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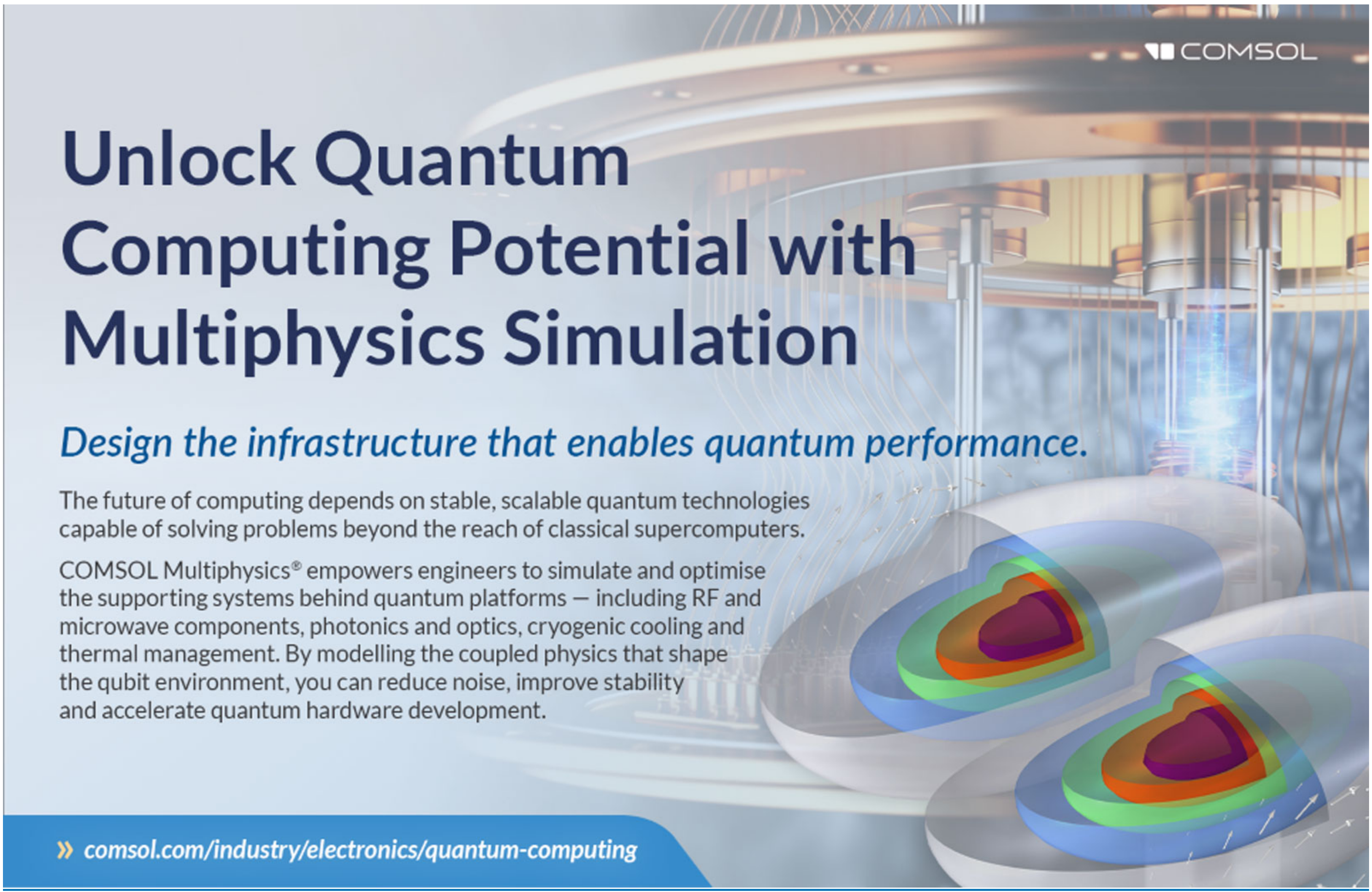

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Quantum foundations for quantum technologies in the International Year of Quantum (2025)

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Abstract

From the very beginning, quantum mechanics has been accompanied by crucial foundational questions: the possibility of visualizing physical processes, the limits of measurement epitomized by Heisenberg's uncertainty principle, the existence of a deeper underlying reality with additional degrees of freedom, the role of measurements, and the status of locality. Long regarded as philosophical speculations, these issues were progressively reformulated into precise mathematical statements and ultimately subjected to experimental verification. The trajectory proved unpredictable: questions once dismissed as metaphysical gave rise to experimental platforms, which in turn matured into devices and technologies powering quantum computation, communication, and sensing. Yet this development is not unidirectional: advances in technology also feed back into foundations, enabling tests of principles that were previously out of reach—for example, whether quantum superposition persists at larger and larger scales and whether reality, gravity included, is fundamentally quantum. In this way, the dialogue between foundational inquiry and technological progress continues to shape both our theoretical understanding and the practical realization of quantum phenomena.

1. 1925–2025: from debates to devices

Quantum mechanics has challenged the scientific worldview since its inception, and the famous debate between Einstein and Bohr [1] made the challenge explicit: for Einstein, quantum mechanics was astonishingly accurate yet incomplete—correct to a very high degree but not offering the full picture of elementary processes—whereas for Bohr it was the complete and correct framework for microscopic phenomena and their observation.

Well before the famous EPR paper, Einstein had already pressed the point[1] at the 1927 Solvay Conference [3]: he considered a single particle whose wave function is spread out in space and asked what happens when its position is detected. He remarked that '*the interpretation according to which* $|\psi|^2$ *expresses the probability that* this *particle is found at the given point assumes an entirely peculiar mechanism of action at a distance, which prevents the wave continuously distributed in space from producing an action in* two *places on the screen. In my opinion, one can remove this objection only in the following way, that one does not describe the process solely by the Schrödinger wave, but at the same time one localizes the particle during the propagation*.' In other words, for a delocalized wave function, a position measurement that (randomly) finds the particle here entails with certainty that it cannot be found elsewhere; then, either there are nonlocal correlations—what happens here constrains what can happen there, in principle far away—or the outcomes were predetermined, as in a classical statistical model. Taking locality for granted, as

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[1] Howard [2] documents threads of Einstein's thinking about the incompleteness of Quantum Theory even before 1927.

Einstein did, only the latter option remains: the properties of the particle must be predetermined, and therefore the quantum-mechanical description offered by the wave function is incomplete.

The 1935 EPR paper [4] presents essentially the same argument: locality + quantum correlations in far away places → pre-determined properties, which in turn implies the incompleteness of quantum theory; as a matter of fact, the paper ends by saying: '*While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible.*' The EPR paper is important because it uses a decisive new ingredient: entanglement between two particles, to encode perfect correlations across space-like separations. That conceptual move furnished the raw material for Bell's inequalities and for later generations to explore quantum resources to their full potential.

Bohr's reply the same year [5] defended completeness, by insisting on the holistic character of quantum phenomena and on complementarity as a constraint on what can be jointly defined and observed. But actually, the first reaction of Bohr to Einstein's argument at the 1927 Solvey conference was [3]: '*I feel myself in a very difficult position because I do not understand what precisely is the point which Einstein wants to [make]. No doubt it is my fault.*' The community's reaction mixed admiration for Einstein with a tendency to dismiss his concern as metaphysical scruple; as Pauli quipped in a 1954 letter to Born [6], '*One should no more rack one's brain about the problem of whether something one cannot know anything about exists all the same than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einstein's questions are ultimately always of this kind.*'

This historical trajectory matters: since the EPR era, entanglement has transformed from a philosophical irritant into the central resource of quantum information science, and today's quantum technologies owe their superior capabilities to precisely those features—entanglement and coherence—that enable tasks unattainable by classical means. That is an apt message for the *International Year of Quantum (2025)*: foundations and technology advance together in a feedback loop in which fundamental questions are distilled into mathematical models susceptible to experimental verification; those models stimulate laboratory tests and generate new technological platforms and protocols, which in turn make it possible to address sharper open questions.

2. Bell's turn: nonlocality and the rise of quantum networks

Although the EPR paper initially received comparatively little attention, Bohm gave it new life and clarity in his textbook reformulation of quantum theory [7], recasting the argument in terms of a pair of spin-1/2 particles prepared in the singlet state, and then sent to distant parties Alice and Bob. Because for a singlet state spin measurements are perfectly anti-correlated along any common axis, if Alice measures the spin along the z direction, represented by the operator σ_z and obtains, say, $+1$, she can infer with certainty that Bob's outcome for σ_z will be -1. Under the locality assumption—Alice's choice and outcome cannot affect Bob's distant system—this licenses an 'element of reality' for Bob particle's σ_z value prior to his measurement. But the same reasoning holds if Alice instead measures along x (or any other direction), so Bob's particle must likewise possess predetermined values for non-commuting observables such as σ_x and σ_z simultaneously. The conclusion is again: locality + perfect quantum correlations → predetermined properties → the wave function is incomplete. Bohm's formulation preserved the spirit of EPR while stripping away technicalities, recasting the argument in terms of states and observables that can be more easily prepared and measured in the laboratory, thereby setting the stage for Bell's inequalities.

The unexpected twist in this story was Bell's 1964 theorem [8]. Bell shared Einstein's worries about the status of quantum theory as a fundamental description of nature and wrote about them repeatedly [9]. He was especially intrigued by de Broglie–Bohm pilot-wave theory [10–12] because it offered a clear, unambiguous dynamics for particles guided by the wave function, thus avoiding any special status for 'measurements' and 'observers'. But the price was explicit nonlocality, and this troubled him. Bell then asked whether such nonlocality was a peculiarity of Bohmian mechanics or an unavoidable feature of *any* theory reproducing the quantum predictions for entangled systems. This is the context in which he derived his famous theorem.

As Bell explains in his 1964 paper, the starting point is precisely the EPR logic in the version of Bohm: under *locality*, the perfect anticorrelations of a singlet pair imply that the outcomes of spin measurements are predetermined (there exist what now are called hidden varaibles). Bell's next step shows that any *local hidden-variable* theory must satisfy certain constraints—Bell inequalities—on joint statistics for space-like measurements along different directions. Quantum mechanics violates those constraints for appropriate choices of settings.

Two remarks are in order. First, in the EPR era the focus was on perfect (anti)correlations obtained when Alice and Bob measure along the *same* spin axis. Bell's key insight was to step away from that trivial case and ask what happens for different measurement directions—precisely where one might expect nothing surprising. The surprise was there: locality imposes quantitative constraints on those cross-axis statistics, captured by Bell's inequality. Second, 'elements of reality' (predetermined values, hidden variables, or what now is sometimes called realism) are not an independent assumption of Bell's theorem. In Bell's 1964 analysis they arise only via the EPR step: locality plus perfect (anti)correlations $\rightarrow$ predetermined outcomes. Bell was clear about this [13]: '*It as only in the context of perfect correlation (or anticorrelation) that determinism could be inferred* [inferred, not assumed, Ed. note] ... *Note well then that the following argument makes no mention whatever of determinism*'. Bell in fact presents in this 1981 paper an alternative derivation of his inequalities, which dispenses with the EPR premise and with perfect anticorrelations altogether, and relies only on Bell's locality together with freedom of settings, to reach the same conclusion: no local theory can reproduce the observed quantum correlations.

The question then passes to experiment: do real systems obey or violate Bell inequalities? Pioneering tests in the 1970s [14] and early 1980s [15, 16] observed violations consistent with quantum mechanics; later 'loophole-free' experiments have confirmed this conclusion with increasingly stringent controls [17–19]. This incredible experimental effort resulted in 2022 the Nobel Prize in Physics awarded to Aspect, Clauser and Zeilinger for 'establishing the violation of Bell inequalities and pioneering quantum information science'.

The upshot is clear: no local theory can account for the observed correlations. In Bell's own terms, the world is *nonlocal*—though in a way that still respects the no-signalling constraints of relativity, since these correlations cannot be used for superluminal communication. That tension remains conceptually striking: entangled, spacelike-separated systems display correlations that defy any local description, and this directly contradicts the hope, voiced in EPR, that a local completion of quantum mechanics might someday be found.

The practical consequences are profound. A measured Bell violation certifies the presence of nonclassical correlations *from statistics alone*, enabling *device-independent* (DI) guarantees in which security or correctness can be established without assuming a detailed or trusted model of the internal functioning of the devices involved. In quantum communication, this idea goes back to Ekert's entanglement-based QKD [20] and was put on a fully DI footing by works showing that observed nonlocality alone implies secrecy against general (even memory-bearing) adversaries [21–24]. These protocols are agnostic to vendor specifics: mismodelling of sources, detectors, or side channels cannot fake a Bell violation large enough to pass the security threshold so long as the spacetime and independence conditions enforced in the analysis are satisfied. In networked scenarios, teleportation [25] and entanglement swapping [26] serve as primitives for quantum repeaters [27]. *Teleportation* transfers an *unknown* quantum state from Alice to Bob by *consuming* a shared Bell pair and sending two classical bits that encode the outcome of a Bell-state measurement (BSM) performed by Alice; conditioned on those bits, Bob can reconstruct the input state, with no quantum signal traversing the channel during the transfer. *Entanglement swapping* extends entanglement over distance: if nodes A–B and B–C each share an EPR pair, a BSM at the intermediate node B projects the remote systems at A and C into an entangled state—heralded by B's classical outcome—even though A and C never interacted. *Quantum repeaters* combine these basic building blocks to overcome the rapid degradation of quantum signals in direct transmission, allowing quantum correlations to be distributed reliably over long distances and thereby enabling tasks such as entanglement-based (and DI) QKD, clock and network synchronization, distributed sensing, and interconnects for modular quantum computing.

3. Foundations for engineering

Foundational results developed after Bell's theorem proved equally powerful in practice and, crucially, capable of being combined and extended. Again, the central question is (non)locality and whether quantum theory admits a completion in terms of additional hidden variables. And again, Bell changed the game.

Contextuality is the failure of a natural, classical-looking assumption: that the outcome assigned to an observable A reflects a pre-existing property of the system *alone* and is *independent* of which other, compatible observables are measured alongside A (the *measurement context*). In a naïve—*noncontextual*, in modern language—hidden-variable picture, one seeks a single value map v that assigns predetermined outcomes to all observables once and for all. The assignment cannot be arbitrary: if a projective measurement is described by orthogonal projectors $\{P_i\}$ with $\sum_i P_i = I$, one demands $v(P_i) \in \{0,1\}$

and $\sum_i \nu(P_i) = 1$, i.e. exactly one outcome 'fires'. A series of no-go results [28–31] makes this program untenable for Hilbert-space dimension $d > 2$. For a time this was read as the end of any deeper (Einsteinian) description, despite the fact that a concrete completion—Bohmian mechanics—already existed.

Bell's 1966 analysis clarified the landscape [32]. He pinpointed which assumptions in early proofs were unwarranted. The price of a completion is that outcomes generally *depend on the full measurement arrangement*—as in de Broglie–Bohm theory, which is explicitly contextual (and nonlocal) [11]. Ironically, it is the orthodox quantum stance that saves hidden variables: measurement outcomes are not mere readouts of pre-existing properties but are defined by the *interaction* of system and apparatus. Put differently, one cannot cleanly separate 'the property of the system' from 'the act of measurement'. The recorded result is a property of the joint system–context pair: *The result of an observation may reasonably depend not only on the state of the system (including hidden variables) but also on the complete disposition of the apparatus* [32].

Beyond foundations, this distinction has very practical consequences. A large and important class of quantum circuits, the *stabilizer* circuit—that is, a quantum circuit consisting solely of controlled-NOT, Hadamard, and phase gates—can be simulated efficiently on a classical computer (Gottesman–Knill theorem). In other words, those dynamics admit a noncontextual description and do not by themselves yield a computational advantage [33, 34]. To go beyond that regime one must inject new ingredients, typically in the form of specially prepared *magic states*. These states fail to admit any noncontextual model; they exhibit interference patterns that classical samplers cannot track efficiently. This is why contextuality is now viewed as a *fuel* for quantum computation [35, 36]. In short, Bell's 1966 lesson—hidden variables are not excluded *per se*, only *noncontextual* ones are—maps cleanly onto engineering: to outrun classically simulable stabilizer dynamics, a scalable device must supply a steady throughput of magic states and preserve enough coherence for them to do useful work.

The *no-cloning* theorem [37, 38] and its mixed-state extension, *no-broadcasting* [39] forbid making perfect copies of unknown quantum states. From a foundational standpoint, no-cloning is crucial because it blocks superluminal signalling: proposals such as Herbert's FLASH device [40] attempted to exploit entanglement plus hypothetical cloning to transmit information faster than light, but no-cloning closes that route. No-cloning and no-broadcasting then migrated from conceptual curiosities to architectural constraints: they forbid naive signal amplification in long-distance links, thereby motivating repeater architectures and error-corrected memories; in cryptography, they underwrite the intuition that adversaries cannot make perfect copies of unknown quantum states (a pillar behind prepare-and-measure and entanglement-based QKD).

Finally, the logic of *quantum error correction* reconciles fragility of quantum states with scalability by encoding information nonlocally so that local noise induces detectable signatures: stabilizer and CSS codes [33, 41, 42] and topological/surface codes [43, 44] make faults *identifiable* and *correctable* while preserving global coherence, and threshold theorems [45, 46] guarantee reliability below a constant physical error rate.

4. From many to one, and back to many

Schrödinger, not only Einstein, was deeply uneasy about the status of quantum mechanics as a theory of nature. His famous 'cat' paradox [47] was meant precisely to dramatize the oddity of applying the linear superposition principle to macroscopic objects: if the theory is taken at face value for individual systems, it seems to predict superpositions of mutually exclusive macroscopic states, which clashes with our experience. The same unease surfaces in his reflections on experimental practice: '*We never experiment with just* one *electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences*' [48]. Read charitably and in context, these statements capture a widespread 1930s–1950s view: quantum mechanics was exquisitely successful as a calculus for *ensembles*—be it ensembles of atoms in condensed-matter systems or of photons in laser physics—while genuine single-particle preparation and control seemed unattainable.

The ensuing history has, of course, rewritten that expectation. Starting from ensembles, advances in laser cooling and trapping put individual atoms at our fingertips: the 1990s toolbox (laser cooling, sub-Doppler techniques, optical molasses and magneto-optical traps) is exemplified by the first MOT [49] and by the observation and theory of (sub-Doppler) cooling [50, 51]. Within a few years, ensembles were driven across a new frontier with the first Bose–Einstein condensates in dilute gases (rubidium at JILA; sodium at MIT), demonstrating macroscopic matter-wave coherence [52, 53]. In parallel on the photonic side, quantum optics matured from ensemble descriptions of fields to exquisitely controlled nonclassical light: Glauber's 1963 papers provided the quantum theory of optical coherence and photon statistics [54, 55], while the advent of *frequency combs* linked optical and microwave frequencies with phase-coherent precision, enabling modern optical clocks and precision metrology [56, 57].

The conceptual leap from 'many' to 'one' became reality with direct manipulation of *individual* quantum systems: cavity-QED experiments 'saw' single photons without destroying them and tracked their quantum jumps [58, 59], while trapped-ion platforms observed quantum jumps in a single ion and achieved ground-state cooling, enabling coherent single-quanta control [60–63]. Foundationally, this was a turning point: the single-system regime that Schrödinger had regarded as practically out of reach became a working laboratory, where superposition, entanglement, and measurement back-action could be prepared, witnessed, and recycled on demand.

With those tools in hand, the field effectively 'closed the loop': having learned to isolate and manipulate single atoms and photons, researchers began to assemble controlled *few-* and *many-body* structures from the bottom up, with the explicit aim of realizing programmable quantum simulators and scalable quantum information processors. Optical lattices loaded with ultracold atoms enabled faithful realizations of Hubbard-model physics with tunable interactions, disorder, and dimensionality; quantum-gas microscopes subsequently pushed these systems to single-site resolution and control, turning textbook lattice Hamiltonians into directly imageable and programmable matter-wave circuits [64–66]. In parallel, Rydberg-atom arrays assembled by optical tweezers provided defect-free registers with strong, controllable interactions and native entangling gates, while trapped-ion chains and, more recently, high-cooperativity cavity and waveguide QED platforms offered complementary routes to scalable entanglement generation, coherent control, and mid-circuit measurement [67–71]. On the photonic front, integrated waveguides and deterministic emitters (semiconductor quantum dots [72]; colour centres in solids [73]) have transformed 'single-photon' generation from a conceptual milestone into an engineering specification, enabling boson-sampling tests of computational hardness and the implementation of measurement-based quantum computation with cluster states [74, 75].

Across these developments, two broad architectural paradigms have emerged for converting single-particle control into scalable quantum information processing and controlled many-body dynamics. Atomic platforms encode qubits in long-lived internal states and exploit interactions that are either mediated collectively, as in trapped-ion processors where entangling gates arise from shared motional modes, or engineered locally, as in neutral-atom systems combining the massive parallelism of quantum-gas microscopes with the programmability of optical tweezers. Photonic platforms follow a complementary strategy: rather than relying on direct interactions, they achieve universality through linear optics, high-quality single-photon sources, and photon counting, where measurement and feedforward promote passive interferometers into fully programmable quantum processors, equivalently described in the cluster-state, measurement-based paradigm.

Conceptually, these machines instantiate Feynman's program [76]: controllable quantum hardware configured to emulate quantum dynamics beyond classical reach—either by *programming gates* (digital) or by *tuning interactions* (analogue)—with foundations (entanglement, measurement back-action, and nonclassical interference) now functioning as design constraints and resources.

This progression—from ensembles to singles and back to engineered many-body systems—is not merely technical; it has reshaped how foundations and technology inform one another. Technology is now pushing toward the creation and control of ever larger quantum states. Schrödinger's cat remains a compelling parable, yet in the laboratory we routinely prepare complex superpositions (involving many particles or many photons), monitor their decoherence channels in real time, stabilize them with measurement-based feedback and error correction, and quantify how 'nonclassical' they are through operational witnesses tailored to specific tasks.

5. The math of quantum technologies

Quantum technologies ultimately draw their power—and encounter their fundamental limitations—from the mathematical structure of quantum theory itself. While many of the phenomena discussed so far can be described operationally or experimentally, a precise understanding of what can and cannot be achieved requires engaging directly with the formal language of states, transformations, and measurements. We now briefly introduce the minimal mathematical framework needed to articulate these constraints, showing how abstract structural features of quantum theory translate into concrete consequences for information processing, control, and scalability.

A compact, operational formulation of quantum theory emerges in the early '30s from the work of Dirac and von Neumann. Dirac's *Principles* [79] introduced the bra–ket calculus and spectral expansions in physics language, identifying observables with Hermitian operators on a complex Hilbert space $\mathcal{H}$ and amplitudes with inner products. Von Neumann then supplied the functional-analytic backbone [28]:

(i) states are positive trace-one operators ρ; (ii) sharp measurements are projection-valued measures obtained from the spectral theorem for self-adjoint operators; (iii) expectation values follow Born's rule $\langle A\rangle = \mathrm{Tr}(\rho A)$; and (iv) closed dynamics are unitary; in this ideal limit, pure states obey Schrödinger's equation and mixed states the von Neumann equation $\dot{\rho} = -\mathrm{i}[H,\rho]$.

Ideal *projective* measurements of an observable $A = \sum_a a\,\Pi_a$ produce outcomes with probabilities $\mathrm{Pr}(a) = \mathrm{Tr}(\rho\Pi_a)$ and update the state via the Lüders rule $\rho \mapsto \rho_a = \Pi_a\rho\Pi_a/\mathrm{Tr}(\rho\Pi_a)$ [80]. When the readout couples to an integral of motion (or a commuting observable), projective measurements can be *quantum non-demolition* (QND) [81, 82]. Real detectors, however, are seldom ideal projectors. The general statistical structure is a positive operator-valued measure (POVM): a set of effects $\{E_x\}$ with $E_x \geqslant 0$ and $\sum_x E_x = \mathbb{1}$, giving $\mathrm{Pr}(x) = \mathrm{Tr}(\rho E_x)$ [83, 84]. Naimark's dilation theorem shows any POVM arises as a projective measurement on a larger space [85].

This is all true for isolated quantum systems. However, realistic devices interact with their surroundings. Stinespring's dilation (and Kraus/Choi representations) characterizes the most general physical evolution as a completely positive, trace-preserving (CPTP) map $\Phi(\rho) = \sum_k K_k\rho K_k^\dagger$, with $\sum_k K_k^\dagger K_k = \mathbb{1}$ [86–88]. When the map is the result of a (Markovian) continuous time evolution Λ_t, the family $\{\Lambda_t\}_{t\geqslant 0}$ forms a quantum dynamical semigroup with generator in *GKSL* (Gorini–Kossakowski–Sudarshan/Linblad) form,

$$\dot{\rho} = \mathcal{L}(\rho) = -\mathrm{i}[H,\rho] + \sum_j \gamma_j\left(L_j\rho L_j^\dagger - \frac{1}{2}\left\{L_j^\dagger L_j, \rho\right\}\right),$$

the unique linear structure compatible with complete positivity, trace preservation, and semigroup composition [89–93]. This form makes explicit that the reduced dynamics of an open quantum system is fully characterized by a competition between coherent unitary evolution and irreversible dissipative processes, the latter encoding both decoherence and noise through a structure that is fixed by complete positivity and trace preservation rather than by microscopic details.

This open-systems calculus [94] has the great merit of explaining and quantifying *decoherence*: why quantum properties are progressively lost when systems interact with the surrounding environment. Quantum Brownian motion models, pioneered by Caldeira and Leggett [95, 96] and later extended to include collisional decoherence [97] and exact master-equation formulations [98], are now routinely employed to assess the impact of external and internal noise in experiments.

Between ideal projective and general POVM readouts lies the regime of *weak measurements* [99–101], which enable gentle monitoring of dynamics, direct retrieval of phases and amplitudes, and—in certain technical-noise regimes—weak-value amplification of detector signals [102–105]. Taking the continuous-time limit yields *continuous quantum measurement*. Belavkin's treatment conditions the system state on a measurement record (photon counts, homodyne currents), producing stochastic master equations (SMEs) driven by Poisson or Wiener processes; Hudson–Parthasarathy quantum stochastic calculus derive the same SMEs from field couplings [106–109]. 'Quantum trajectories' then unravel GKSL dynamics into single-shot state paths whose ensemble average reproduces the unconditional evolution [110–112].

These ingenious mathematical structures have redefined laboratory capability. In *circuit QED*, dispersive QND readout produces a homodyne current carrying information about a qubit Bloch component; the SME quantifies information gain vs backaction, enabling real-time feedback to stabilize Rabi oscillations, and even *catch and reverse* an impending quantum jump [113–117]. *In cavity and levitated optomechanics,* continuous position readout via homodyne detection implements the same SME toolkit: measurement-based feedback and optimal control cool mechanical motion to (or near) the quantum ground state and stabilize trajectories in real time, turning the standard-quantum-limit tradeoff between imprecision and backaction into an engineered resource [81, 118–120, 124]. Backaction-evading, single-quadrature measurements and QND strategies for mechanical observables further enable sub-SQL standard quantum limit force sensing and state preparation, with squeezed/filtered probes and high-cooperativity cavities suppressing added noise while preserving coherence for subsequent tasks.

Thus the same mathematics—POVMs and dilations, CPTP channels and semigroups, weak and continuous measurement SMEs—both grounds foundational debates and provides the design language for devices whose performance can be predicted, certified, and improved.

6. Technology probing foundations

Two near-term scientific frontiers show how technology now pushes back on foundations. *First: the assessment of quantumness of gravity.* Gravity is not just another force on a fixed stage—it *is* the stage:

the geometry of space and time. Turning that stage itself into a quantum object is conceptually challenging, and the usual techniques that tame infinities in other quantum field theories fail for gravity. A halfway, semiclassical picture—classical spacetime guided by quantum matter—sidesteps the deepest question: what happens when matter is in a superposition of masses or positions? These tensions motivate operational tests that can reveal whether gravity is genuinely quantum, without committing to any single theory.

Away from the Planck scale, where quantum and gravitational phenomena are expected to be equally important but remain experimentally inaccessible, a clean low-energy program asks whether gravity can act as a *quantum mediator*. The core idea is to prepare two mesoscopic masses in spatially separated superpositions and let them interact *only* via gravity; if entanglement appears, then the mediator must be quantum [125, 126]. The challenge is fundamental: gravitational interactions become stronger for larger masses and separations, while quantum control is most effective for smaller, colder, and more isolated objects. Reaching the 'sweet spot' demands aggressive gains in isolation, cryogenics, ground- and vibration-noise suppression, charge control and patch-potential mitigation, and quantum-limited readout. Reaching the 'sweet spot' demands aggressive gains in isolation, cryogenics, ground- and vibration-noise suppression, charge control and patch-potential mitigation, and quantum-limited readout. Steady progress in cavity/levitated optomechanics [118] and precision control has moved this from gedanken to campaign: ground-state cooling and quantum control of mechanical motion are now routine goals for nanoparticles and membranes [119, 120, 124]. A positive observation would be the first tabletop evidence for gravity's quantum character; a sustained null result over a carefully delimited parameter window would prune semiclassical alternatives [121–123] and redirect designs toward architectures where gravitation is operationally classical at relevant scales.

Second: objective-collapse dynamics. In standard quantum mechanics, closed systems evolve linearly and unitarily by Schrödinger dynamics, yet measurements yield single, definite outcomes with Born-rule probabilities. When a system S interacts with an apparatus A, the joint evolution produces an S–A entangled superposition; the projection postulate (Lüders/von Neumann update) then stipulates a nonunitary, stochastic 'collapse' yielding a definite outcome. The collapse however is tied to an imprecise notion of measurement, raising the question when a configuration can be called a measurement—causing the collapse of the wave function—and when it can not [9]. These tensions define the measurement problem in quantum mechanics and have led to several proposed resolutions, including objective-collapse models (GRW/CSL), hidden-variable theories (de Broglie–Bohm), and many-worlds approaches. We focus below on collapse models, which offer experimentally testable departures from Schrödinger evolution.

Spontaneous-collapse models (GRW/CSL and variants) posit a universal, weak, mass-weighted noise that localizes the wave function in position [127–130]; they predict small, testable departures from linear Schrödinger evolution that grow with system size. Two complementary strategies are closing in. Interferometric tests [131] push matter-wave coherence to higher masses and larger path separations, hunting for loss of visibility that *exceeds* environmental decoherence—progress spanning molecular interferometry to proposals for macroscopic superpositions with opto- and magneto-mechanical objects [132–135]. Noninterferometric tests [136] search for the universal momentum diffusion and spontaneous radiation implied by CSL: ultralow-noise cantilevers, levitated particles, and cryogenic resonators set bounds from excess heating and force noise [137–139], while x-ray emission constraints and bulk-heating analyses bound the collapse rate in complementary parameter regions [140, 141].

The moral in both frontiers is the same: the very techniques that power quantum technologies—ultrahigh vacuum, cryogenics, laser/charge control, ground-state cooling, quantum-limited detection, and meticulous system identification—turn deep foundational questions into empirical targets with credible error bars. Culture matters too: where the twentieth century sometimes caricatured foundations as metaphysics, the twenty-first treats them as part of physics, susceptible to theoretical and experimental investigations.

7. Conclusions

Foundations are not a preface to technology; they are its operating system. The same features of quantum theory that long appeared paradoxical—superposition, entanglement, contextuality—are precisely those that enable technological advantage when they are stabilized, controlled, and certified. The counterintuitive features of quantum mechanics that capture public imagination are the very same features that enable new forms of information processing and technological advantage. Bell's migration from philosophy to inequalities taught us how to turn conceptual questions into experimental benchmarks; the maturation of quantum control now allows us to run that logic in reverse, using advanced platforms to probe first principles themselves—whether linear quantum theory is exact at all relevant scales, whether gravity can mediate entanglement, and where the true quantum limits lie. Seen in this light, the International Year of Quantum (2025) is not only a celebration, but an invitation to let our most sophisticated devices answer our deepest questions. The dividends are twofold: for science, experiments that move long-standing debates from the speculative to the empirical; for technology, the continued drive toward more powerful devices and protocols. Ultimately, the future of quantum theory will be limited only by how boldly we allow foundational insight to shape it.

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Data availability statement

No new data were created or analysed in this study.

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