigeration requirements. Some photonic detectors still need cryogenic cooling. These schematics are functional explanations, not construction specifications. [R8, R3, R21]



Original educational diagram 05. Functional superconducting control chain; the return signal requires amplification and digitization.

11 Noise and error correction

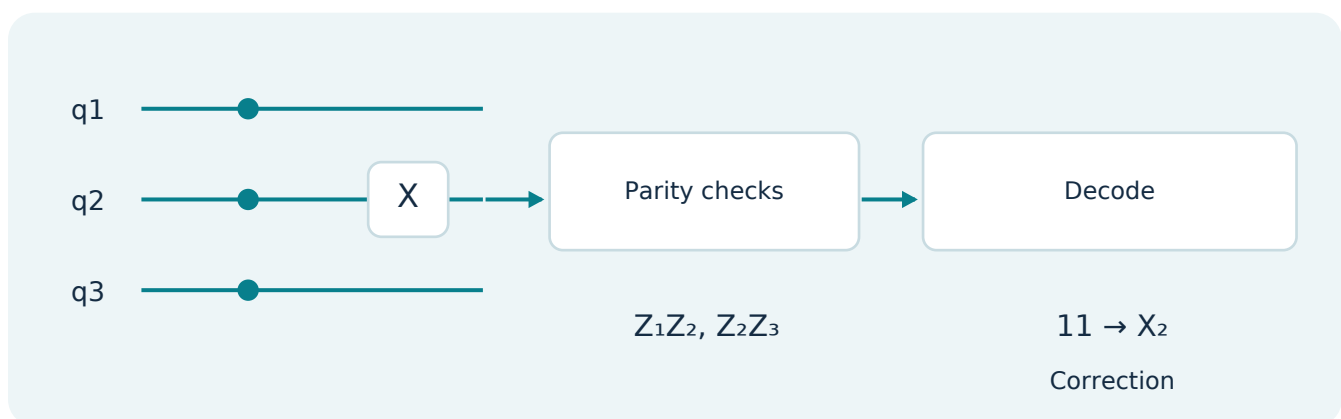
Relaxation (often characterized by T_1) changes excitation populations; dephasing reduces phase coherence (T_2). Gate and measurement errors, loss and correlated disturbances have different effects. Error mitigation estimates less-biased results through extra sampling or modelling; it does not generally provide scalable fault tolerance.

Quantum error correction encodes logical information across physical degrees of freedom and measures error syndromes without directly reading the logical amplitudes. A three-qubit repetition code maps $\alpha|0\rangle + \beta|1\rangle$ to $\alpha|000\rangle + \beta|111\rangle$ and can correct a single bit flip under its assumed error model; it cannot correct arbitrary phase errors. Full protection needs richer codes. Syndrome measurements themselves can fail and therefore usually must be repeated. [R4, R12]

12 Logical qubits and fault tolerance

A surface code uses local parity checks on a lattice. Code distance controls the smallest undetectable logical error, and increasing distance costs more physical qubits. Below a suitable noise threshold, logical error can decrease as code size grows. The threshold depends on the noise model, circuits and decoder; it is not a universal hardware specification.

Fault tolerance also requires reliable logical gates, state preparation, measurements and real-time decoding. Some non-Clifford operations need expensive auxiliary resources such as distilled magic states. Bosonic codes and quantum LDPC codes explore alternative tradeoffs. A protected memory demonstration does not establish a complete useful fault-tolerant computer. Resource estimates must specify the algorithm, target failure probability, physical noise, cycle time, code and connectivity. [R4, R13]



Original educational diagram 06. Three-qubit bit-flip code: parity syndromes identify a single bit flip; phase errors are not corrected.

13 The quantum software stack

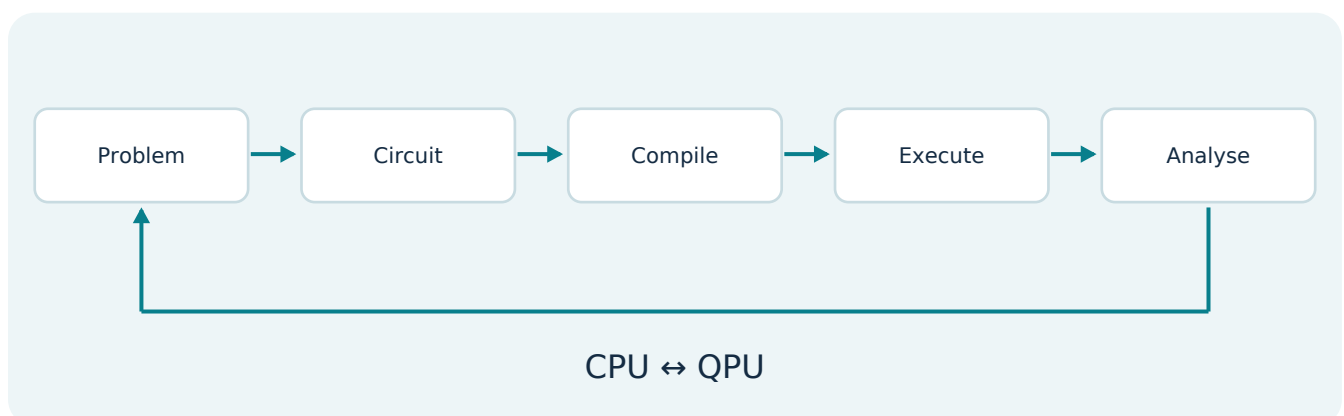
A typical workflow starts with a problem model and a classical baseline. An algorithm becomes a circuit or another intermediate representation. Compilation decomposes operations into native gates, chooses physical qubits and routes interactions. Scheduling and pulse control connect the program to the device. Measurement samples return to classical post-processing, and hybrid methods repeat this loop.

Frameworks such as Qiskit, Cirq and PennyLane support parts of this workflow; OpenQASM provides a language for describing quantum programs. Interfaces and supported features change, so runnable examples should pin versions and cite current documentation. A simulator may model ideal states, noisy channels or special circuit structures. Classical simulation cost depends on the structure, not only qubit count. Preserve code, seeds, compilation choices, calibration records and raw outcomes for reproducibility. [R14, R15]

14 Benchmarks that answer meaningful questions

Report physical and logical qubits separately. Useful metrics include gate and readout error, coherence, connectivity, circuit depth, throughput, logical error per cycle and total time to a target precision. Randomized benchmarking estimates error under assumptions; cross-entropy and application benchmarks ask different questions. A single score hides tradeoffs.

A credible advantage claim identifies the task and accuracy, includes state preparation, repetitions and classical overhead, and compares with the best relevant classical methods. Verify results or use an appropriate statistical validation procedure. Distinguish an experiment difficult to simulate from an economically useful application. Vendor roadmaps are forecasts. A laboratory record from one calibration run is not automatically a sustained production capability. [R1, R16, R20]



Original educational diagram 07. Software workflow: measurements return to classical analysis and may trigger another run.

15 Communication and the quantum internet

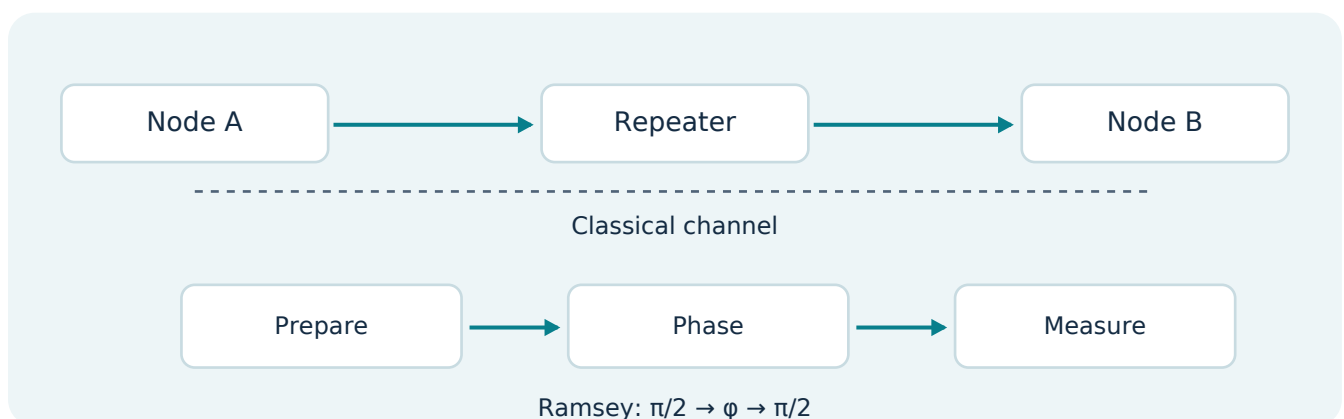
Photons can carry quantum states through fibre or free space. Loss grows with distance, and an unknown state cannot be amplified by ordinary copying. Quantum repeaters aim to combine entanglement generation, memories and entanglement swapping, sometimes purification or error correction, to extend usable links.

Teleportation transfers a quantum state using a shared entangled pair and two classical bits in the standard qubit protocol; it does not move matter or bypass light-speed limits. Networks could connect processors, distribute keys or improve joint sensing. Demonstrated links and small networks are important, but a universal, scalable quantum internet remains a development goal. Trusted-node key networks and repeater-based entanglement networks offer different security and functionality. [R3]

16 Sensors and precision measurement

Quantum sensors translate a field, acceleration or frequency into changes of a controlled quantum state. In a Ramsey sequence, a first pulse creates coherence, free evolution accumulates a signal-dependent phase, and a second pulse converts phase to a measurable population. Atomic clocks, atom interferometers and spin-based magnetometers implement related ideas.

For independent ideal probes, statistical precision commonly improves as $1/\sqrt{N}$. Entangled resources can offer stronger scaling under suitable assumptions, but noise, loss, preparation and readout can erase that benefit. Evaluate sensitivity, bandwidth, spatial resolution, drift and operating environment together. Some quantum sensing technologies are mature; many biomedical or distributed applications remain research projects and should not be described as validated diagnostic devices. [R5, R17]



Original educational diagram 08. Quantum links need classical coordination. Ramsey sensing converts phase into a measurable signal.

17 Post-quantum cryptography versus QKD

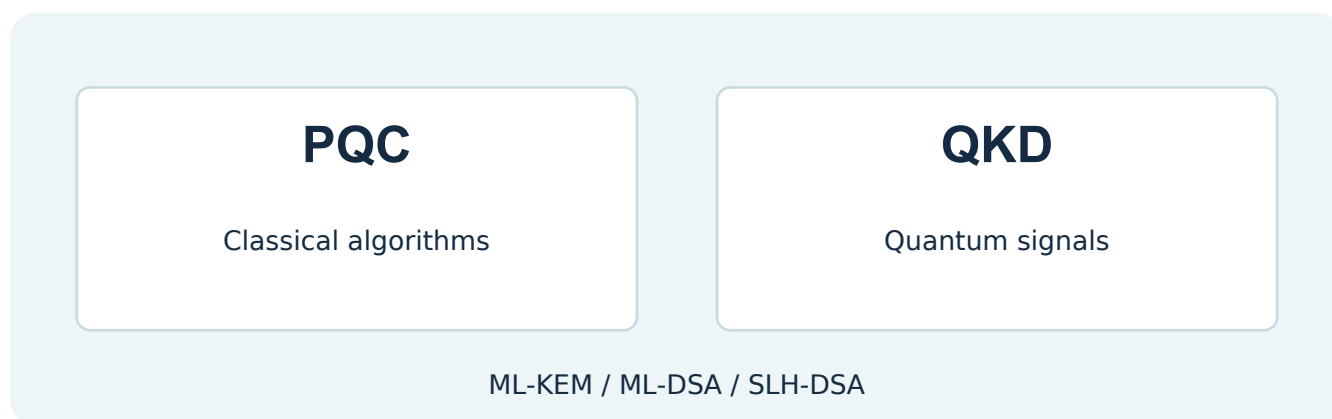
Post-quantum cryptography (PQC) uses classical algorithms designed to resist known classical and quantum attacks. It runs on classical infrastructure. NIST's 2024 FIPS 203 specifies ML-KEM for key establishment; FIPS 204 and 205 specify ML-DSA and SLH-DSA digital signatures. These are different functions, not three interchangeable encryption methods.

Quantum key distribution (QKD) uses quantum signals plus an authenticated classical channel to establish keys under explicit assumptions. It does not by itself authenticate identities, secure compromised endpoints or eliminate implementation attacks. PQC migration requires a cryptographic inventory, protocol compatibility testing and maintained implementations; this guide is not a deployment specification. Long-lived secrets motivate attention to “harvest now, decrypt later”. Consult current standards, errata and security guidance before implementation. [R6, R7, R9, R18]

18 Evidence at the 2026 review date

Published experiments establish controllable processors, quantum communication links and progress in logical error suppression. Google's surface-code work, first published online in December 2024 and appearing in Nature in 2025, reports below-threshold behaviour in a specific experimental setting. It does not demonstrate arbitrary large-scale fault-tolerant applications. The 2025 milli-kelvin CMOS spin-control study addresses a concrete integration bottleneck. [R13, R8]

DARPA's Quantum Benchmarking Initiative asks whether industrially useful quantum computation can be achieved by 2033; the date is a programme target, not a guaranteed arrival time. No single ranking captures all platforms or applications. This edition uses selected verified milestones rather than an exhaustive record table; performance claims should always be read with their publication date, assumptions and benchmark. [R16]



Original educational diagram 09. PQC uses classical hardware; QKD requires quantum signals and authenticated classical communication.

19 Future directions: conditional, not inevitable

Leading directions include more reliable logical operations, lower-overhead codes, better decoders, modular interconnects, improved fabrication and integrated control. Heterogeneous systems could assign memory, computation and communication to different physical platforms. DARPA HARQ studies this integration problem; the programme does not establish that heterogeneous machines will universally outperform other architectures. [R19]

Quantum machine learning, neuromorphic proposals, topological encodings and distributed sensing remain active areas with different levels of evidence. Claims of universal exponential acceleration, unlimited parallel answers or technology beyond quantum physics are unsupported. A useful roadmap specifies a testable milestone: logical accuracy, sustained runtime, link success rate or end-to-end application benefit. Forecasts need assumptions and should be revised when evidence changes. [R1, R2, R16]

20 Learning path and exercises

Begin with vectors, complex numbers, probability and small circuits. Work through H, X and CNOT on paper, then reproduce them in an ideal simulator. Add a simple noise model and compare distributions. Study one hardware platform, then syndrome extraction and logical operations. Use the library manifest to move from introductory resources to reviews and original experiments.

Exercise 1: If $\alpha = \sqrt{3}/2$ and $\beta = 1/2$, what is $P(1)$? Answer: $1/4$. Exercise 2: Why can 00/11 counts alone not prove entanglement? Answer: a classical mixture gives the same counts. Exercise 3: For 1,000 independent shots with $p = 1/2$, the standard deviation of the count is $\sqrt{(1000 \times 1/2 \times 1/2)}$, about 15.8. Exercise 4: Does a repetition code correct every qubit error? Answer: the three-qubit bit-flip code does not correct general phase errors.



Original educational diagram 10. Research milestones are conditional; arrows are not delivery promises.

21 Reading the library responsibly

Each external entry records its author, topic, original source, license, verification date and publication recommendation. Local PDF copies are included only where checked terms permit this use. Free access without a redistribution grant is treated as link-only. NonCommercial restrictions are not assumed compatible with a company website. Original third-party files are preserved unchanged and are not relabelled as LIGHT BRIDGE GROUP publications.

The master guide and its conceptual figures are original educational material created for LIGHT BRIDGE GROUP. References support factual claims but do not imply endorsement by the cited institutions. Bibliographic titles remain in their original language so they can be found reliably. Recheck external links and publication errata periodically, especially for cryptographic standards.

01 → 06 → 11 → 17

R10 Introduction to Classical and Quantum Computing, 1st edition, 4th printing

R1 Quantum Computing in the NISQ era and beyond

R2 Quantum algorithms: an overview

R4 A Short Introduction to Quantum Error Correction

R3 Quantum networks with neutral atom processing nodes

R5 Quantum sensing

R21 A Quantum Engineer's Guide to Superconducting Qubits

R6 FIPS 203: Module-Lattice-Based Key-Encapsulation Mechanism Standard

Bibliography and further reading

R1 John Preskill / Caltech (2018). Quantum Computing in the NISQ era and beyond.

<https://quantum-journal.org/papers/q-2018-08-06-79/>

R2 Ashley Montanaro / University of Bristol (2016). Quantum algorithms: an overview.

<https://www.nature.com/articles/npjqi201523>

R3 Jacob P. Covey; Harald Weinfurter; Hannes Bernien (2023). Quantum networks with neutral atom processing nodes.

<https://www.nature.com/articles/s41534-023-00759-9>

R4 Thiago Lucena de Macedo Guedes (2026). A Short Introduction to Quantum Error Correction.

<https://link.springer.com/article/10.1007/s13538-026-02007-9>

R5 C. L. Degen; F. Reinhard; P. Cappellaro (2017). Quantum sensing.

<https://arxiv.org/abs/1611.02427>

R6 National Institute of Standards and Technology (NIST) (2024). FIPS 203: Module-Lattice-Based Key-Encapsulation Mechanism Standard.

<https://csrc.nist.gov/pubs/fips/203/final>

R7 National Institute of Standards and Technology (NIST) (2024). FIPS 204: Module-Lattice-Based Digital Signature Standard.

<https://csrc.nist.gov/pubs/fips/204/final>

R8 Bartee, Samuel K. et al. (2025). Spin-qubit control with a milli-kelvin CMOS chip.

<https://www.nature.com/articles/s41586-025-09157-x>

R9 National Institute of Standards and Technology (NIST) (2024). FIPS 205: Stateless Hash-Based Digital Signature Standard.

<https://csrc.nist.gov/pubs/fips/205/final>

R10 Thomas G. Wong / Creighton University (2023). Introduction to Classical and Quantum Computing, 1st edition, 4th printing.

<https://www.thomaswong.net/>

R11 John Preskill / Caltech (updated chapters). Lecture Notes for Physics 219: Quantum Computation.

<https://www.preskill.caltech.edu/ph219/index.html>

R12 Joschka Roffe (2019). Quantum Error Correction: An Introductory Guide.

<https://arxiv.org/abs/1907.11157>

R13 Google Quantum AI and Collaborators (2024 online / 2025 volume). Quantum error correction below the surface code threshold.

<https://www.nature.com/articles/s41586-024-08449-y>

R14 IBM Quantum (2026). IBM Quantum documentation and learning.

<https://quantum.cloud.ibm.com/docs/en/guides>

R15 OpenQASM contributors (2026). OpenQASM Live Specification.

<https://openqasm.com/>

R16 DARPA (2026). Quantum Benchmarking Initiative (QBI).

<https://www.darpa.mil/research/programs/quantum-benchmarking-initiative>

R17 Daniele Faccio / University of Glasgow (2024). The future of quantum technologies for brain imaging.

<https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.3002824>

R18 Valerio Scarani; Helle Bechmann-Pasquinucci; Nicolas J. Cerf; Miloslav Dusek; Norbert Lutkenhaus; Momtchil Peev (2009). The Security of Practical Quantum Key Distribution.

<https://arxiv.org/abs/0802.4155>

R19 DARPA (2025-2026). Heterogeneous Architectures for Quantum (HARQ).

<https://www.darpa.mil/research/programs/heterogeneous-architectures-for-quantum>

R20 Akel Hashim et al. (2025). Practical Introduction to Benchmarking and Characterization of Quantum Computers.

<https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.6.030202>

R21 Philip Krantz; Morten Kjaergaard; Fei Yan; Terry P. Orlando; Simon Gustavsson; William D. Oliver (2019). A Quantum Engineer's Guide to Superconducting Qubits.

<https://arxiv.org/abs/1904.06560>

Created by LIGHT BRIDGE GROUP | lbgroup.rs. Version 1.0, 26 September 2026. Original text, translations and diagrams prepared for LIGHT BRIDGE GROUP. This edition has not undergone independent scientific peer review. External publications retain their authorship and separate licenses. The English and Serbian editions contain the same scope; translations preserve the scientific distinctions.