Quantum Computing: A Contemporary Review of Qubit Platforms, Algorithms, Error Correction, and Emerging Applications

Thamer A. Alamoudi
Quantum Technologies and Advanced Computing Institute
King Abdulaziz City for Science and Technology (KACST)
Riyadh, Saudi Arabia

ABSTRACT
Quantum computation exploits superposition, entanglement, interference, and measurement to process information. Research has moved from theoretical algorithms to functional devices where the performance is not only limited by qubit physics, but also by the control, compilation, error mitigation, and error correction. This review considers quantum computing on various levels of abstraction, including physical qubits, quantum algorithms, system architecture, fault-tolerance, and emerging applications. Study-specific evidence regarding scale, operational quality, connectivity, control and suppression of errors is compared across the different types of superconducting circuits, trapped ions, semiconductor spin qubits, neutral atoms and photonic processors. The review of the fundamental algorithms, noisy intermediate-scale quantum computing, variational and hybrid quantum-classical approaches, quantum simulation, quantum machine learning, and security implications is also discussed. Measurable progress has been demonstrated in published experiments for logical-qubit operation, below-threshold surface-code memory, programmable photonic sampling and platform-specific scaling. However, the reported metrics are not directly interchangeable, and practical advantage remains task- and baseline-dependent. Further progress will need to be accompanied by coordinated developments in hardware reliability, error correction, classical control, estimates of algorithmic resources, and clear classical method comparisons.

General Terms
Quantum computing; quantum information science; algorithms; computer architecture; security

Keywords
Quantum computing; qubits; quantum algorithms; NISQ; quantum error correction; quantum architecture; quantum machine learning; post-quantum cryptography

1. INTRODUCTION
A complementary computational method is called quantum computing, in which information is encoded, manipulated and measured based on quantum-mechanical principles. It is motivated by the fact that certain tasks such as simulating quantum systems, structured algebraic problems, and certain search or optimisation processes may require resources that differ from those required by classical approaches. Quantum computing is not a replacement for classical computing; it provides another model where quantum states, unitary transformations, interference and measurement are all computational resources [1].

The field has matured from algorithmic speedups in theory to processor, control, compiler, error correction protocol and application-specific field engineering. While the existing processors are still vulnerable to noise and decoherence, there are experimental advances in superconducting circuits, trapped ions, semiconductor spin qubits, neutral atoms and photonic processors. There are various technological traits to each platform. Evaluation, thus, is not just about physical qubit number, but also about high-quality qubits, connectivity, stability and calibration, error correction, classical control, and demonstrating computational advantage in specific tasks [1]-[6].

This review will explore quantum computing from three complementary angles – physical implementation of the qubit, algorithmic models that offer computational advantage and architectural requirements for fault tolerance. It deals with qubit platforms, fundamental and NISQ algorithms, hybrid quantum-classical algorithms, quantum error correction, applications and quantum-security implications. Seminal studies are kept for conceptual foundations, the comparative evaluation with a focus on recent peer-reviewed experiments and official standards.

In Section 2, the qubit states and quantum operations are introduced. In Section 3, the top hardware platforms are compared. In Section 4, basic and hybrid quantum-classical algorithms are studied. Section 5 covers computer architecture and access to the cloud, while Section 6 deals with decoherence, error correction and migrating to logical qubits. Section 7 reviews some recent advances and uses of experiments. Technical challenges and research directions are discussed in Section 8, and the conclusion in Section 9.

1.1 Review Scope and Evaluation Framework
Evidence was synthesised using five criteria: demonstrated physical or logical scale; operational quality, including gate, readout, or logical error; connectivity and control; evidence of error suppression or fault tolerance; and the strength of the classical baseline or application benchmark. These dimensions were kept separate because the different questions they address in experiments are answered by qubits, optical modes, logical error rates, quantum volume, and sampling runtimes. For this reason, Tables 1 and 2 detail study-specific evidence and limitations, rather than a composite platform ranking and Figure 4 provides a chronological evidence map.

2. BACKGROUND OF QUANTUM COMPUTATION
In a classical computer, information is encoded in bits, which are 0 or 1. Qubits are two-level systems (specified by state vectors) that encode information in quantum computers. A pure qubit is described by the state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, with complex

amplitudes α and β such that $|\alpha|^2 + |\beta|^2 = 1$. Measurement maps the quantum state to a classical outcome according to the Born rule. As a result, even if the evolution of any given system is deterministic, the result of any specific measurement is probabilistic.

Superposition is the ability of a qubit to occupy a coherent combination of basis states, and entanglement is the ability of a composite state to be that which, in general, cannot be factored into independent states of its constituent qubits. Computational advantage is not automatically bestowed by either property. Advantage requires an algorithm that uses interference so that amplitudes of desired outcomes increase while those of undesired outcomes decrease. This distinction lies between the loose analogy of quantum parallelism and the actual design and analysis of quantum algorithms, or programs.

Reversible quantum operations are implemented through gates represented by unitary matrices. Single-qubit gates, including Pauli rotations and the Hadamard gate, change the position of a state on the Bloch sphere. Two-qubit operations such as controlled-NOT, controlled-phase, and hardware-native entangling gates create correlations that independent classical bits cannot represent. A universal gate set can approximate an arbitrary quantum circuit to a desired precision, provided that gate fidelity is sufficient and coherence persists for the required circuit duration.

Several criteria remain influential when assessing whether a physical system can support quantum computation. DiVincenzo identified scalable physical qubits, initialisation, coherence, universal gate operations, and measurement as core requirements [2]. Modern engineering adds system-level needs, including cryogenic or optical infrastructure, automated calibration, low-latency classical feedback, fault-tolerant compilation, and high-throughput verification. Figure 1 provides an author-generated contrast between classical and quantum information encoding.

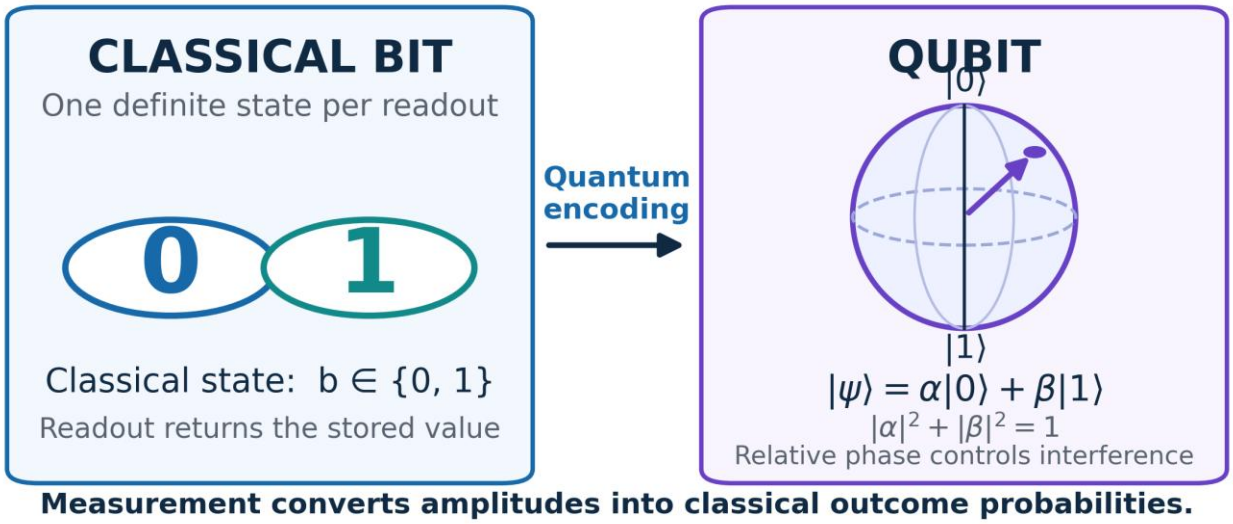

Figure 1. Conceptual distinction between a classical bit and a qubit state.

Source: *Author-Created.*

Figure 1 shows the difference between state representation and the measurement outcome. A classical bit stores one definite value, whereas a qubit stores two complex amplitudes whose magnitudes determine the probabilities of 0 and 1 and whose relative phase controls interference. This does not imply that both answers are read at once; one outcome from the measurement is read, and multiple shots estimate the distribution of the outcomes. A useful computation thus must be based on ideal preparation of the initial state, gates that preserve the phases of the constituent states, and interference that enhances the desired outcomes and suppresses the alternatives.

3. QUBIT TECHNOLOGIES

The physical qubit is the central engineering component of a quantum computer. Different platforms encode qubit states in trapped-ion levels, electron or nuclear spins in semiconductors, neutral-atom hyperfine or Rydberg states, superconducting circuits, or photonic modes. These choices determine the dominant noise mechanisms, connectivity, operating environment, gate speed, fabrication route, and scaling strategy.

Superconducting qubits are Josephson-junction circuits operated at millikelvin temperatures. They offer fast gates, microwave control, and compatibility with lithographic fabrication. Superconducting processors have demonstrated random-circuit sampling and increasingly complex error-correction cycles [3], [5], [6]. Their engineering constraints include classical-control bandwidth, calibration drift, materials loss, leakage, crosstalk, packaging, and cryogenic wiring.

Trapped-ion processors store qubits in long-lived internal ionic states confined by electromagnetic fields. They support high-fidelity state preparation and measurement, long coherence times, and all-to-all or reconfigurable interactions in several architectures. Experiments have demonstrated fault-tolerant logical operations and processor designs that permit qubit transport and reuse [7], [8]. Scaling nevertheless requires advances in optical delivery, ion shuttling, sympathetic cooling, trap fabrication, and control electronics.

Semiconductor spin qubits encode information in electron or nuclear spins in quantum dots or donor systems. Their small footprint and potential compatibility with semiconductor manufacturing make them attractive for dense integration [9]. High-fidelity silicon logic and universal control in multi-qubit arrays have been demonstrated [10], [11]. Key challenges include charge noise, electrostatic tuning, isotopic purification, microwave integration, readout, and device-to-device uniformity.

Neutral-atom systems use optically trapped atoms arranged in programmable arrays. Rydberg interactions enable entangling operations, while optical tweezers provide flexible geometry and reconfiguration. A logical processor based on reconfigurable atom arrays demonstrated encoded operations using hundreds of physical qubits [12]. Large arrays and connectivity are important strengths, although atom loss, gate fidelity, laser stability, and rapid mid-circuit operations remain active engineering challenges.

Photonic processors encode information in optical modes, polarisation, time bins, or paths. Photons support room-temperature propagation and communication, while measurement-based models use entangled resource states for computation. Programmable photonic processors have demonstrated quantum computational advantage in sampling experiments [13]. Scaling requires efficient sources, low-loss interferometry, fast feedforward, high-efficiency detection, and integration with error-corrected architectures.

No single platform satisfies every requirement simultaneously. A meaningful comparison must therefore use multiple metrics rather than physical-qubit count alone. Table 1 summarises the principal platform-level advantages and constraints, while Figure 2 shows the system stack required to turn physical qubits into usable quantum computations.

Table 1. Comparative Overview of Leading Qubit Platforms

Platform	Principal advantages	Key constraints and representative sources
Superconducting circuits	Fast gates, lithographic fabrication, microwave control, and active error-correction demonstrations	Cryogenic overhead, crosstalk, materials loss, leakage, calibration drift [3], [5], [6]
Trapped ions	Long coherence, high-fidelity operations, flexible connectivity, qubit movement, and reuse	Optical complexity, shuttling, motional control, modular scaling [7], [8]
Semiconductor spins	Compact devices, possible CMOS compatibility, dense integration	Charge noise, device variability, tuning, readout integration [9]-[11]
Neutral atoms	Large arrays, programmable geometry, Rydberg-mediated interactions	Atom loss, gate fidelity, optical stability, mid-circuit measurement [12]
Photonic processors	Room-temperature propagation, communication compatibility, measurement-based models	Source efficiency, loss, feedforward, detector integration [13]

As shown in Table 1, the selection of the platform is a multi-criteria decision. Superconducting circuits are the combination of fast gates and lithography fabrication, but come with a cryogenic, crosstalk, leakage, and calibration burden. Trapped ions are more coherent, more faithful and more flexible in connectivity, albeit at the expense of optical and transport complexity. Semiconductor spins can provide high density, neutral atoms can enable a large array that can be reconfigured, and photonics can enable propagation that's compatible with communication. However, if the advantage is different from the control/scaling bottleneck, the number of qubits in a system alone cannot determine scalability or readiness for applications.

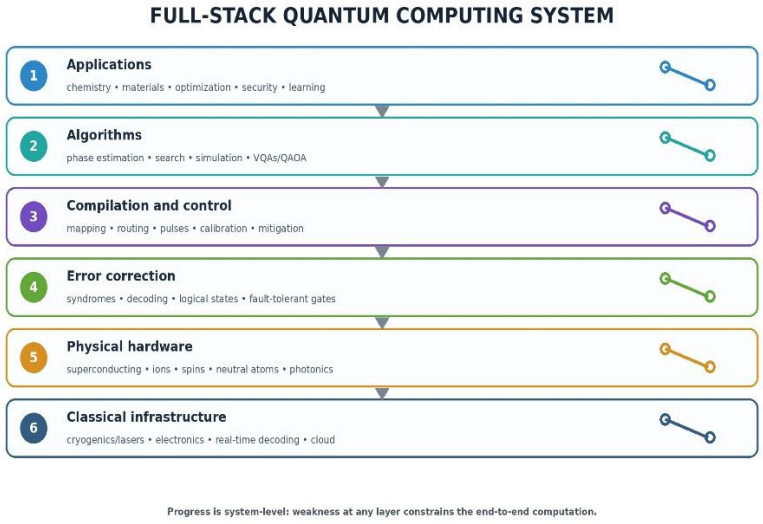

Figure 2. Layered view of a quantum computing system.
Source: Author-Created synthesis based on [1], [4], and [14].

Figure 2 shows that quantum performance is an end-to-end system property. Hardware quality is insufficient unless compilation preserves native connectivity and gate efficiency, error correction or mitigation controls accumulated error, and classical infrastructure provides timely calibration and decoding. In the opposite direction, application precision and resource requirements constrain algorithm design, circuit depth, and acceptable logical error. Progress at one layer becomes practically meaningful only when it can be integrated with the layers above and below it.

4. QUANTUM ALGORITHMS AND HYBRID QUANTUM-CLASSICAL COMPUTING

Coherent evolution may be used to transform non-classical resources into verifiable computational gain in quantum algorithms. Shor's algorithm brought factoring and discrete logarithms into the quantum circuit model, thereby linking quantum computing to public-key cryptography [15]. Grover's algorithm provided a quadratic query improvement for unstructured search [16]. Lloyd demonstrated that one quantum system can efficiently simulate another, a principle fundamental to quantum chemistry and materials science [17].

Noisy intermediate-scale quantum (NISQ) devices, which can perform non-trivial circuits but are not fault-tolerant, strongly influence the design of current algorithms. NISQ methods include shallow-circuit design, hybrid quantum-classical optimisation, noise-aware compilation, and error mitigation. Major approaches include variational eigensolvers, quantum approximate optimisation, quantum simulation, and application-oriented benchmarking [4], [14].

Variational quantum algorithms constitute one of the most explored NISQ approaches. A parameterised circuit is set up, a trial state is prepared, and measurements are made to estimate an objective function, which is then optimised using a classical optimiser that updates circuit parameters. This loop is the basis for the variational quantum eigensolver and the quantum approximate optimisation algorithm. Although hardware adaptability is advantageous, barren plateaus, measurement cost, optimisation instability, noise, and problem-dependent trainability can limit performance [18].

One such application is quantum simulation, in which the controlled system can act as a substitute for another system. Near-term chemistry workflows use variational methods, active-space approximations, and error mitigation, whereas long-term proposals rely on phase estimation and fault-tolerant logical qubits [17], [19]. Any claims of practical value should include precision targets, as well as resource estimates, state-preparation and measurement costs and comparison with strong classical chemistry benchmarks.

Quantum machine learning is the fusion of quantum circuits and learning systems. It contains quantum models of classical or quantum data, the proposed acceleration of learning procedures, and machine learning for characterising the hardware. There is evidence to suggest the advantage is application-specific and not general. To be meaningful, however, the evaluation needs proper data encoding, expressivity analysis, noise handling, training-cost accounting and comparison with optimised classical baselines [20], [21].

5. QUANTUM COMPUTER ARCHITECTURE AND CLOUD ACCESS

A quantum computer is not just a series of qubits; it is an integrated system of hardware, controllers, compilers, calibration routines, measurement systems, classical processors and user interfaces. The architecture influences how algorithms are mapped to hardware, how errors are detected and corrected, and how the quantum and classical components interact during execution. Applications, hardware constraints, and software should consequently be co-designed [1].

In the hardware, it is essential to isolate qubits from environmental noise, while keeping them coupled for gates, measurement and feedback. This tension leads to several problems in the layout of qubits, connectivity between qubits, allocation of frequencies, scheduling of gates, cooling, multiplexed readout and signal routing.

Quantum compilers convert high-level programs into circuits that work with a processor's native set of gates and connectivity. Compilation may involve routing, gate decomposition, pulse control, timing and hardware-specific optimisation. Compilation and error mitigation go hand in hand on NISQ processors: extra routing and circuit depth may have a significant impact on output fidelity.

Cloud access has made quantum processors available without local cryogenic or optical infrastructure, supporting prototyping, education, benchmarking, and comparison across backends. Its limitations include queue times, restricted pulse-level control, calibration drift, backend variability, and incomplete insight into hardware noise. Reproducible cloud experiments should report the backend, execution date, shot count, transpilation settings, calibration data, and error-mitigation procedure.

Future architectures will integrate quantum processing units with high-performance classical processors. The classical layer will submit circuits and also coordinate calibration, decoding, scheduling, optimisation, and feedback. Low-latency processing is especially important for error correction, where syndrome data must be decoded quickly enough to prevent the correction loop from overwhelming quantum-memory timescales.

6. DECOHERENCE, ERROR CORRECTION, AND FAULT TOLERANCE

Decoherence is the loss of quantum coherence through coupling between a system and its environment. In a processor, it interacts with gate errors, leakage, crosstalk, state-preparation errors, measurement errors, and classical-control imperfections. Error rate is therefore a system-level outcome of materials, fabrication, control, calibration, architecture, and operating conditions rather than a single fixed property of a qubit.

Quantum error correction encodes one logical qubit across multiple physical qubits. Syndrome measurements reveal information about errors without directly measuring the encoded state. The surface code is widely studied because it uses local interactions on a two-dimensional layout and can tolerate comparatively high physical error under suitable noise assumptions. Error correction becomes useful when adding physical qubits lowers the logical error rate rather than introducing more error than the code can remove.

Experiments have advanced the practical status of quantum error correction. Repeated surface-code cycles have been demonstrated in superconducting circuits [22], followed by error suppression with increasing code distance and below-threshold memory with real-time decoding [3], [5]. Trapped-ion systems have demonstrated fault-tolerant control of encoded qubits [7], while bosonic and qudit experiments have reported beyond-break-even memory behaviour in specific encodings [23], [24].

Fault-tolerant computing requires more than one logical memory: it needs logical state preparation, gates, measurements, repeated correction cycles, decoding, and resource management at sufficiently low error. Resource estimates reveal the engineering scale. Under specified surface-code assumptions, Gidney and Ekerå estimated that factoring RSA-2048 in eight hours would require about 20 million noisy

physical qubits and highly optimised fault-tolerant circuits [25].

Error mitigation differs from error correction because it estimates improved expectation values from noisy measurements without encoding logical qubits. Methods include zero-noise extrapolation, probabilistic error cancellation, symmetry verification, and measurement-error mitigation. These approaches may support near-term workloads, but they often incur substantial sampling overhead and do not enable arbitrarily long computations. Figure 3 summarises the closed-loop logic of encoding, syndrome extraction, decoding, and correction.

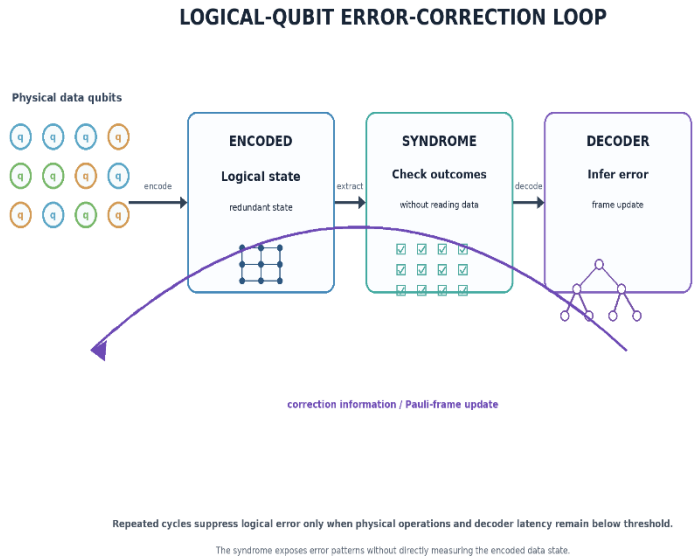

Figure 3. Logical-qubit encoding and syndrome-based correction loop.

Source: *Author-Created synthesis based on [3], [5], and [22].*

Figure 3 illustrates the closed-loop correction process, in which physical data qubits are used to store a logical state, syndrome measurements are used to detect check violations, a classical decoder is used to infer a likely error, and the correction/pauli-frame is used to close the loop. Reliability is determined by repeated errors per cycle and how this changes as code distance is varied, since only a small pattern is seen in a single cycle. Extra redundancy helps reduce logical error below the threshold, but can increase it above the threshold. Latency and correlated errors in the decoder are hence fundamental measures of performance.

7. RECENT DEVELOPMENTS AND APPLICATIONS

Quantum computational-advantage experiments verify that a processor can perform a clearly defined sampling/computation more efficiently than the most efficient classical processors. Superconducting and photonic processors have been used in such demonstrations [6], [13], [26]. Their scientific relevance is to test hardware scaling, classical simulation limits and validation methods. Their practical value depends on whether the task maps to a useful application and whether the full quantum-classical cost is favourable.

Long-term candidate applications include quantum chemistry, materials simulation, cryptanalysis of quantum-vulnerable public-key schemes, selected scientific simulations, and quantum communication or post-quantum workflows. Quantum simulation is closely connected to the hardware because controllable quantum systems can represent other quantum systems [17], [19]. Practical chemistry workflows still need to account explicitly for state-preparation and measurement costs, resource counts, logical operations, and accurate problem mappings.

Optimisation claims are highly problem-specific. However, any relevant advantage of QAOA or similar variational / annealing-inspired circuits must be compared to optimised classical heuristics, including data loading/preprocessing, and transparently include the entire hybrid workflow [4], [18]. Optimisation should therefore not be regarded as a current application advantage but be seen as an active research direction.

For quantum machine learning, the same type of benchmarking is needed. Possible applications include hybrid models in which trainable quantum circuits are used as components within a larger pipeline, as well as quantum-data and kernel methods. Ill-defined or weak comparative baselines, encoding cost, noise, optimisation effort, sample complexity, and uncertainty must be considered [20], [21].

Cybersecurity is already affected by quantum computing because a future fault-tolerant implementation of Shor's algorithm would threaten RSA and elliptic-curve cryptography [15], [25]. NIST has finalised post-quantum key-encapsulation and signature standards in FIPS 203, FIPS 204, and FIPS 205 [27]-[29]. Migration to quantum-resistant cryptography is therefore a present policy and engineering requirement, even though the arrival date of cryptographically relevant quantum computers remains uncertain.

7.1 Comparative Evaluation of Representative Experimental Evidence

Table 2 summarises some of the typical experimental setups and results that have been reported on the various platforms. The metrics used come from the original studies and are interpreted within their experimental context and not normalised to a single score. This approach preserves quantitative detail while avoiding invalid comparisons between logical memory, gate fidelity, quantum volume, and sampling speed.

Table 2. Representative Experimental Results and Evaluation Boundaries

Platform/evidence	Study-specific configuration or result	What the result demonstrates	Evaluation boundary
Superconducting QEC [3]	101-qubit distance-7 surface-code memory; 0.143% ± 0.003% error per cycle; Λ = 2.14 ± 0.02; logical lifetime 2.4 ± 0.3 times the best physical qubit.	Below-threshold logical memory with real-time decoding and measurable error suppression as code distance increases.	Memory benchmark, not yet a full fault-tolerant application with a universal logical gate set.
Trapped-ion QCCD [8]	32 qubits; SPAM error $1.6(1) \times 10^{-3}$; one-qubit infidelity $2.5(3) \times 10^{-5}$; two-qubit infidelity $1.84(5) \times 10^{-3}$; QV = 2^{16}.	High operational quality with qubit transport, reuse, system benchmarks, and 32-qubit GHZ entanglement.	Scaling still depends on transport scheduling, optical delivery, cooling, and control complexity.
Silicon spin [10]	Universal control of a six-qubit processor with measurement-based initialisation, real-time feedback, and two- and three-spin entangled-state tests.	Integrated control, initialisation, readout, and calibration across a larger semiconductor spin array.	Scale remains modest; uniform fabrication, tuning, readout, and crosstalk must be sustained in larger arrays.
Neutral atom [12]	Up to 280 physical qubits; 40 colour-code qubits; circuits with up to 48 logical qubits, 228 logical two-qubit gates, and 48 logical CCZ gates.	Programmable logical processing, error-detected algorithmic improvement, and reconfigurable connectivity at scale.	Reported encodings and tasks do not by themselves establish universal fault-tolerant operation.
Photonic GBS [13]	216 squeezed modes; 36 µs per sample; exact classical estimate above 9,000 years per sample; events up to 219 photons.	Large, dynamically programmable Gaussian boson-sampling experiment with task-specific computational advantage.	Sampling result is not equivalent to general-purpose speedup or demonstrated application utility.
Superconducting RCS [26]	105-qubit processor; 83-qubit, 32-cycle random-circuit sampling; 10^6 samples in hundreds of seconds; reported fidelities of 99.90%, 99.62%, and 99.13% for one-qubit gates, two-qubit gates, and readout.	High-scale random-circuit execution with a very large estimated classical simulation cost.	Classical cost is model- and algorithm-dependent, and the sampled task is not a direct practical application.

Three distinct forms of evidence emerge from Table 2. First, component and system benchmarks quantify control quality, as in the trapped-ion and silicon demonstrations. Second, logical-qubit experiments test whether added redundancy improves reliability, as shown by the superconducting and neutral-atom results. Third, sampling experiments compare a specialised quantum task with estimated classical cost, as in the photonic and superconducting RCS studies. None of these results alone establishes general application advantage: each must be judged against its task, uncertainty, validation method, and classical baseline.

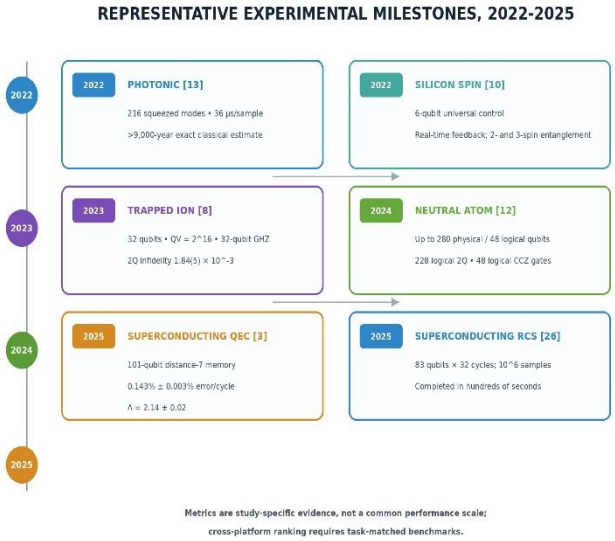

Figure 4. Evidence map of representative experimental milestones from 2022 to 2025.

Source: *Author-Created synthesis of results reported in [3], [8], [10], [12], [13], and [26].*

Experimental emphasis started to spread between 2022 and 2025, with the addition of large, photonic sampling systems, mobile trapped-atom architectures, programmable logical neutral-atom circuits and below-threshold, superconducting memory. The sequence suggests movement across a number of orthogonal axes, not towards a single 'winning' platform. It also provides the rationale for the need to maintain the original metric and experimental edge of every outcome in a valid evaluation.

8. CHALLENGES AND FUTURE DIRECTIONS

The main challenge is to move from a noisy physical system to reliable logical computation. It demands simultaneous progress in fabrication, control stability, error rate, connectivity, readout fidelity, calibration, automation and real-time classical processing. Without corresponding improvements in error rates and system integration, increasing the number of physical qubits is necessary but not sufficient.

Scalability has a different meaning for each platform. For superconducting circuits it includes cryogenic integration, microwave routing, materials, packaging, and multiplexed control; for trapped ions, transport, optical control, trap fabrication, and modular interconnects; for semiconductor

spins, CMOS-compatible fabrication, variability, tuning, and dense readout; for neutral atoms, atom loss, laser stability, gate fidelity, and mid-circuit measurement; and for photonics, source efficiency, loss, switching, feedforward, and detector integration.

Benchmarking is a methodological challenge due to the fact that different properties are measured by qubit counts, quantum volume, circuit fidelity, randomised benchmarking, cross-entropy benchmarking, algorithmic qubits and logical error rates. One metric alone cannot ensure application performance. A high value on one metric does not guarantee application performance. Reproducible reports should specify circuit depth, native gates, connectivity, noise and calibration conditions, shot budget, uncertainty, decoder or mitigation settings, and the classical baseline.

Claims of quantum advantage must be qualified as both hardware and classical algorithms continue to improve. A sampling task that is difficult to simulate today may become easier after an algorithmic advance. A robust claim therefore needs a precise task definition, transparent assumptions, validation tests, uncertainty, a reproducible comparison procedure, and a clear statement of computational usefulness.

Future research will emphasise reliable logical qubits, modular processors, error-corrected memory, low-latency decoding, hardware-tailored algorithms, domain-specific resource estimates, and integration with classical high-performance computing. Table 3 summarises the corresponding challenges and research directions.

Table 3. Major Challenges and Research Directions in Quantum Computing

Challenge	Technical significance	Research direction
Noise and decoherence	Limits circuit depth and reduces output reliability	Materials improvement, shielding, calibration, error correction, error mitigation
Scaling physical qubits	Increases wiring, control, fabrication, and verification complexity	Modular architectures, multiplexing, integrated control, automated tuning
Logical-qubit overhead	Fault tolerance requires many physical qubits per logical qubit	Efficient codes, better decoders, improved physical fidelity, resource-aware compilation
Benchmarking and validation	Different metrics capture different aspects of performance	Application benchmarks, transparent reporting, strong classical baselines
Cybersecurity migration	Current public-key systems are vulnerable to future fault-tolerant quantum attacks.	Post-quantum cryptography, hybrid migration, asset discovery, protocol updates

Table 3 indicates that the central barriers are coupled, not independent. Reduction in physical error results in a reduction in logical-qubit overhead; better packaging (and control) enables larger codes; faster decoding can enable real-time error correction; and transparent benchmarks indicate whether these improvements hold at the application level. Cybersecurity migration is different in timing but similar in systems character: it requires coordinated inventory, standards adoption, protocol updates, and interoperability rather than one isolated technical change.

9. CONCLUSION

Quantum computing has evolved into a multidisciplinary engineering and science discipline that includes quantum physics, computer hardware, algorithms, control and domain expertise. The information-theoretic building blocks are qubits, but computation needs reliable devices, classical infrastructure, scalable architectures and algorithms tailored to the capabilities of these systems.

Recent experiments report the steps towards the use of logical qubits, multiple corrections, real-time decoding, and system-level benchmarking from discrete physical-qubit demonstrations. Superconducting circuits, trapped ions, semiconductor spins, neutral atoms and photonics have different advantages and limitations. This variety creates the opportunity of taking multiple paths towards fault tolerance, but also makes it impossible to make a universal platform ranking based on any single measure.

The use of simulation, variational methods, benchmarking, and hardware-aware software will continue to be stressed in the near term. In chemistry, materials science, cryptanalysis and some scientific simulations, longer-term value is more likely to be based upon fault-tolerant logical computation. Lower logical error, lower resource overhead, scalable control, and comparisons with the best classical approaches, matched to the tasks at hand, will be required to achieve it.

Quantum computers therefore should not be viewed either as replacements for classical computers or as an abstract theory divorced from engineering. They are new computational accelerators whose scientific and practical significance will depend on reproducible end-to-end performance.

10. REFERENCES

[1] Y. Alexeev et al., "Quantum computer systems for scientific discovery," PRX Quantum, vol. 2, no. 1, Art. no. 017001, Feb. 2021, doi: 10.1103/PRXQuantum.2.017001. [Online]. Available: https://doi.org/10.1103/PRXQuantum.2.017001

[2] D. P. DiVincenzo, "The physical implementation of quantum computation," Fortschritte der Physik, vol. 48, no. 9-11, pp. 771-783, 2000, doi: 10.1002/1521-3978(200009)48:9/11<771::AID-PROP771>3.0.CO;2-E. [Online]. Available: https://doi.org/10.1002/1521-3978(200009)48:9/11%3C771::AID-PROP771%3E3.0.CO;2-E

[3] R. Acharya et al., "Quantum error correction below the surface code threshold," Nature, vol. 638, no. 8052, pp. 920-926, Feb. 2025, doi: 10.1038/s41586-024-08449-y. [Online]. Available: https://doi.org/10.1038/s41586-024-08449-y

[4] K. Bharti et al., "Noisy intermediate-scale quantum algorithms," Reviews of Modern Physics, vol. 94, no. 1, Art. no. 015004, Feb. 2022, doi: 10.1103/RevModPhys.94.015004. [Online]. Available: https://doi.org/10.1103/RevModPhys.94.015004

[5] R. Acharya et al., "Suppressing quantum errors by scaling

a surface code logical qubit," Nature, vol. 614, pp. 676-681, Feb. 2023, doi: 10.1038/s41586-022-05434-1. [Online]. Available: https://doi.org/10.1038/s41586-022-05434-1

[6] Y. Wu et al., "Strong quantum computational advantage using a superconducting quantum processor," Physical Review Letters, vol. 127, no. 18, Art. no. 180501, Oct. 2021, doi: 10.1103/PhysRevLett.127.180501. [Online]. Available: https://doi.org/10.1103/PhysRevLett.127.180501

[7] L. Egan et al., "Fault-tolerant control of an error-corrected qubit," Nature, vol. 598, pp. 281-286, Oct. 2021, doi: 10.1038/s41586-021-03928-y. [Online]. Available: https://doi.org/10.1038/s41586-021-03928-y

[8] S. A. Moses et al., "A race-track trapped-ion quantum processor," Physical Review X, vol. 13, no. 4, Art. no. 041052, Dec. 2023, doi: 10.1103/PhysRevX.13.041052. [Online]. Available: https://doi.org/10.1103/PhysRevX.13.041052

[9] G. Burkard, T. D. Ladd, J. M. Nichol, A. Pan, and J. R. Petta, "Semiconductor spin qubits," Reviews of Modern Physics, vol. 95, no. 2, Art. no. 025003, Jun. 2023, doi: 10.1103/RevModPhys.95.025003. [Online]. Available: https://doi.org/10.1103/RevModPhys.95.025003

[10] S. G. J. Philips et al., "Universal control of a six-qubit quantum processor in silicon," Nature, vol. 609, pp. 919-924, Sep. 2022, doi: 10.1038/s41586-022-05117-x. [Online]. Available: https://doi.org/10.1038/s41586-022-05117-x

[11] X. Xue et al., "Quantum logic with spin qubits crossing the surface code threshold," Nature, vol. 601, pp. 343-347, Jan. 2022, doi: 10.1038/s41586-021-04273-w. [Online]. Available: https://doi.org/10.1038/s41586-021-04273-w

[12] D. Bluvstein et al., "Logical quantum processor based on reconfigurable atom arrays," Nature, vol. 626, pp. 58-65, Feb. 2024, doi: 10.1038/s41586-023-06927-3. [Online]. Available: https://doi.org/10.1038/s41586-023-06927-3

[13] L. S. Madsen et al., "Quantum computational advantage with a programmable photonic processor," Nature, vol. 606, pp. 75-81, Jun. 2022, doi: 10.1038/s41586-022-04725-x. [Online]. Available: https://doi.org/10.1038/s41586-022-04725-x

[14] J. Preskill, "Quantum computing in the NISQ era and beyond," Quantum, vol. 2, Art. no. 79, Aug. 2018, doi: 10.22331/q-2018-08-06-79. [Online]. Available: https://doi.org/10.22331/q-2018-08-06-79

[15] P. W. Shor, "Polynomial-time algorithms for prime factorisation and discrete logarithms on a quantum computer," SIAM Journal on Computing, vol. 26, no. 5, pp. 1484-1509, Oct. 1997, doi: 10.1137/S0097539795293172. [Online]. Available: https://doi.org/10.1137/S0097539795293172

[16] L. K. Grover, "A fast quantum mechanical algorithm for database search," in Proceedings of the 28th Annual ACM Symposium on Theory of Computing, 1996, pp. 212-219, doi: 10.1145/237814.237866. [Online]. Available: https://doi.org/10.1145/237814.237866

[17] S. Lloyd, "Universal quantum simulators," Science, vol. 273, no. 5278, pp. 1073-1078, Aug. 1996, doi: 10.1126/science.273.5278.1073. [Online]. Available: https://doi.org/10.1126/science.273.5278.1073

[18] M. Cerezo et al., "Variational quantum algorithms," Nature Reviews Physics, vol. 3, pp. 625-644, Aug. 2021, doi: 10.1038/s42254-021-00348-9. [Online]. Available: https://doi.org/10.1038/s42254-021-00348-9

[19] D. Claudino, "The basics of quantum computing for chemists," International Journal of Quantum Chemistry, vol. 122, no. 23, Art. no. e26990, 2022, doi: 10.1002/qua.26990. [Online]. Available: https://doi.org/10.1002/qua.26990

[20] M. Schuld and N. Killoran, "Is quantum advantage the right goal for quantum machine learning?" PRX Quantum, vol. 3, no. 3, Art. no. 030101, Jul. 2022, doi: 10.1103/PRXQuantum.3.030101. [Online]. Available: https://doi.org/10.1103/PRXQuantum.3.030101

[21] A. Melnikov, M. Kordzanganeh, A. Alodjants, and R.-K. Lee, "Quantum machine learning: From physics to software engineering," Advances in Physics: X, vol. 8, no. 1, Art. no. 2165452, 2023, doi: 10.1080/23746149.2023.2165452. [Online]. Available: https://doi.org/10.1080/23746149.2023.2165452

[22] S. Krinner et al., "Realising repeated quantum error correction in a distance-three surface code," Nature, vol. 605, pp. 669-674, May 2022, doi: 10.1038/s41586-022-04566-8. [Online]. Available: https://doi.org/10.1038/s41586-022-04566-8

[23] V. V. Sivak et al., "Real-time quantum error correction beyond break-even," Nature, vol. 616, pp. 50-55, Apr. 2023, doi: 10.1038/s41586-023-05782-6. [Online]. Available: https://doi.org/10.1038/s41586-023-05782-6

[24] B. L. Brock et al., "Quantum error correction of qudits beyond break-even," Nature, 2025, doi: 10.1038/s41586-025-08899-y. [Online]. Available: https://doi.org/10.1038/s41586-025-08899-y

[25] C. Gidney and M. Ekerå, "How to factor 2048-bit RSA integers in 8 hours using 20 million noisy qubits," Quantum, vol. 5, Art. no. 433, Apr. 2021, doi: 10.22331/q-2021-04-15-433. [Online]. Available: https://doi.org/10.22331/q-2021-04-15-433

[26] D. Gao et al., "Establishing a new benchmark in quantum computational advantage with a 105-qubit Zuchongzhi 3.0 processor," Physical Review Letters, vol. 134, no. 9, Art. no. 090601, Mar. 2025, doi: 10.1103/PhysRevLett.134.090601. [Online]. Available: https://doi.org/10.1103/PhysRevLett.134.090601

[27] National Institute of Standards and Technology, Module-Lattice-Based Key-Encapsulation Mechanism Standard, FIPS 203. Gaithersburg, MD, USA: U.S. Department of Commerce, 2024, doi: 10.6028/NIST.FIPS.203. [Online]. Available: https://doi.org/10.6028/NIST.FIPS.203

[28] National Institute of Standards and Technology, Module-Lattice-Based Digital Signature Standard, FIPS 204. Gaithersburg, MD, USA: U.S. Department of Commerce, 2024, doi: 10.6028/NIST.FIPS.204. [Online]. Available: https://doi.org/10.6028/NIST.FIPS.204

[29] National Institute of Standards and Technology, Stateless Hash-Based Digital Signature Standard, FIPS 205. Gaithersburg, MD, USA: U.S. Department of Commerce, 2024, doi: 10.6028/NIST.FIPS.205. [Online]. Available: https://doi.org/10.6028/NIST.FIPS.205