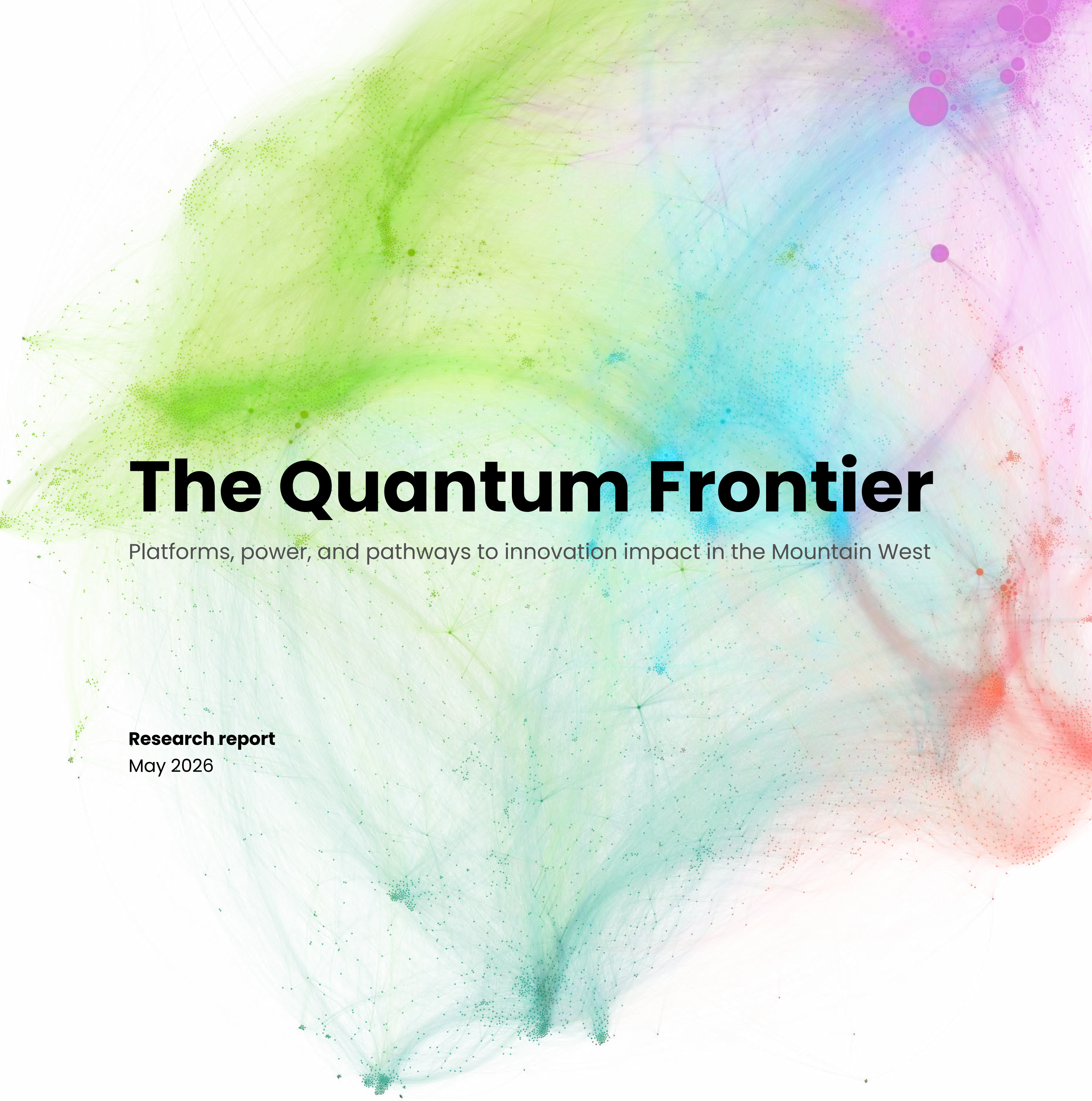

The Quantum Frontier

Platforms, power, and pathways to innovation impact in the Mountain West

Research report
May 2026

NSF | ASCEND | Innosphere TECH. SCIENCE. ACCELERATED. | OEDIT

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Acknowledgements

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Preface

Innosphere commissioned this study to assess how quantum sensing and adjacent enabling technologies are evolving, where commercialization is beginning to take shape, and how those developments may bear on U.S. NSF ASCEND Engine’s interests in advanced sensing and computation for environmental decision-making in the Mountain West. In recent years, quantum has attracted growing policy attention, investment, and strategic interest. It has also been discussed in ways that can blur important distinctions: between scientific promise and operational capability, between laboratory demonstration and real-world deployment, and between individual technical advances and the broader technical and institutional conditions that make those advances usable. This report is intended to bring sharper definition to those distinctions.

The work focuses on quantum sensing and the enabling layers that determine whether sensing capabilities can move beyond the lab: photonics, precision optics, instrumentation, control systems, materials, and integration. It asks which parts of this broader technical base are becoming more usable in practice, what still shapes the pace of translation from demonstration to repeatable field performance, and where regional strengths are most likely to matter. In a field like this, regional significance does not rest only on promising applications or standout firms. It also depends on the shared infrastructure, validation capacity, and integration capabilities that make advanced technologies reliable enough to deploy.

The study was initially framed around quantum sensing pathways with possible relevance to environmental and climate applications. As the analysis progressed, it became clear that those pathways could only be assessed credibly within the wider quantum system in which they sit. That wider view makes it possible not only to identify where the field intersects most meaningfully with advanced sensing and environmental decision-making (“ASCEND”) technologies, but also to understand those intersections in the context of shared platforms, bottlenecks, and uneven commercialization conditions. For that reason, the report treats sensing as part of a broader quantum stack rather than as a self-contained market.

The analysis is grounded in a global corpus of roughly 27,000 quantum-related inventions filed since 2010. It examines where inventive activity is concentrating, how the three quantum application areas overlap, and which enabling platforms recur across the field. The purpose is not to catalogue companies or assemble a set of technology profiles. It is to clarify the structure of the system itself: where capabilities are clustering, where dependencies are tightening, and where the path from technical progress to real-world use remains uncertain.

This report does not forecast breakthroughs or timelines. It is not a technical evaluation of specific devices, vendors, or architectures, nor a policy prescription. Its purpose is to give Innosphere and its partners a grounded way to judge what is advancing, what remains constrained, and where the Mountain West may hold a meaningful position.

Summary

Why quantum matters now

Quantum offers new capabilities in three areas every advanced economy cares about: computing, communications, and measurement. Unlike classical systems, quantum systems exploit quantum effects, such as superposition, entanglement, and interference. Those properties enable ultra-precise clocks and sensors, new approaches to secure communications, and potentially powerful computing systems for optimization, chemistry, and materials discovery. In practical terms, quantum is less like a single-product market than enabling infrastructure: closer to the transistor or GPS than to a standalone application.

The hard part is not only discovery. It is control. Quantum effects are powerful because they are delicate. They degrade under noise, vibration, temperature shifts, fabrication defects, and imperfect control. A useful quantum system must therefore do much more than demonstrate a scientific effect. It must reliably generate that effect, stabilize it, measure it precisely, calibrate it against standards, and connect it to classical electronics, software, and operational workflows. That is why the field's central challenge now lies in integration, validation, and repeatable use rather than in scientific novelty alone.

That is also why quantum has become a geopolitical issue. Countries are competing to shape the platforms, standards, interfaces, and validation regimes through which quantum capabilities become usable. In some parts of the stack, especially deployment-adjacent sensing and communications, China's centralized model has moved quickly. In enabling platforms, control layers, and collaborative system integration, the U.S.-allied model remains structurally strong. Quantum competition is therefore not a single race. It is a contest over who shapes the system that others must work through.

Why it matters to ASCEND technologies

ASCEND technologies sit closest to quantum, where real-world sensing matters most. Environmental intelligence, infrastructure monitoring, geospatial decision systems, and resilient timing and navigation all depend on whether advanced measurement can move from the lab into trusted operating environments. Quantum sensing is especially relevant because it is the first quantum application area to prove itself under real-world conditions: noise, drift, vibration, calibration burdens, legacy systems, and user trust.

The broader systems view is necessary because ASCEND-relevant applications depend on the same enabling layers that govern progress across quantum as a whole. Photonics, precision optics, instrumentation, control systems, software, and validation routines do not belong exclusively to a single quantum application area. They recur across computing, communications, and sensing. Treating ASCEND technologies as a narrow side case would therefore miss the point. ASCEND technologies are an applied frame for understanding whether the parts of quantum closest to trusted measurement and deployment are becoming real.

How quantum is actually developing

Quantum is not advancing as three independent quantum application areas. It advances as one co-evolving system. The global invention record contains roughly 27,000 quantum-related inventions filed since 2010. One-third span more than one quantum application area. The largest overlap sits between computing and communications, with 4,047 shared inventions. Another 1,545 span computing and sensing, and 895 sit at the intersection of all three. The implication is that quantum's building blocks are shared, rather than siloed.

The field is being built around a shared stack of enabling platforms. Hardware and device architectures form the physical foundation. Photonics provides light-generation, control, and readout. Precision optics and spectroscopy translate fragile effects into measurable signals. Magnetometry and interferometric measurement anchor high-sensitivity sensing and calibration. Software and systems integration make lower-layer advances usable. The field is still building these tools faster than it is scaling mature downstream applications.

Commercial progress is therefore a system-assembly problem. Materials quality, fabrication reproducibility, calibration, validation, and classical integration remain binding constraints. A quantum system may work in a lab and still fail to deploy because it cannot hold performance outside controlled conditions, cannot be calibrated against trusted standards, or cannot be integrated into existing workflows without custom engineering. Quantum sensing matters for quantum development and commercialization because it forces these constraints to the surface earlier than the other quantum application areas do.

What the Mountain West already has

The Mountain West's quantum significance lies less in how much it does than in where it is concentrated. Since 2010, inventors and patent sponsors in Colorado, New Mexico, and Wyoming have produced 594 quantum inventions: 439 in Colorado, 144 in New Mexico, and 19 in Wyoming. The region is active across all three quantum application areas, with 358 inventions in computing, 300 in sensing, and 255 in communications. That is enough scale to treat the region as a real quantum system rather than an anecdotal cluster.

The strongest regional signal is concentration in sensing and in measurement-adjacent enabling layers. On an employment-normalized basis, the Mountain West's overall quantum concentration is 2.88x the U.S. average. By state, New Mexico reaches 3.27x, Colorado 2.96x, and Wyoming 1.33x. By quantum application area, sensing is the strongest regional signal at 3.31x, ahead of computing at 2.96x and communications at 2.64x. That pattern matters because it aligns the region's strength with the layers of the quantum technology stack where readout, stability, calibration, and validation constraints tend to bind first.

The region's platform specialization is even more revealing. Platform-level concentration relative to employment is especially high in photonics at 4.53x the U.S. average, lasers at 4.51x, quantum gyroscopes at 8.86x, single-photon detectors at 3.42x, magnetometry at 3.21x, and optics at 3.05x. Those are not generic strengths. They are the layers where quantum systems are measured, stabilized, calibrated, and made trustworthy enough for real-world use.

The institutional base matches that technical profile. Boulder's precision-measurement complex, especially NIST and its jointly operated institute JILA, anchors one side of the region's strength. Sandia and Los Alamos anchor the other through mission-oriented national-lab infrastructure, validation-relevant environments, and long-cycle engineering capacity. The result is not a region that can do everything in quantum. It is a region unusually concentrated in the layers where difficult systems become testable and usable.

What the momentum signals say

The regional wave is recent, real, and still selective. Roughly 53 percent of Mountain West quantum inventions since 2010 were filed since 2020, and roughly 70 percent since 2018. Mountain West quantum invention grew at about 31 percent annually from 2010 through 2023. Growth was faster in computing and communications, but the most important point is that the regional position is not merely a historical artifact. It has continued to strengthen sharply in the past several years.

Commercialization signals are credible, but they do not yet prove broad readiness. Government sponsors account for 18.5 percent of Mountain West quantum inventions, versus 6.1 percent nationally. Growth-capital-backed invention sponsors account for 14.0 percent, versus 9.6 percent nationally. This gives the region an unusual profile: more dependent on institutions and more capable of converting institutional strength into commercial opportunity. Commercialization signals are promising but still thin. Regional quantum startups raised $1.943 billion between 2010 and 2025, and roughly three-quarters of that total arrived in 2024 and 2025. That mix is meaningful because it combines mission anchoring with venture-backed translation. But it still describes an early, uneven, and concentrated pattern of commercialization rather than a mature, diversified regional engine.

What this means for the U.S. NSF ASCEND Engine

The strongest conclusion for the NSF ASCEND Engine is not that quantum already constitutes a broad, ready environmental market. It is that ASCEND technologies sit near a strategically important pre-invention quantum frontier. The science is real, and the technical adjacency is real, but the overlap remains thin relative to the broader sensing system. The report's own interpretation is disciplined: climate and environmental pathways like ASCEND technologies are plausible, but they remain systems-limited and depend heavily on validation, standards, integration, and workflow embedding.

The most useful way to read the ASCEND-quantum technology opportunity is therefre as a measurement-and-trust agenda. The region's evidence-backed strength lies in the technology layers that enable future ASCEND-quantum applications: photonics, precision optics, instrumentation, metrology, software control, validation routines, and integration capacity. For the NSF ASCEND Engine, that means the most strategic interventions are not likely to begin with a long list of ASCEND-related quantum-enabled end products ready to be developed. They are more likely to begin with the technical and institutional layers that make trusted quantum sensing in ASCEND applications possible in the first place.

Decision frame for the NSF ASCEND Engine

The NSF ASCEND Engine should treat the Mountain West's quantum position as consequential, but conditional. The region's advantage will not become durable through branding, isolated demonstrations, or headline investment rounds alone. It will become more durable if the region builds around the layers it already owns and uses them to reduce the friction that still slows deployment.

Four strategic questions follow from that diagnosis:

- **Can the region build more of the trust infrastructure that quantum still lacks?** That includes calibration capacity, shared test environments, qualification pathways, and stronger standards participation.
- **Can the NSF ASCEND Engine focus on early "signature assembly arenas" rather than broad market claims?** The strongest candidates are the areas where deployment pressure arrives first: resilient navigation and timing, infrastructure-adjacent sensing, and other measurement-intensive systems where error costs are high.
- **Can the region translate sensing strength into repeatable integration capacity?** Progress should be judged less by demonstrations alone than by whether systems can be packaged, validated, calibrated, and embedded in operational workflows.
- **Can the Mountain West remain outward-facing enough to matter nationally and with allies?** The region's strength will be most durable if Colorado's measurement strengths and New Mexico's mission-validation strengths are used to support wider U.S. and allied standards, procurement, and deployment pathways.

Bottom line

The Mountain West is already in quantum. The question is what role it will build from that position. The evidence does not support a generic claim of leadership across the board. It supports a narrower and more durable claim: the region is unusually strong in the layers where quantum becomes measurable, validated, and usable in practice.

For ASCEND applications, that makes quantum more than an adjacent emerging technology. It makes quantum a serious strategic frontier in trusted sensing, systems integration, and infrastructure—the systems-assembly work required to turn advanced environmental measurement into real decisions. The opportunity is real. It is also conditional. The region will benefit most if it uses its current position to build more validation, integration, and deployment capacity that the broader quantum system still requires.

Introduction

Quantum technology has expanded from laboratory to application. Policymakers are funding it, defense agencies are prioritizing it, investors are scanning for commercial inflection points, and regional leaders are asking what a credible position looks like. Yet the language around quantum still often lags the state of the work. It is frequently described through headline milestones, race metaphors, and broad promises of transformation. That language generates excitement, but it also hides the more difficult question that now matters most: how quantum capabilities transition from scientific achievement to operational deployment, and why that shift is so inconsistent.

That question matters because quantum technologies are genuinely different from most advanced technologies they are often casually grouped with. Their unique promise does not come from being faster, smaller, or more precise in the usual engineering way. It comes from exploiting quantum properties—superposition, entanglement, and interference—to measure, transmit, or process information in ways classical systems cannot easily mimic. Those possibilities are real, but demanding. Quantum effects are powerful because they are delicate. They are extremely sensitive to noise, temperature changes, manufacturing flaws, imperfect control, and environmental disturbances. A functioning quantum device, therefore, is never just a device. It is a control achievement: a system that creates, stabilizes, manipulates, reads out, and interprets fragile states long enough to be meaningful.

Seen this way, quantum should not be viewed as three separate fields—computing, communications, and sensing—progressing independently. It is better understood as a co-evolving technological system with interconnected components that depend on common enabling layers: specialized materials, device architectures, photonics, precision optics, cryogenics, calibration routines, control electronics, software, and the standards and workflows that ensure trustworthy outputs. A breakthrough in photonic control can affect secure communications, advanced sensing, and multiple computing architectures at once. Improved measurement stability can raise performance limits well beyond the initial domain of application. What appears from a distance as distinct quantum markets is actually a tightly integrated system with shared bottlenecks.

The field's central challenge is no longer discovery alone. The tough work centers on bottlenecks: materials that cannot yet be produced reliably; fabrication processes that remain custom and low-yield; readout systems that are sensitive but difficult to stabilize; calibration burdens that become overwhelming outside controlled environments; validation methods that are still underdeveloped; and interfaces with classical infrastructure that often need to be built manually. Interoperability is hard because most quantum systems are still designed for specific research or demonstration purposes. Connecting components from different developers or integrating them into existing systems remains costly, labor-intensive, and inconsistent. Many of quantum's most significant obstacles are no longer purely scientific. They are also engineering, institutional, and organizational challenges that shape whether a demonstrated capability can function in the real world.

In that environment, commercialization does not resemble simply releasing a finished product into a ready market. It resembles system assembly. Hardware must be integrated with sensing and readout layers, which must be controlled and interpreted through software. The full configuration then needs to be qualified, benchmarked, maintained, and incorporated into trusted workflows. The key questions are often unglamorous: Can the device maintain calibration? Can its outputs be compared against a standard? Can it operate long enough, cheaply enough, and reliably enough to justify adoption? Can it connect to larger systems without custom engineering each time? These questions sit at the intersection of scientific progress and economic or strategic impact. They also explain why the field's progress often occurs more slowly and unevenly than public rhetoric suggests.

Quantum sensing brings those realities into focus earlier than the other major application areas. A sensor cannot stay abstract; it must deal with vibration, drift, noise, size, weight, power limits, environmental interference, calibration needs, and the practical demands of users who require reliable measurements. In that regard, sensing is not just another application area. It is the part of the quantum system in which operational reality first and most clearly appears. It shows where quantum platforms are becoming practical, where they remain fragile, and where the real challenge of translation occurs.

Its significance goes beyond sensing alone. The same enabling layers that make sensing possible—photonics, precision optics, timing, readout, control systems, calibration, and validation routines—also influence performance in communications and computing. A portable inertial sensor, a reliable magnetometer, or a durable timing device all depend on many of the same capabilities that larger quantum architectures require. Sensing is, therefore, diagnostic. It shows where the system is beginning to harden into something deployable and why the most valuable parts of the field are not always the most visible. Influence does not go only to those who announce the most impressive milestones. It also goes to those who control the enabling layers and validation environments through which many downstream capabilities must pass.

Quantum geopolitics is still often described as a race. But races suggest a single track, a shared finish line, and a clear idea of what winning looks like. Quantum offers none of those advantages. Different countries and companies are focusing on different layers of the stack. Some are expanding deployment-related pathways. Others are building strength in upstream platforms, standards, or control layers. Still others are gaining influence by occupying central roles in collaboration networks or by controlling chokepoints in photonics, metrology, fabrication, and software. The field is better understood as a contest over system positioning: who shapes the platforms, interfaces, validation regimes, and deployment pathways through which quantum capabilities become reliable and useful. That contest is already happening, and it is far more significant than the headline language of being first.

This is the broader context in which the Mountain West should be understood. The region does not need to dominate every aspect of quantum technology to be significant. The more important question is whether the Mountain West holds a meaningful role in the layers where fragile performance is transformed into trusted capability: measurement, photonics, precision instrumentation, testing, validation, and mission-oriented engineering. Colorado and New Mexico, especially, anchor a regional concentration of capabilities unusually close to the points in the stack where deployment challenges become critical. That does not automatically confer an advantage, but it does provide a credible basis for influence in a field where many of the hardest problems are solved well below the level of the final application.

Advanced sensing and computing for environmental decision-making (or "ASCEND") technologies fit within the broader argument as a practical frame. These technologies are a major strength of the Mountain West's innovation ecosystem and have become an important focus codified through federal investment in the U.S. NSF ASCEND Engine. ASCEND-related technology applications do not define the entire quantum field, but the capabilities most relevant to ASCEND technologies—trusted measurement, resilient timing and navigation, advanced sensing, and stronger interfaces between physical signals and decision systems—rely on many of the same enabling layers that are increasingly important across the wider quantum landscape. Understanding where ASCEND technology opportunities lie requires understanding the larger system in which they are developing. That is why this report starts broadly. It then returns to the parts of the stack where the region's position matters for environmental intelligence, infrastructure monitoring, and decision systems that depend on precision, resilience, and trust.

The analysis that follows draws on a global corpus of roughly 27,000 quantum-related inventions filed since 2010. The report organizes that analysis around three interpretive lenses. The system lens shows how the three quantum application areas overlap, recombine, and rely on shared enabling platforms. The platform lens focuses on the enabling technologies that organize inventive effort and shape downstream possibilities. The stack lens makes the dependencies vertical and explicit: it shows how progress at higher layers can outpace maturation at lower layers, and why commercialization outcomes are frequently determined by system-assembly constraints. These lenses are introduced in Chapter 1, which looks at how the field is structured, and elaborated on through Chapter 3. The report then shifts outward to competition and commercialization. Finally, it turns to the Mountain West itself, exploring the role its current strengths plausibly support, where those strengths are concentrated, and what would be needed to turn them into lasting advantage.

That progression leads us to the Quantum Frontier. In quantum, the frontier is not just the edge of what science can do; it is the more precise boundary where delicate effects become reliable systems. Frontiers are not just remote locations on a map; they are places where uncertainty is faced, systems are tested under tough conditions, and capabilities shift from being merely impressive to genuinely credible. The Mountain West is a frontier region in the literal American sense. This report argues that it could also be a practical frontier for the quantum system—a place where real-world quantum deployment is figured out, especially in sensing and measurement layers closest to operational use. Whether that role endures depends on more than research excellence or bold claims. It depends on whether the region can turn its strengths in photonics, measurement, validation, and mission-driven engineering into lasting influence over how the broader quantum system is assembled, trusted, and used.

1. The quantum technology system

Quantum technologies are often described through headline applications, breakthrough claims, or national competition. Those frames are useful, but they do not explain how the field is organized. At this stage, quantum is better understood as a co-evolving technology system built on shared enabling platforms and layered dependencies. Computing, communications, and sensing remain useful application areas, but progress in each depends on common capabilities in materials, photonics, measurement, control, software, and integration.

This chapter defines that system. It begins by explaining what makes a technology distinctly quantum and why useful systems depend on controlling fragile quantum behavior long enough for it to be measured, interpreted, and used. It then shows that the invention record does not support a view of the field as three separate trajectories. Instead, inventive effort concentrates in a small set of cross-cutting platforms that form a technology stack with hard vertical dependencies.

That structure changes how quantum progress should be interpreted. Visible acceleration at the top of the stack does not necessarily indicate readiness below it. Lower-layer constraints in materials, fabrication, calibration, validation, and integration still determine whether technical performance can become dependable use. Sensing is the first place where the broader quantum system must perform outside controlled settings, and for that reason, it offers one of the clearest tests of whether the field is becoming usable in practice.

1.1 What makes quantum technology quantum?

Quantum technologies differ from classical ones because they exploit physical behaviors that have no direct classical equivalent. Three behaviors matter most for this analysis:[1]

- **Superposition** allows a quantum system to exist in multiple states at once until measurement forces a result. In computing, that opens new ways to represent and explore complex solution spaces. In sensing, it allows extraordinarily fine comparisons of phase, frequency, and motion.
- **Entanglement** links quantum states so tightly that measuring one immediately constrains the other, even across distance. That makes possible forms of coordination, correlation, and secure information exchange that classical systems cannot reproduce in the same way.
- **Interference** allows quantum states to reinforce some outcomes and cancel others. That is what lets quantum systems extract weak signals, sharpen measurement, and steer computation toward useful results rather than random ones.

These behaviors are the source of quantum's promise, but also of its difficulty. Quantum states are fragile. They degrade under noise, vibration, thermal fluctuation, fabrication defects, and imperfect control. A useful quantum technology, therefore, depends on much more than a successful device demonstration. It requires the ability to reliably generate quantum effects, maintain them long enough to matter, measure them with precision, and connect the resulting outputs to classical electronics, software, and operational workflows.[2] In practice, quantum technology is best understood as a control problem: the task of making delicate quantum behavior stable enough to be measured, interpreted, and used.

That challenge has an important consequence for how the field should be read. Quantum progress depends on shared enabling layers—materials, device architectures, photonics, precision optics, control electronics, software, and calibration routines—that recur across the field. The familiar application labels therefore tell only part of the story.

1.2 From three application areas to one co-evolving system

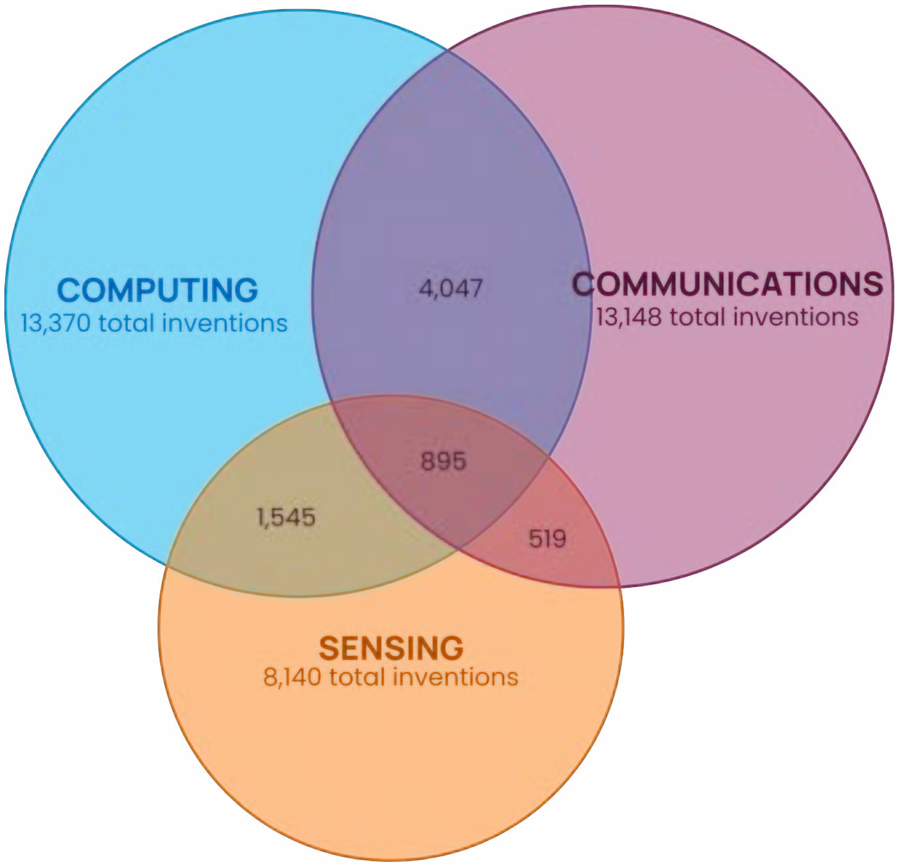
That common technical base helps explain why quantum is usually described one way but develops another. Policy, strategy, and investment discussions still divide the field into three quantum application areas: computing, communications, and sensing.[3]

- **Quantum computing** uses controlled quantum states to perform calculations that classical systems cannot easily replicate. Its long-run promise spans cryptography, optimization, materials science, artificial intelligence, and drug discovery. Its near-term limits remain severe because progress depends on error correction, hardware stability, and integration with classical high-performance computing environments.
- **Quantum communication** focuses on secure information transfer and the development of distributed quantum networks. In this report, the emphasis is on quantum-native approaches such as quantum key distribution (QKD), which use the physical properties of photons to detect eavesdropping and secure a transmission. That is distinct from post-quantum cryptography (PQC), which relies on classical mathematical methods to defend against future quantum attacks and therefore sits outside the physical quantum invention corpus analyzed here.[4]
- **Quantum sensing** uses the sensitivity of quantum states to detect tiny changes in time, gravity, magnetic fields, motion, and other physical signals. It is regarded as the application area closest to real-world use because several sensing modalities are already moving beyond the laboratory, with applications to navigation, environmental monitoring, health, and defense. Deployment depends on ruggedization, calibration, validation, and system integration rather than performance alone.[5]

Those categories usefully distinguish different technical goals and use cases, but they do not describe the field's internal structure particularly well. The invention record shows convergence around a shared technical core, not divergence into three separate technological trajectories.

Figure 1. Quantum domains are converging into an integrated technology system

CONVERGENCE AMONG QUANTUM TECHNOLOGY DOMAINS
Relative size and overlap between the corpuses of patented inventions filed from 2010 to 2025



Source: Denizens LLC analysis of Lens data.

Quantitative evidence from nearly 27,000 quantum-related inventions filed globally since 2010 makes that point clearly. Roughly one-third of the global corpus is classified under more than one quantum application area, which makes overlap a structural feature of the field. The largest overlap sits between computing and communications, with 4,047 shared inventions. Another 1,545 span computing and sensing, 519 span communications and sensing, and 895 sit at the intersection of all three. These overlaps show that the boundaries between application areas are most permeable where the field is doing its most inventive work.

That convergence reflects shared technical dependencies. Computing and communications overlap most strongly because both depend on control electronics, networking protocols, and readout architectures.[6] Across all three application areas, the same enabling capabilities recur: photonics, precision optics, measurement and control systems, and software. Sensing inventions frequently embed algorithmic control and data-processing techniques associated with computing research. Communications inventions increasingly depend on high-precision measurement and calibration methods refined in sensing contexts.[7] These are not incidental spillovers. They are structural linkages in a system built on shared platforms.

The technical literature points in the same direction. Reviews of quantum sensing repeatedly stress dependence on photonics, materials science, and control systems developed outside sensing proper. Work on quantum computing foregrounds readout fidelity, noise suppression, and measurement stability—problems that draw directly on capabilities often associated with sensing. What the literature often describes as spillovers, the invention record shows more plainly as cross-domain dependence.

The division between computing, communications, and sensing is better understood as application areas layered atop a shared technical and industrial base. Seen that way, quantum resembles enabling infrastructure more than a set of isolated end markets. Like the transistor, GPS, or the internet, its significance lies in the common platforms it supports across many downstream systems. The next sections turn from application areas to the enabling platforms and stack layers that increasingly organize the field.

1.3 The platform logic of quantum innovation

Overlap across quantum application areas resolves into a small number of enabling platforms that recur across the field. Among 26,861 quantum-related inventions filed since 2010, inventive effort concentrates less on end-use applications than on the capabilities that generate, control, measure, and translate quantum effects.

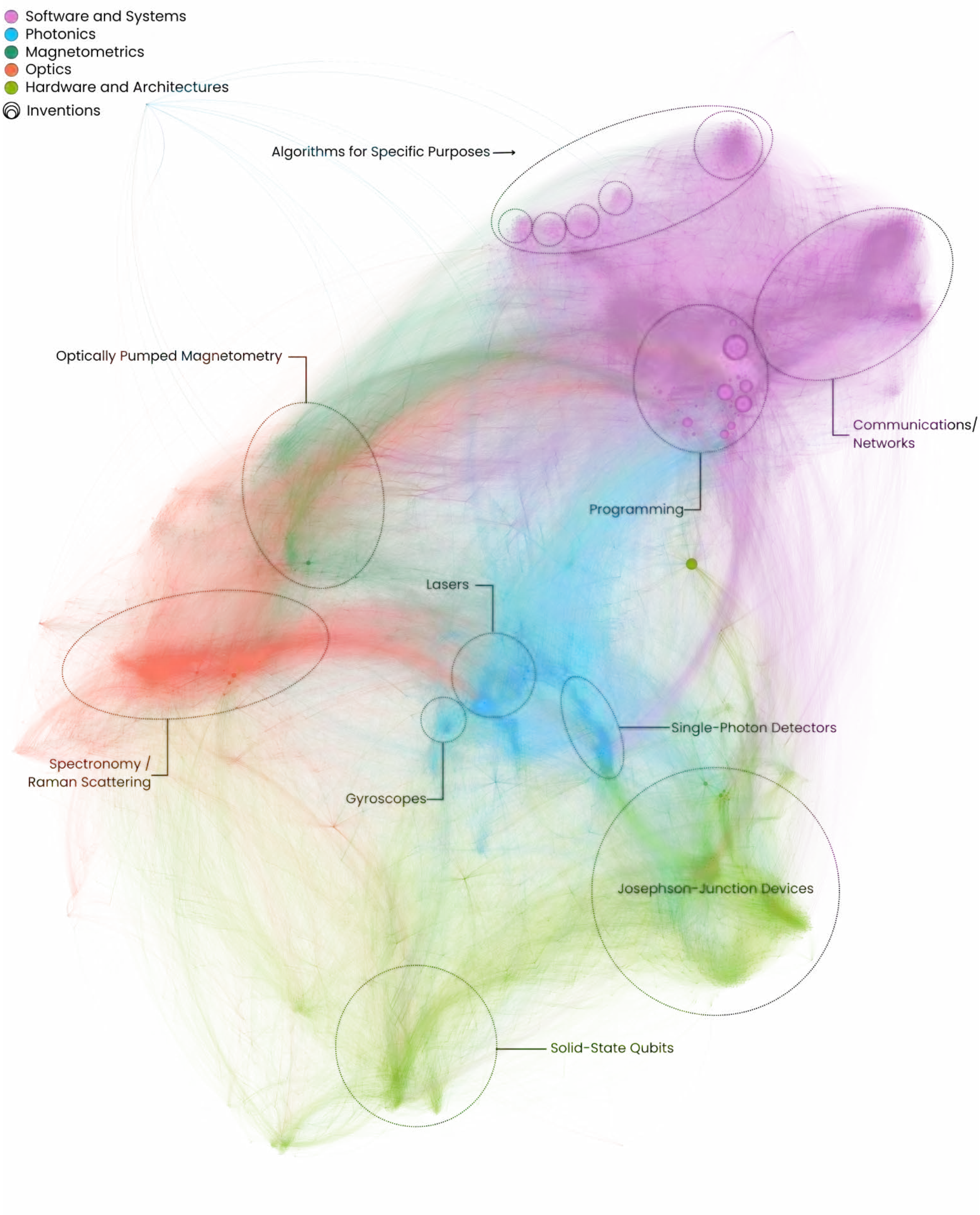
Figure 2 shows that pattern through CPC co-occurrence across the global invention corpus. Five dense platform clusters stand out. Figure 3 shows their relative scale. Software and systems account for 16,131 inventions, compared with 6,956 in hardware and architectures, 4,819 in photonics, 3,217 in precision optics and spectroscopy, and 2,652 in magnetometry and interferometric measurement. The field is still concentrating on enabling capabilities rather than optimizing mature end uses.

Five platform areas now organize most of the field’s inventive effort:

- **Hardware and device architectures** form the physical foundation of the system. This platform includes superconducting circuits, Josephson-junction devices, solid-state qubits, ion traps, and related architectures for creating and manipulating quantum states. Progress here is slow because materials quality, fabrication precision, and, in many cases, cryogenic operation still constrain performance. These architectures sit beneath computing, communications, and sensing alike.[8]
- **Photonics** provides the light-generation, control, and readout infrastructure used across the field. This platform includes lasers, single-photon sources and detectors, and photonic integrated circuits. It underpins quantum sensing through interferometry and precision measurement, quantum communications through photon-based information transfer, and many computing architectures through control and readout. Advances in photonics propagate across application areas quickly because the same components recur throughout systems.[9]

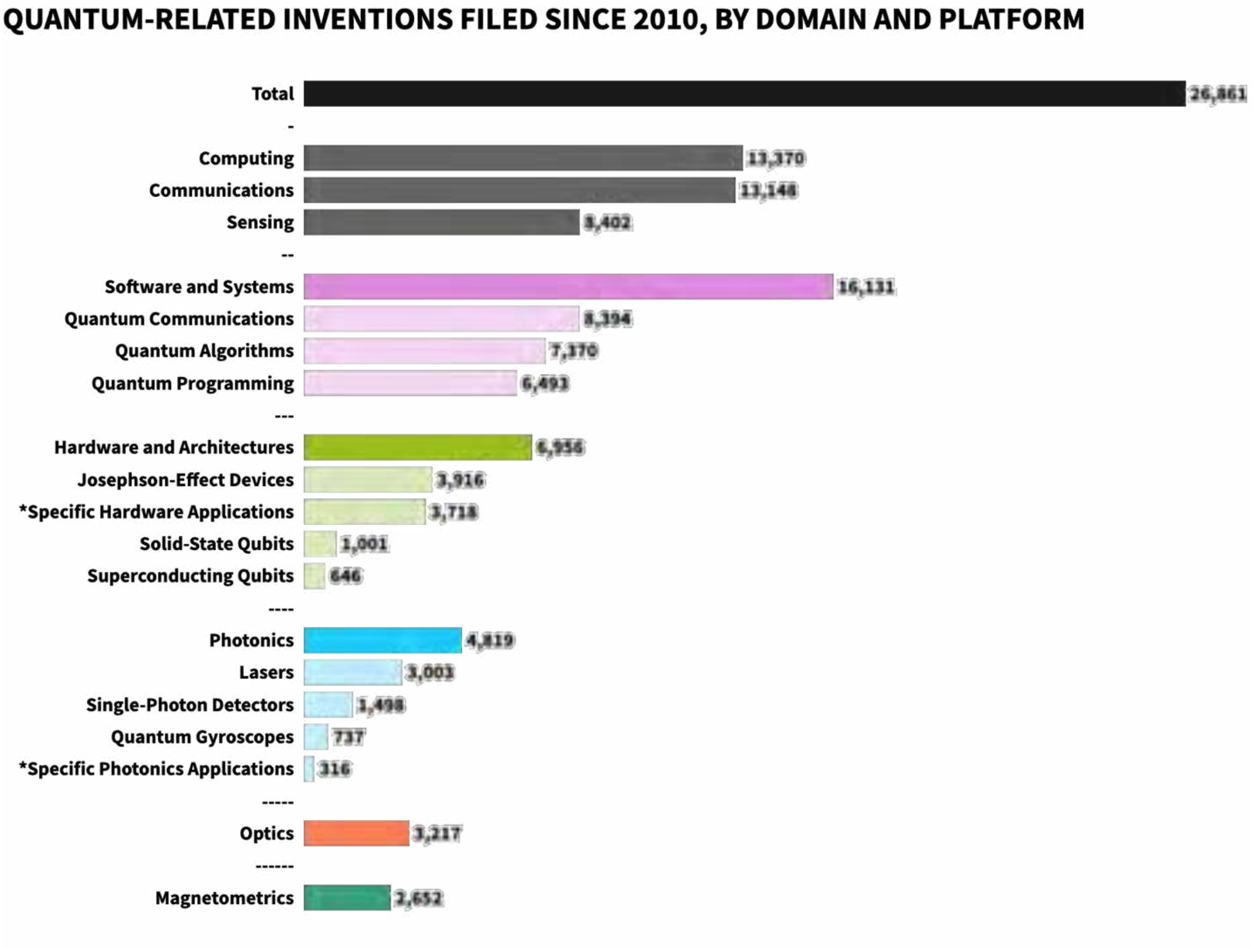
Figure 2. Quantum's building blocks cluster into platform technologies

THE NETWORK OF QUANTUM TECHNOLOGIES
Connections between CPC codes on quantum technology inventions filed since 2010



Source: Denizens LLC analysis of Lens data.

Figure 3. "Soft" quantum platforms have grown larger than physical platforms



* These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens data.

- **Precision optics and spectroscopy** focus on controlling and measuring phase, frequency, and energy transitions with extreme accuracy. Interferometry, Raman scattering, and optical frequency stabilization are central here. These techniques support atomic clocks, gravimeters, and other measurement-intensive sensing systems, but they also stabilize and calibrate computing and communications platforms. This is the bridge between fragile physical effects and trustworthy signal.[10]
- **Magnetometry and interferometric measurement** provide the high-sensitivity interface through which quantum systems detect weak physical signals. This platform includes SQUIDs, atomic magnetometers, gyroscopes, gravimetric techniques, and related measurement technologies. It supports some of the most operationally promising sensing applications—navigation, subsurface detection, and environmental monitoring—while also contributing to internal calibration and noise suppression.[11]

- **Software, algorithms, and systems** integration sit closest to use. This platform includes control firmware, error mitigation, signal processing, data interpretation, programming, and secure networking. It is the largest and fastest-moving platform in the invention record because it faces lower capital barriers and shorter iteration cycles than the physical platforms below it.[12] Its job is to make lower-layer advances usable, but it cannot outrun the constraints imposed by those lower layers.

In sensing, performance gains matter only if devices can be ruggedized, calibrated against standards, integrated with legacy systems, and produced at workable cost.[13] In computing and communications, the equivalent constraints appear as readout fidelity, error mitigation, orchestration, and integration. Deployment, therefore, turns on platform-level capabilities long before it becomes a question of application uptake.

That pattern helps explain why application-specific invention activity remains thin. CPC codes tied directly to environmental monitoring, navigation, and similar use cases account for only a small share of total quantum invention activity and sit at the edge of the network rather than at its center.[14] Applications motivate interest. Platforms absorb inventive effort. The field is still building the tools needed to support many downstream uses.

A quantum gravimeter, a quantum communication link, and a superconducting processor serve different purposes, but they draw from overlapping photonic components, control systems, and measurement techniques. Progress in one can lower barriers in others because the same platforms sit underneath them all.[15] Those platforms do not operate side by side, however. They form a layered system with hard dependencies, which is why the next section turns from horizontal platform structure to the quantum technology stack.

Table 1. Quantum technology platforms play distinctive roles in the system

Platform	Core Technologies	Strategic Role
Hardware and Architectures	Superconducting circuits, Josephson-junction devices, ion traps, solid-state qubits	Physical foundation of the system; slowest and most capital-intensive layer
Photonics	Lasers, single-photon sources, single-photon detectors, photonic integrated circuits	Cross-domain light-generation, control, and readout infrastructure
Precision Optics and Spectroscopy	Interferometry, Raman scattering, optical frequency stabilization	Phase and frequency control; bridge from physical effect to measurable signal
Magnetometry and Interferometric Measurement	SQUIDs, atomic magnetometers, gyroscopes, gravimetric techniques	High-sensitivity measurement interface for external sensing and internal calibration
Software and Systems	Error mitigation, control firmware, signal processing, networking, programming	Fastest iteration layer; translates lower-layer advances into usable systems

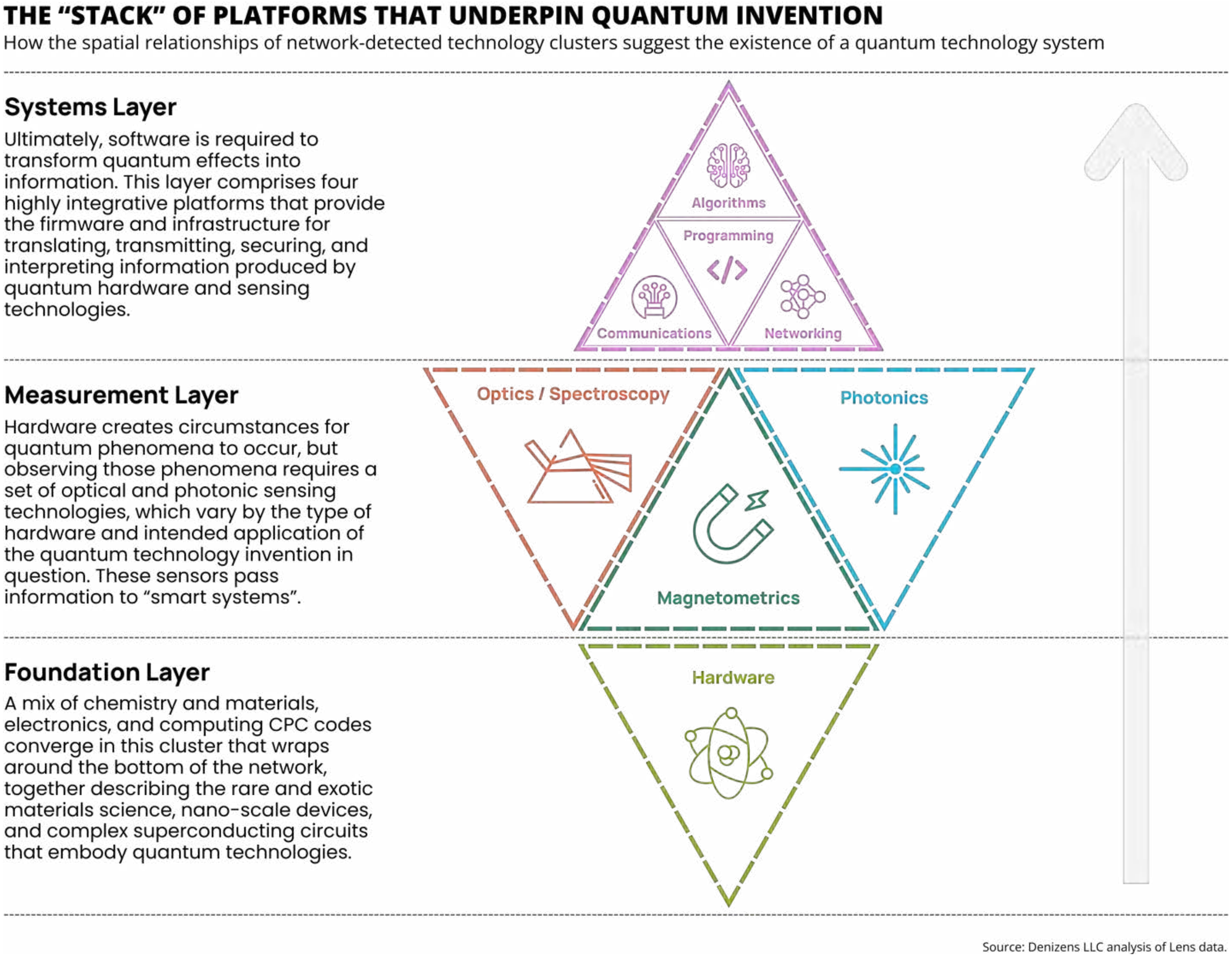
Source: Denizens LLC analysis of Lens data.

1.4 The quantum technology stack

The five platforms described above do not operate side by side. They form a layered stack of dependencies through which quantum effects become usable systems. This vertical structure matters because progress in one part of the field does not automatically translate into deployable capability elsewhere. A breakthrough in software, control, or readout can accelerate work higher in the stack, but it cannot remove constraints in materials, fabrication, calibration, or integration below it.

Figure 4 organizes the quantum technology stack into three interdependent layers: a foundational layer of materials and device architectures, a measurement layer of sensing and control platforms, and a systems layer of software, algorithms, and integration. Each depends on the integrity of those beneath it. Lower layers set the conditions under which higher layers can perform, scale, and stabilize. That is why quantum can appear to advance quickly overall while still struggling at the points where laboratory performance must become repeatable, validated, and usable in the world.

Figure 4. Quantum platforms create a vertical "stack" of dependencies



THE "STACK" OF PLATFORMS THAT UNDERPIN QUANTUM INVENTION

How the spatial relationships of network-detected technology clusters suggest the existence of a quantum technology system

Systems Layer

Ultimately, software is required to transform quantum effects into information. This layer comprises four highly integrative platforms that provide the firmware and infrastructure for translating, transmitting, securing, and interpreting information produced by quantum hardware and sensing technologies.

Measurement Layer

Hardware creates circumstances for quantum phenomena to occur, but observing those phenomena requires a set of optical and photonic sensing technologies, which vary by the type of hardware and intended application of the quantum technology invention in question. These sensors pass information to "smart systems".

Foundation Layer

A mix of chemistry and materials, electronics, and computing CPC codes converge in this cluster that wraps around the bottom of the network, together describing the rare and exotic materials science, nano-scale devices, and complex superconducting circuits that embody quantum technologies.

Source: Denizens LLC analysis of Lens data.

The subsections that follow show how those dependencies work in practice. The foundational layer determines whether quantum behavior can be produced reliably at all. The measurement layer determines whether it can be observed, calibrated, and trusted under real operating conditions. The systems layer determines whether those capabilities can be translated into workflows, networks, and applications that users can actually adopt. Read together, the three layers show why the field's hardest problems sit closer to the bottom of the stack than to its most visible edge.

1.4.1 The foundational layer: materials and device architectures

At the base of the quantum technology stack sit the materials and device architectures that make quantum behavior possible in the first place.[16] This layer includes superconducting circuits, solid-state devices, ion traps, nanostructured materials, fabrication processes, and, in many cases, the cryogenic systems needed to sustain operation. It is the most capital-intensive and path-dependent part of the field. Progress here is slow because it depends on a demanding combination of scientific discovery, precision engineering, specialized facilities, and manufacturing control. When this layer does not perform reliably, the rest of the stack cannot compensate for long.

That helps explain an important empirical pattern in the invention data. Foundational technologies account for a smaller share of total quantum invention volume than software- or systems-oriented layers, yet they occupy a far more central position in the network of quantum inventions.[17] Hardware- and materials-related CPC codes recur across computing, communications, and sensing, indicating that advances at this level support nearly every major quantum application area. Leadership in quantum, therefore, does not begin at the point of use. It begins with the ability to produce and control the physical conditions on which the rest of the system depends.

Materials quality remains a binding constraint because quantum performance depends on purity, uniformity, and defect control at levels that are difficult to achieve consistently.[18] Fabrication reproducibility is equally hard. Many devices are still built to custom specification, with meaningful variation across runs, units, and facilities. That means each prototype carries its own engineering history, and lessons from one setting do not always transfer cleanly to another. Low yields, unstable performance, and narrow supplier bases raise cost, slow iteration, and make it difficult to build the manufacturing learning curves that would support broader deployment.

These are not secondary engineering problems. They set the ceiling on system performance. Whether the goal is a scalable quantum processor, a robust sensor, or a secure communication link, limitations in coherence, noise, stability, and reproducibility ultimately cap what can be achieved at higher levels in the stack.[19] For that reason, the foundational layer functions as the rate-limiting substrate of the quantum system. It is where much of the field's difficulty still resides, and where long-term advantage is most likely to accrue to actors that can combine research strength with precision fabrication, specialized infrastructure, and sustained manufacturing capability.

1.4.2 The measurement layer: sensing and control of quantum states

Above the foundational layer sits the measurement layer: photonics, optics, magnetometry, interferometry, and related readout and control technologies that make quantum states observable, stabilizable, and usable.[20] This layer does more than enable external sensing applications. It also provides the internal measurement, calibration, and control functions that quantum computing and communications depend on. Quantum effects do not become operationally meaningful until they can be detected, compared, and stabilized with enough precision to guide action.

That centrality is visible in the invention data. Measurement-related platforms appear across all three quantum application areas and frequently co-occur with both hardware and software technologies within the same inventions.[21] Reliable measurement is therefore not a niche concern limited to sensing. It is a prerequisite for progress across the broader system. Advances in readout, control, and metrology improve system stability, reduce error, and support more sophisticated software and firmware higher in the stack. That is why sensing-related platforms can be highly generative even when their invention growth is slower than that of the software layer above them. Their importance lies in the fact that they stabilize and enable the layers above them.

This is also where some of the field's most persistent deployment constraints come into view. Many quantum sensing modalities achieve impressive performance under laboratory conditions. Holding that precision in the presence of temperature variation, vibration, electromagnetic interference, and other real-world disturbances is much harder.[22] Calibration and metrology, therefore, become central bottlenecks. A system is only as useful as the regime that keeps it calibrated and the standards that make its outputs comparable and trustworthy. Progress at this layer depends not only on better devices, but on calibration infrastructure, shared metrology standards, and test environments that expose systems to operating conditions rather than idealized ones.

Validation is a distinct challenge on top of calibration. A device may produce a strong result in controlled conditions and still lack a credible path to wider use if there are no settled test protocols, qualification environments, or widely accepted benchmarks against which its performance can be judged.[23] That keeps promising systems in pilot mode longer than their underlying science might suggest. It also raises risk for adopters, who must decide whether a result is repeatable, how it compares with alternatives, and whether it will hold under operational conditions. In this layer, the absence of trusted validation pathways slows deployment almost as much as technical underperformance.

For that reason, the measurement layer more clearly marks the boundary between demonstration and deployment than any other part of the stack. It is where fragile quantum behavior must first prove it can survive contact with the world. When this layer is strong, it unlocks progress across computing, communications, and sensing alike. When it is weak, promising architectures remain trapped in controlled settings, unable to translate technical performance into dependable use.

1.4.3 The systems layer: software, algorithms, and integration

At the top of the quantum technology stack sits the systems layer: software, algorithms, control firmware, networking, and data interpretation. This is the fastest-moving part of the field because it faces lower capital barriers and shorter development cycles than hardware or measurement platforms.[24] It is also where much of the visible acceleration in quantum invention is concentrated. But this layer does not create quantum effects on its own. Its role is to make those effects usable. Software coordinates interactions among hardware and measurement subsystems, suppresses noise, mitigates errors, and translates fragile quantum behavior into outputs that can be interpreted and acted on.

That role extends across all three quantum application areas. In sensing, the systems layer includes signal processing, drift compensation, and the software that turns measurements into decision-grade outputs. In computing, it encompasses control logic, orchestration, error management, and interfaces connecting quantum devices to classical computing environments. In communications, it encompasses networking, synchronization, and the protocols that enable distributed quantum systems to operate. System-level innovation, therefore, occupies a central place in the field's effort to make lower-layer advances usable in practice. Its rapid growth reflects the fact that many of the most immediate opportunities in quantum now lie in coordination, control, and translation rather than in hardware alone.

Classical integration becomes unavoidable in this layer. Quantum devices do not enter an empty technical environment. They must connect to existing electronics, software stacks, data systems, communications networks, and user workflows that were not designed for them.[25] That interface work includes packaging, control logic, signal processing, data interpretation, and the practical question of how a quantum output becomes usable inside a larger operating system. The systems layer is where quantum capabilities are made legible to the rest of the world.

Interoperability is difficult for a straightforward reason. Most quantum systems are still built for specific research or demonstration settings rather than for repeatable use across many environments. Shared interfaces, common performance benchmarks, and widely used calibration regimes remain limited. The architectures themselves are still unsettled, so components from different developers often do not fit together cleanly or behave predictably when integrated. As a result, subsystems still must be connected and tuned through custom engineering, often from one deployment to the next. That keeps abstraction thin and makes integration slower, costlier, and less repeatable than it appears from the outside.[26]

The systems layer is therefore easy to misread. Its rapid growth can create the appearance of readiness because software can iterate quickly and, to a point, compensate for lower-layer weaknesses. It can filter noise, manage complexity, and make partial systems easier to use. But it cannot eliminate constraints in materials, fabrication, calibration, or environmental stability.[27] When the lower layers remain unsettled, the systems layer becomes a site of intensive experimentation rather than a mature layer of repeatable abstraction. Its progress is real, but conditional. That tension is central to the asymmetry of the quantum stack.

1.4.4 Asymmetry and path dependence

The layered structure of the quantum field produces a central asymmetry. Progress at the top of the stack can be rapid even when the layers beneath it remain unsettled. Software, control firmware, networking, and signal-processing tools can iterate quickly because they face lower capital barriers and shorter development cycles.[28] Materials, device architectures, calibration regimes, and validation environments do not. The result is a field that can appear to be moving quickly overall while remaining slow at the points where deployable performance is actually determined.

That asymmetry helps explain one of the defining tensions in quantum technology. The fastest growth in invention activity often appears in the systems layer, where algorithms, orchestration tools, and error-management techniques can advance faster than new hardware can be fabricated, stabilized, or qualified. Much of that work is valuable. It makes incomplete systems easier to operate and reveals where performance can improve. But it can also create the appearance of maturity before the lower layers are stable enough to support repeated use. A platform that still depends on custom fabrication, constant recalibration, or bespoke integration has not yet crossed from technical promise to dependable deployment, no matter how quickly its software evolves.

Path dependence follows from the same structure. Because computing, communications, and sensing draw on shared platforms, early choices in materials, device architectures, photonic components, control protocols, fabrication pathways, and metrology standards shape what becomes easier to build later. Those choices attract complementary suppliers, facilities, skills, and engineering routines. Over time, they harden into technical trajectories that are difficult and expensive to reverse.[29] Quantum leadership, therefore, accrues to those who occupy the stack's chokepoints as much as to those who announce the most visible applications. Influence lies in setting the conditions under which many downstream systems must operate.

For that reason, the hardest problems in quantum sit near the center of the field's trajectory. Materials quality, fabrication reproducibility, calibration, environmental robustness, validation, and classical integration determine which architectures remain laboratory achievements and which mature into usable systems.[30] Progress depends not only on better science but on shared standards, calibration infrastructure, validation environments, and interface engineering that can turn custom systems into repeatable ones. Sensing brings that logic into sharper focus because it is where the stack must first survive contact with the world.

1.5 Sensing is quantum's real-world interface

Not all quantum application areas play the same role in the development of the field. Computing, communications, and sensing each matter, but they do not place the same demands on the underlying system. Quantum sensing is the first point at which the stack must perform outside controlled settings. It is where fragile quantum behavior must survive vibration, drift, noise, temperature changes, calibration burdens, and the practical requirements of users who need measurements they can trust.[31] In that respect, sensing is not just one application area among others. It is the part of the quantum system that first confronts operational reality.

That position gives sensing importance that can be missed if the field is read mainly through invention counts or headline investment figures. Sensing does not dominate the global patent record, nor does it expand as quickly as some parts of computing and communications. Yet it plays a disproportionately important role because it links the quantum stack to external systems in navigation, infrastructure, environmental monitoring, health, defense, and industrial operations. Once a sensing application moves toward use, it pulls demand through the rest of the system: for better measurement fidelity, more stable control, stronger calibration regimes, cleaner integration with software and legacy infrastructure, and more reliable performance over time.[32] Sensing matters both for what it can do directly and for the pressure it places on the wider stack to become usable.

This is why scale, maturity, and strategic importance should not be treated as the same thing. A part of the field can remain modest in size and still be highly consequential if it is the place where system bottlenecks first become visible. Quantum sensing fits that pattern. It is often the first area in which quantum technologies move toward deployment, not because its challenges are solved, but because unresolved constraints can no longer be hidden. Sensing, therefore, appears both promising and constrained, which is the expected profile for the first application area in which the stack must survive the real world. It offers some of the clearest near-term pathways to use, while also exposing the unresolved problems of calibration, validation, ruggedization, and interoperability that still limit the field more broadly.[33] Read in that way, sensing is not peripheral to the quantum system. It is one of the clearest indicators of whether the system as a whole is becoming ready for real-world use.

* * *

Chapter 1 has recast quantum as a system rather than a set of isolated application stories. Computing, communications, and sensing draw on shared platforms; those platforms form a stack with hard dependencies; and lower-layer constraints still govern whether quantum effects become dependable systems. Sensing is the first point at which those constraints must survive contact with the world. For that reason, it offers one of the clearest indicators of whether the broader field is becoming usable in practice.

2. Quantum technology progress

Chapter 1 showed that quantum technologies develop less as separate application stories than as a shared system of platforms and stack layers. Chapter 2 turns from structure to motion. It asks how that system is evolving, where progress is concentrating, and what uneven growth reveals about the field's underlying direction.

Quantum has now reached meaningful scale. The invention record no longer looks episodic or confined to isolated breakthroughs. But scale is only the beginning of the story. Growth is uneven across application areas, platforms, and layers of the stack because different parts of the system face different technical burdens and play different roles in how progress unfolds. Three signals orient the analysis. The first is sustained scale. The second is structural unevenness: that growth is distributed in ways that follow from how the system is built, not from random variation. The third is leverage migration: when the field is read through the lens of generativity and emergence, that unevenness becomes interpretable as a shift in where structural importance is accumulating.

That unevenness is the subject of this chapter. It shows where the field remains exploratory, where capabilities are hardening, and where integration and coordination are becoming more important than the volume of inventions alone. The sections that follow first establish the scale of quantum growth, then explain why it is structurally uneven, and then use novel metrics of generativity and emergence to identify where structural importance is shifting. This evidence shows that quantum is maturing selectively rather than uniformly.

2.1 Sustained growth at meaningful scale

Quantum invention has moved beyond episodic breakthrough moments into sustained expansion. Since 2010, the global corpus has grown to nearly 27,000 quantum-related inventions, expanding at a compound annual growth rate of roughly 19 percent from 2010 through 2023. Annual filings rise through the mid-2010s, accelerate in the latter half of the decade, and continue into the early 2020s. The pattern is cumulative and durable rather than short-lived or speculative.

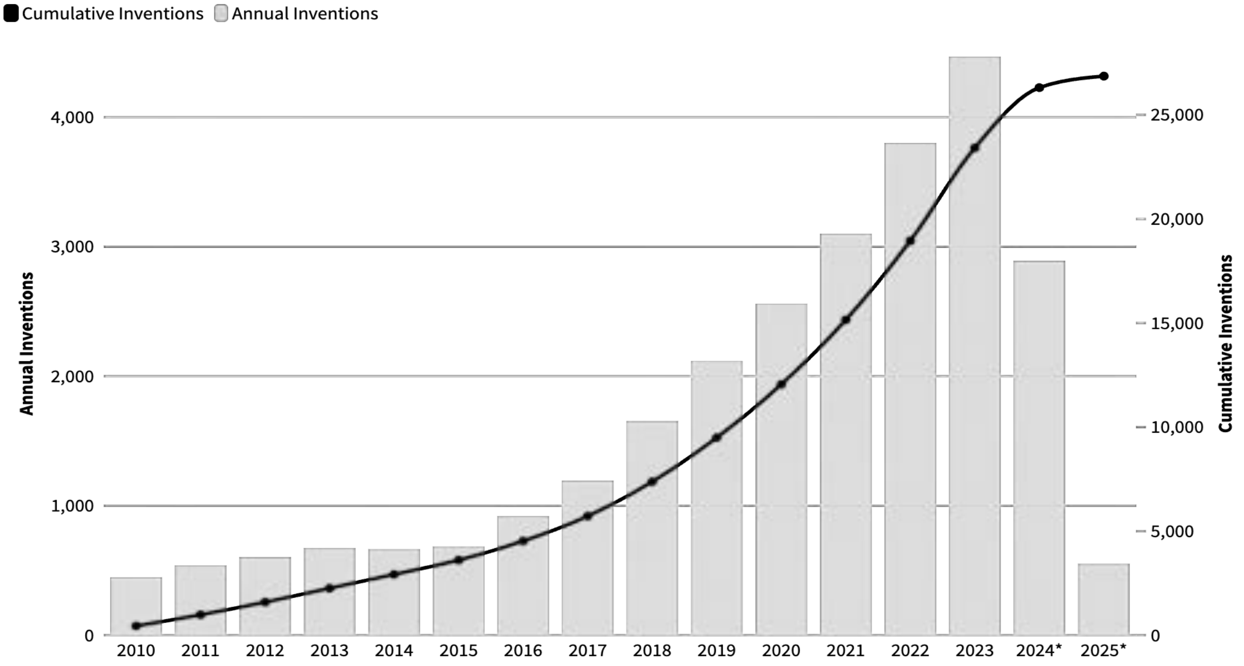
That growth is visible across all three quantum application areas. Over the period analyzed, quantum computing grew at roughly 27 percent annually and quantum communications at about 24 percent. Quantum sensing expanded more slowly, at roughly 9 percent, but still accumulated steadily over the period. The field is therefore not scaling in only one corner. It is expanding broadly, even though its parts are moving at different speeds.

The same is true at the platform level. Software and systems clusters, including programming environments and control systems, have grown fastest. Hardware-related technologies have grown more moderately. Photonics, optics, and magnetometry have expanded more slowly, but with consistent momentum rather than sporadic surges. At this stage, the important point is not how to interpret those differences, but that they are persistent features of the data rather than one-off deviations.

Figure 5. Quantum technology invention has expanded dramatically in recent years

GLOBAL GROWTH IN QUANTUM TECHNOLOGY INVENTIONS SINCE 2010

Number of new quantum inventions filed by year of first filing

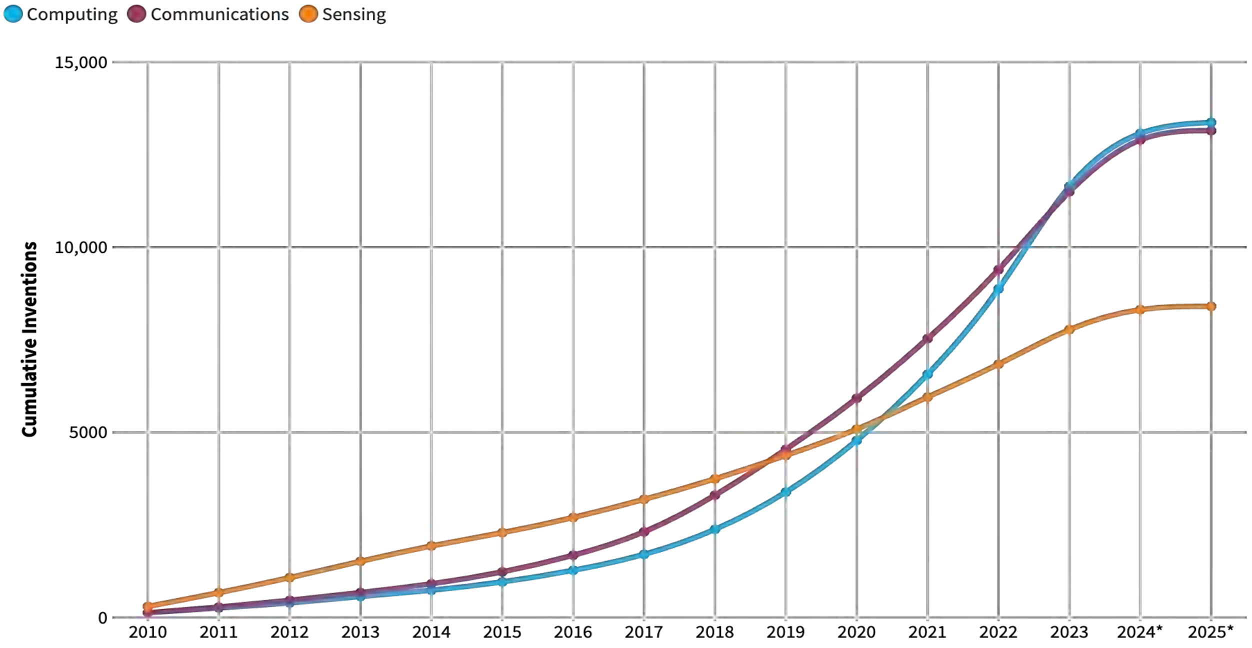


* Partial year data. • Source: Denizens LLC analysis of Lens data.

Figure 6. Invention growth in computing and communications outpaced sensing

GLOBAL GROWTH IN QUANTUM TECHNOLOGY INVENTIONS SINCE 2010, BY DOMAIN

Number of new quantum inventions filed by year of first filing



Source: Denizens LLC analysis of Lens.org data.

Two cautions matter when reading the recent record. Patent publication lags mean that apparent plateaus in 2024 and 2025 likely reflect indexing delays rather than a sudden loss of momentum. And the growth rates reported here capture only the quantum-specific portion of broader technological fields. This matters especially for sensing, where many photonic and measurement techniques have long histories outside quantum. Only inventions that explicitly combine those techniques with quantum states or control appear in this corpus.

The baseline is clear. Quantum is no longer a narrow research niche or a temporary wave of attention. It has reached sustained scale and deep institutional embedding. The next question is how that growth is distributed across the system, and what that distribution reveals about how progress is actually being made.

2.2 Acceleration is real but structurally uneven

Uneven growth is not a temporary imbalance in the quantum field. It follows from how the system is built. Different platforms sit at different layers of the stack, face different technical burdens, and contribute differently to what progress requires. Some can iterate quickly because they depend mainly on design, coordination, and software refinement. Others move more slowly because they carry the burden of physical performance: materials quality, fabrication precision, calibration, environmental robustness, and integration with demanding operating conditions.

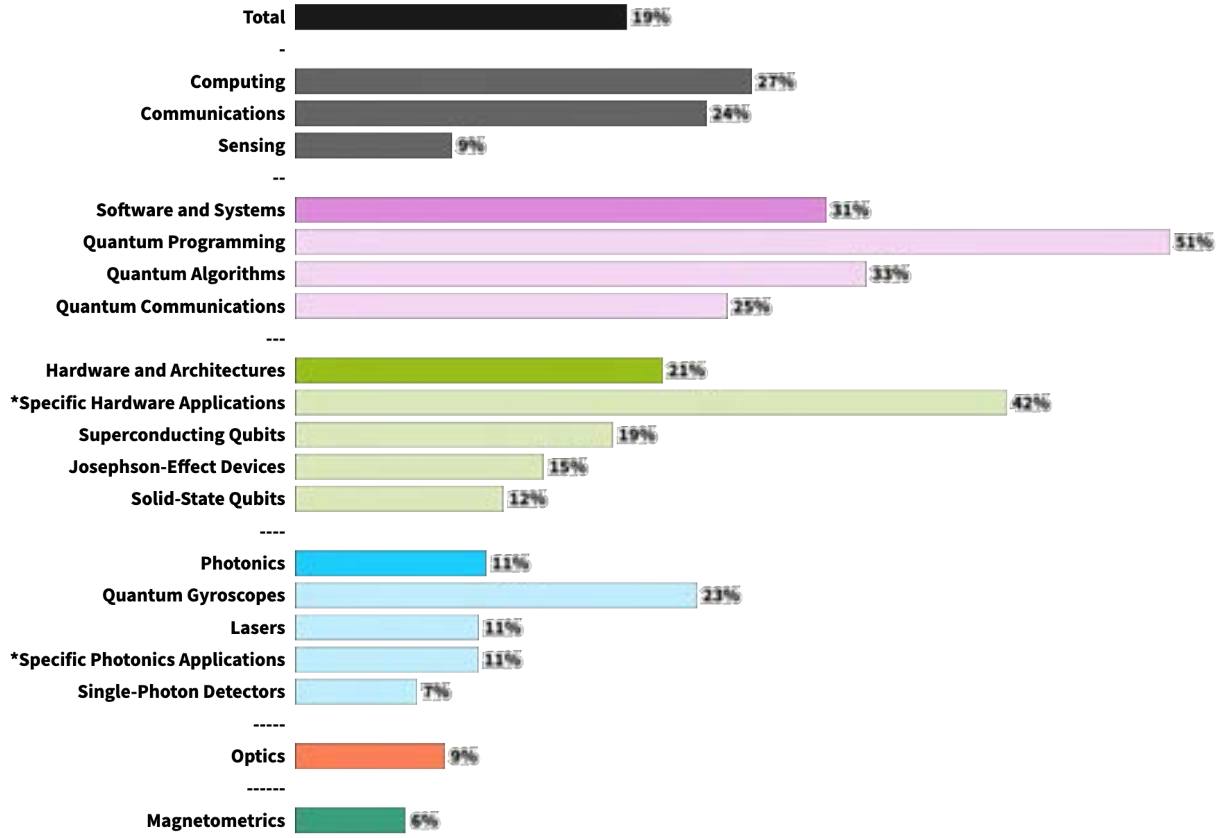
The fastest growth therefore appears where iteration is cheapest and recombination is easiest. Software, algorithms, and control systems can be modified, tested, and redeployed far more quickly than new hardware architectures can be fabricated or new measurement systems can be stabilized. Those upper layers can absorb inventive effort rapidly because they help manage complexity across many parts of the system at once. Their growth is real, but it reflects the relative ease of iteration as much as intrinsic strategic importance.

Lower layers follow a different rhythm. Hardware, photonics, optics, and measurement platforms improve through longer cycles of engineering and validation. Progress there depends on reproducibility, precision, and stability under physical constraints that cannot be solved through abstraction alone. Slower growth at those layers does not signal marginality. It often signals the opposite: these are the parts of the system that determine whether anything above them can become dependable in practice.

Sensing makes that logic especially visible. It is the first application area in which the stack must perform outside controlled settings. Noise, drift, ruggedization, calibration, and compatibility with existing infrastructure become binding there sooner than they do in more insulated research environments. For that reason, slower expansion in sensing-related platforms can coincide with rising strategic importance. The field encounters its hardest real-world tests there first.

Figure 7. Invention growth has been uneven across quantum technology platforms

COMPOUND ANNUAL GROWTH RATE OF QUANTUM INVENTION, 2010 – 2023



* These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens data.

Uneven growth is therefore analytically valuable. It shows where experimentation can spread quickly, where physical constraints still govern progress, and where the system is beginning to differentiate by role. The next section builds on that point by asking a harder question than scale alone can answer: which platforms are becoming more important to how the quantum system develops?

2.3 What uneven growth reveals about how progress is made

Uneven growth does more than show that quantum is moving at different speeds. It reveals how the system is differentiating. Some platforms absorb large volumes of inventive effort without materially changing how the field develops. Others remain smaller by scale but become increasingly important because they stabilize interfaces, support other layers of the stack, or shape how capabilities can be combined and extended. To distinguish growth from structural importance, this section introduces two measures—generativity and emergence—and uses them to show where the field is merely expanding and where it is beginning to reorganize around more consequential capabilities.

2.3.1 Why scale alone fails to capture progress

Growth rates show where inventive activity is expanding. They do not show where progress depends most heavily. In quantum, some parts of the system can scale quickly because they are easier to iterate, recombine, and refine. Software, algorithms, and control systems fall into that category. Other parts move more slowly because they depend on difficult work in materials, fabrication, calibration, and physical engineering. Hardware, photonics, optics, and measurement platforms often face those burdens.

That asymmetry makes changes in invention volume a misleading guide to structural importance. Faster-growing layers can dominate the visible record without determining what the rest of the system can actually do. Slower-growing layers can matter more because they enable, stabilize, or constrain progress elsewhere in the stack. In a field organized around shared platforms rather than isolated applications, a technology's importance cannot be inferred from growth alone. The question, then, is not simply which platforms are getting bigger. It is which ones are becoming more consequential to how the system develops. Answering that question requires measures that capture system role as well as scale.

2.3.2 Generativity and Emergence: diagnosing system-level change

Generativity and emergence provide a way to read progress that growth rates alone cannot. Generativity captures a platform's enabling role within the system. A highly generative platform is one that other parts of the field repeatedly draw on: it appears across invention contexts, supports advances in multiple layers of the stack, and makes further development easier elsewhere. Emergence captures change in that role over time. A platform is emergent when it is becoming more important to how progress is organized, even if its absolute scale remains modest. Generativity shows which platforms the system already depends on. Emergence shows which ones are gaining importance.

These measures deepen the analysis because they distinguish embedded importance from visible activity. A platform can be large and fast-growing without becoming more central to the system. Another can remain smaller while becoming harder to bypass because more of the field depends on it. High generativity with weaker emergence points to a platform that is already deeply embedded in the stack. Rising emergence points to a platform whose system role is strengthening now. Together, the two measures show whether quantum innovation is merely accumulating effort or reorganizing around more consequential capabilities.

That distinction matters in quantum because progress is shaped by shared platforms, layered dependencies, and persistent bottlenecks. Slower-moving layers can remain highly generative because the rest of the stack cannot advance without them. Other layers become emergent when they begin to organize how those bottlenecks are managed, coordinated, or worked around. Generativity and emergence therefore clarify more than where activity is concentrated. They show where structural importance is accumulating and how the system is differentiating as it matures. The next section uses them to trace that change across the stack.

2.3.3 Migration of generative leverage across the stack

Figures 8 and 9 show that generativity and emergence are not distributed evenly across the quantum field. They cluster in three recognizable role patterns. Sensing-adjacent platforms increasingly function as infrastructure: other parts of the system repeatedly depend on them, even when their raw growth is not the fastest. Software and systems function more as organizing layers: their importance rises as coordination, control, and integration become harder. Foundational platforms remain indispensable but internally unsettled, with influence shifting across competing physical approaches rather than converging on a single dominant trajectory.

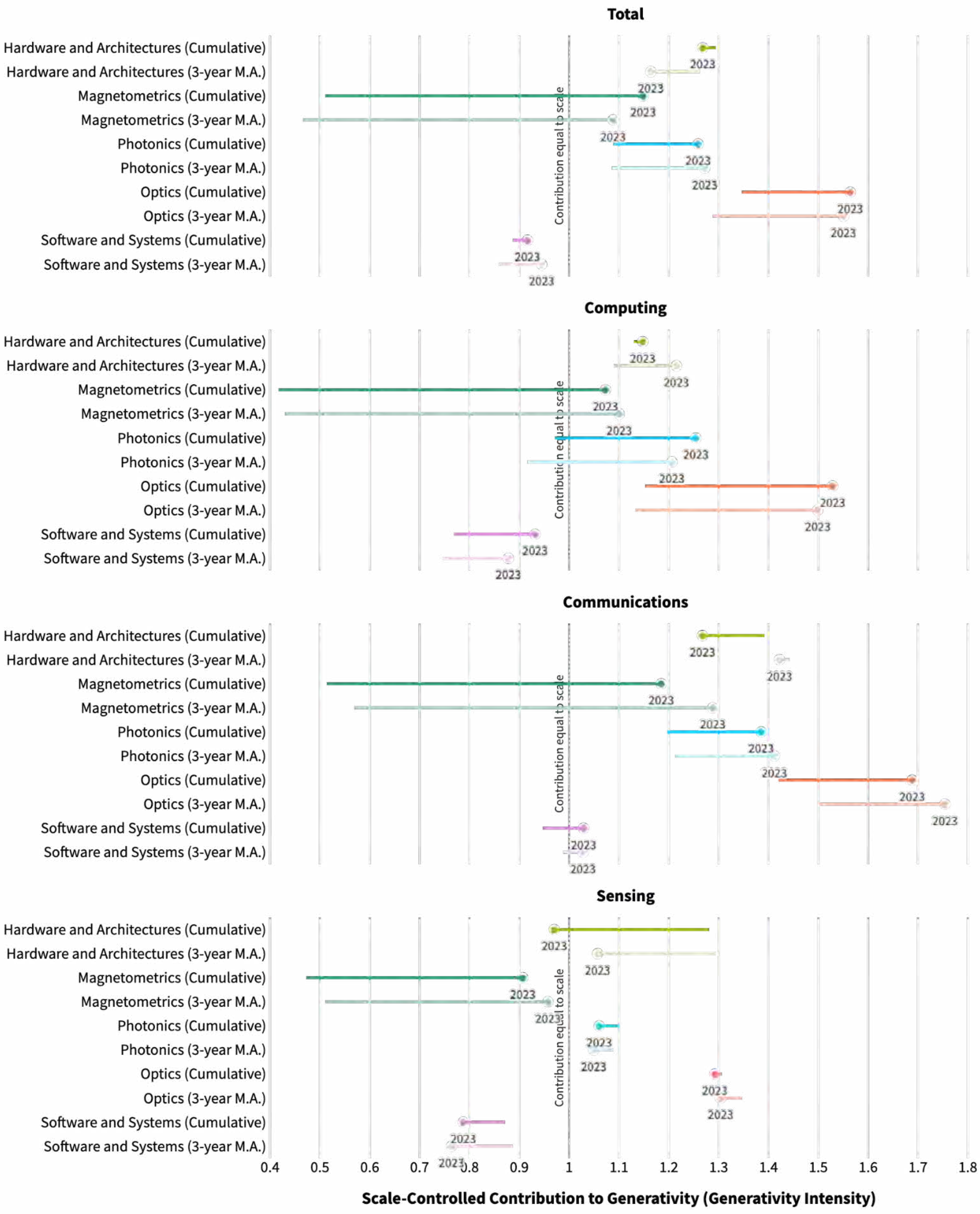
Sensing platforms—magnetometry, photonics, and optics—most consistently occupy the infrastructure role. Across the full quantum system and across the three quantum application areas, they tend to sit above the contribution-equal-to-scale line on both generativity and emergence. The pattern is especially pronounced in computing and communications, where optical and photonic capabilities repeatedly enable advances elsewhere in the stack. Within sensing itself, magnetometry stands out because it links measurement performance to calibration, navigation, and other uses closest to deployment. These platforms remain central because other capabilities repeatedly depend on them.

Software and systems show a different pattern. They account for the largest volume of invention activity in the field, but their generativity and emergence remain closer to the system average, with communications and quantum algorithms as partial exceptions. Their role is growing as coordination, orchestration, and integration become more demanding. But that role is still bounded by the stability of lower-layer hardware, measurement, and interfaces. Software is becoming more consequential, but it is not yet the part of the field that sets the terms for the system as a whole.

Foundational platforms—hardware, architectures, and materials—occupy a more mixed position. They remain highly generative, especially in computing, because the rest of the stack still depends on the physical conditions they create. Their emergence, however, is less uniform. That pattern points less to weakening than to internal reallocation. Influence within the foundational layer is shifting toward particular approaches, including solid-state and superconducting qubits, while smaller capabilities such as cryogenics are gaining importance because they support performance and reproducibility across the wider system. The foundational layer remains indispensable, but its center of gravity is still moving.

Figure 8. Quantum sensing platforms have grown more generative across domains

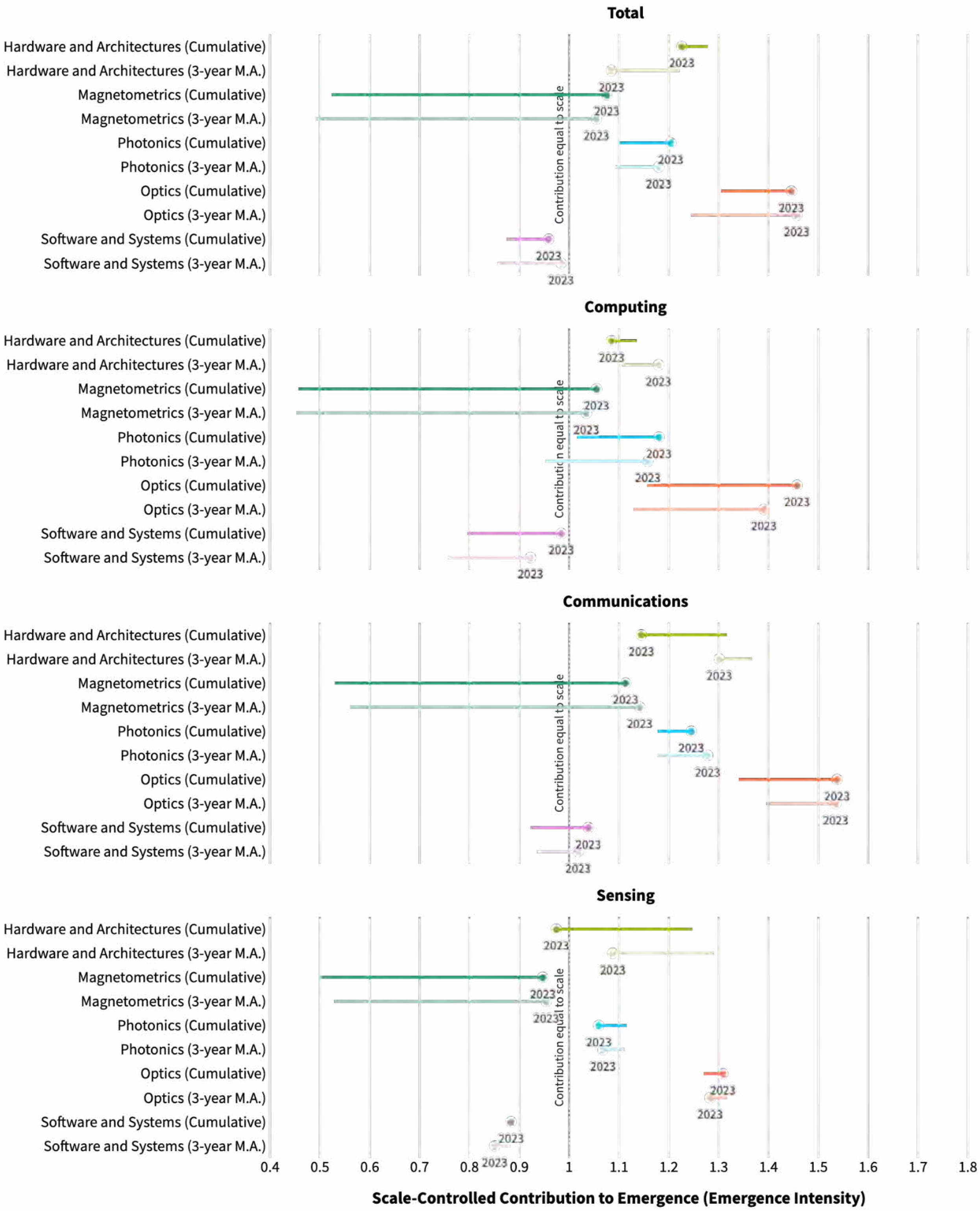
RELATIVE GENERATIVITY OF QUANTUM PLATFORMS, 2013 – 2023



Source: Denizens LLC analysis of Lens data.

Figure 9. Quantum sensing platforms have grown more emergent across domains

RELATIVE EMERGENCE OF QUANTUM PLATFORMS, 2013 – 2023



Source: Denizens LLC analysis of Lens data.

2.3.4 Domain-specific expressions of system change

System change does not unfold uniformly across sensing, communications, and computing. By 2023, sensing sits above the contribution-equal-to-scale line on both generativity and emergence. Communications remains below average on both. Computing, after beginning the period as the most generative application area, trends back toward parity. The field is not advancing along a single trajectory. Each application area reveals a different pattern of dependence, coordination, and constraint within the broader system.

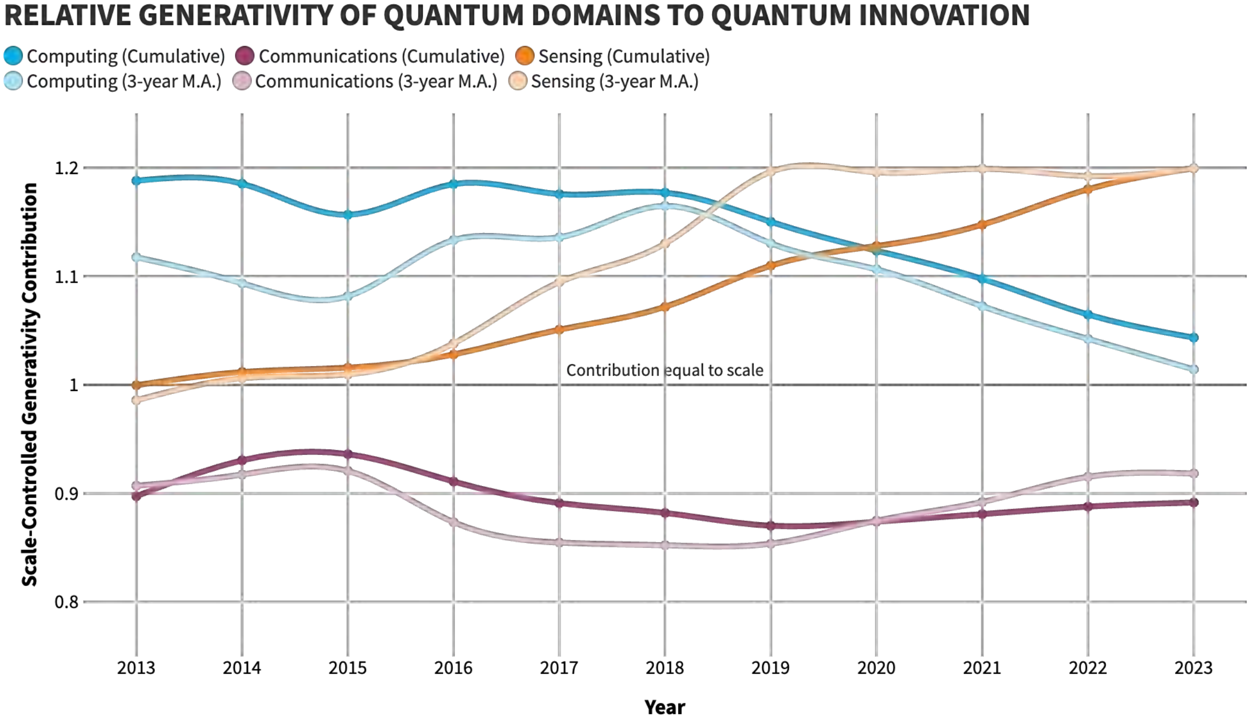
Quantum sensing shows the clearest rise in structural importance. Magnetometry, optics, and photonics carry much of that weight. Hardware remains necessary, but increasingly as part of a broader measurement stack that includes calibration, validation, and systems integration. Sensing can therefore remain smaller by invention volume while becoming more consequential to how the system develops. It is the application area in which measurement, control, and trust have to work together under real operating conditions.

Quantum communications shows a different pattern. Its aggregate scores remain below the system average, but its internal structure points toward rising coordination pressure. Optics and photonics remain central because transmission, detection, and signal integrity still govern performance. Software and systems also play a larger role here than in the field overall because usable communications depend on protocols, synchronization, network management, and fault tolerance across distributed nodes. Communications sits at the boundary between physical capability and system orchestration. Its next gains depend less on isolated device advances than on tighter interface management across heterogeneous components.

Quantum computing follows a third path. It begins the period as the most generative application area, then moves back toward parity as the rest of the system catches up and the field shifts from early exploration toward integration and engineering discipline. Computing remains deeply important, but its influence is no longer exceptional in the way it appeared when the field was more exploratory. Hardware architectures, photonics, and measurement-and-control platforms remain deeply embedded in computing, while software and systems gain importance without escaping the constraints imposed by the layers below. Computing is consolidating, but around unresolved architectures and difficult integration problems rather than a settled dominant design.

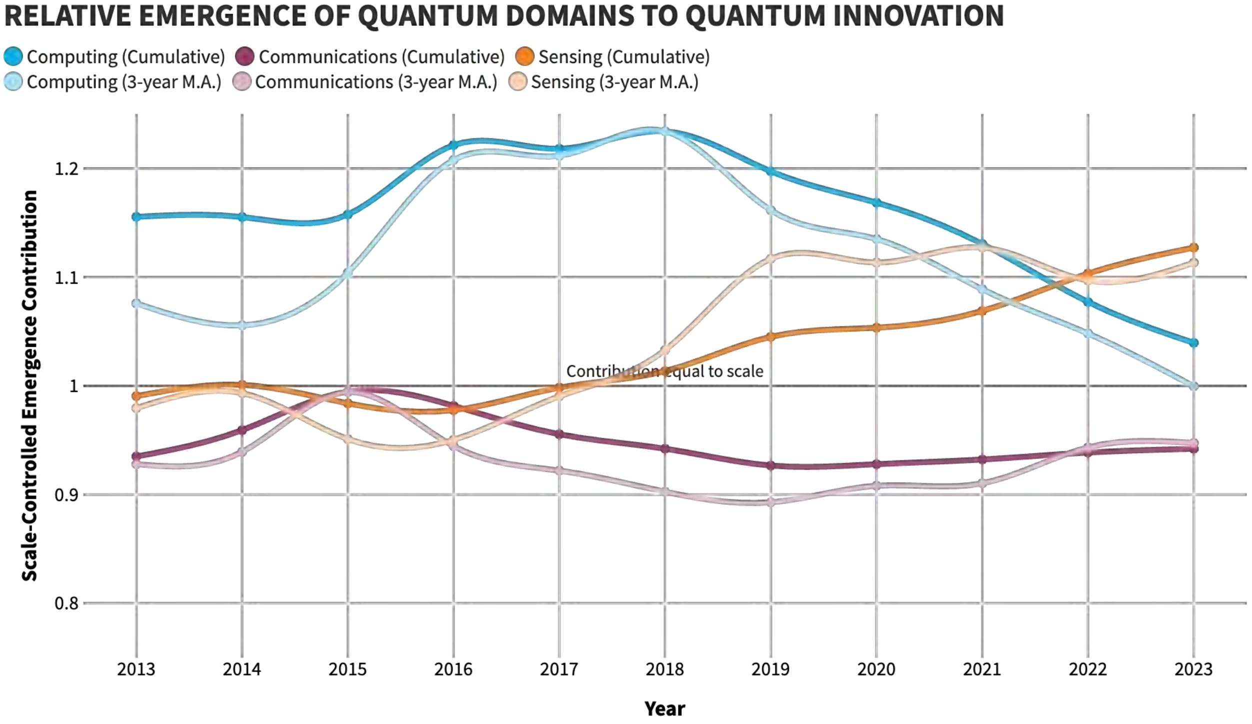
Taken together, these differences show that structural importance is conditional rather than uniform. The same platform does not play the same role everywhere, and the same growth rate does not signal the same kind of progress across the field. Sensing provides the clearest view of system assembly under real-world pressure. Communications highlights the challenge of orchestration across distributed systems. Computing shows how a field can scale rapidly while remaining architecturally unsettled. Those differences help explain why quantum will mature selectively rather than uniformly. The next section takes up that question directly.

Figure 10. The quantum sensing domain became disproportionately generative



Source: Denizens LLC analysis of Lens.org data.

Figure 11. The quantum computing domain grew less generative after the mid 2010s



Source: Denizens LLC analysis of Lens.org data.

2.4 Selective maturation across an unsettled system

Quantum is maturing unevenly. Some platforms are becoming shared infrastructure, some are gaining importance as organizing layers, and others remain unsettled because the physical burdens of reproducibility, calibration, and integration have not yet been resolved. These are roles, not fixed categories. The same platform can play different roles across application areas and at different moments in the system's development. Together, they explain why quantum can show real consolidation without system-wide convergence. Coordination and integration can stabilize before foundational designs settle, and deployment pressures can surface before industrial architectures fully mature. Selective maturation is therefore not a temporary imbalance. It is the form progress takes in a field whose enabling layers are consolidating under physical and institutional constraints.

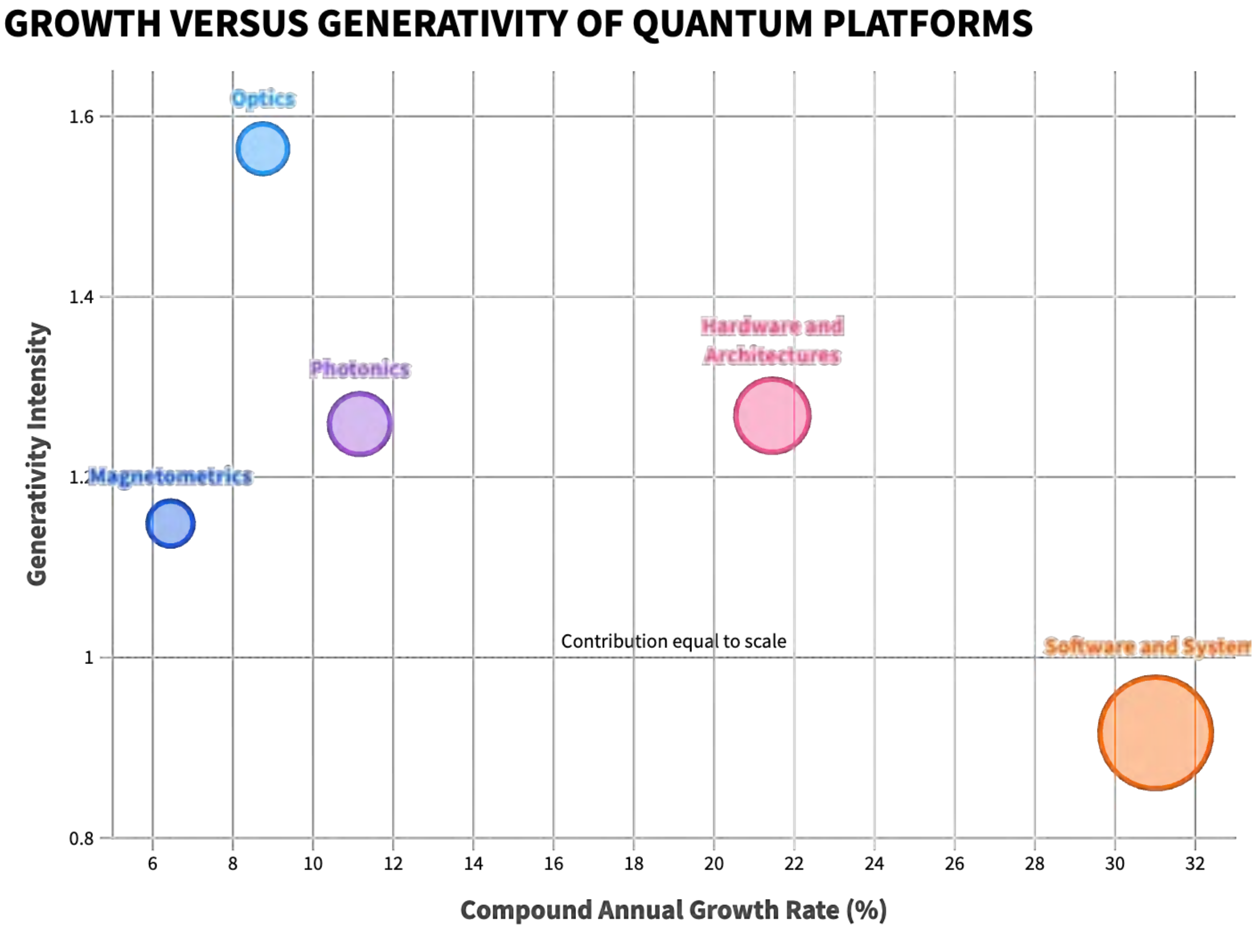
2.4.1 Where maturation is visible

Consolidation is visible first in the platforms that the rest of the system now depends on. Figure 12 makes that shift clear: several physical platforms pair slower invention growth with above-scale generativity. Hardware architectures, photonics, optics, and precision measurement no longer need to be the fastest-growing parts of quantum invention to remain central to it. They are beginning to function less like speculative frontiers and more like infrastructure roles—capabilities that other parts of the stack repeatedly draw on and cannot easily bypass. In a field like quantum, that is one of the clearest signs that maturation is beginning.

A second sign of consolidation appears in the composition of invention itself. Recent activity is doing less to open wholly new technical spaces and more to make existing capabilities function together reliably. More inventive effort is now directed toward control, coordination, readout, and interface work because quantum performance increasingly depends on whether disparate components can be assembled into repeatable systems. Figure 13 points to the same change from another angle: physical layers are carrying more software content, while software remains deeply entangled with physical performance. The field is devoting more attention to system assembly than to isolated proof-of-principle advances.

The generativity and emergence results sharpen this picture. Sensing-adjacent platforms—especially magnetometry, photonics, and optics—have hardened most clearly into infrastructure roles. Software and systems, though still less cumulatively embedded than some physical platforms, are becoming more consequential as organizing layers. The system is not settling around a single finished artifact. It is settling around a narrower set of indispensable layers that other capabilities must repeatedly draw on, coordinate through, and work around. That is where consolidation is real, even as large parts of the foundational layer remain unresolved.

Figure 12. Physical platforms maintain high leverage despite slower growth



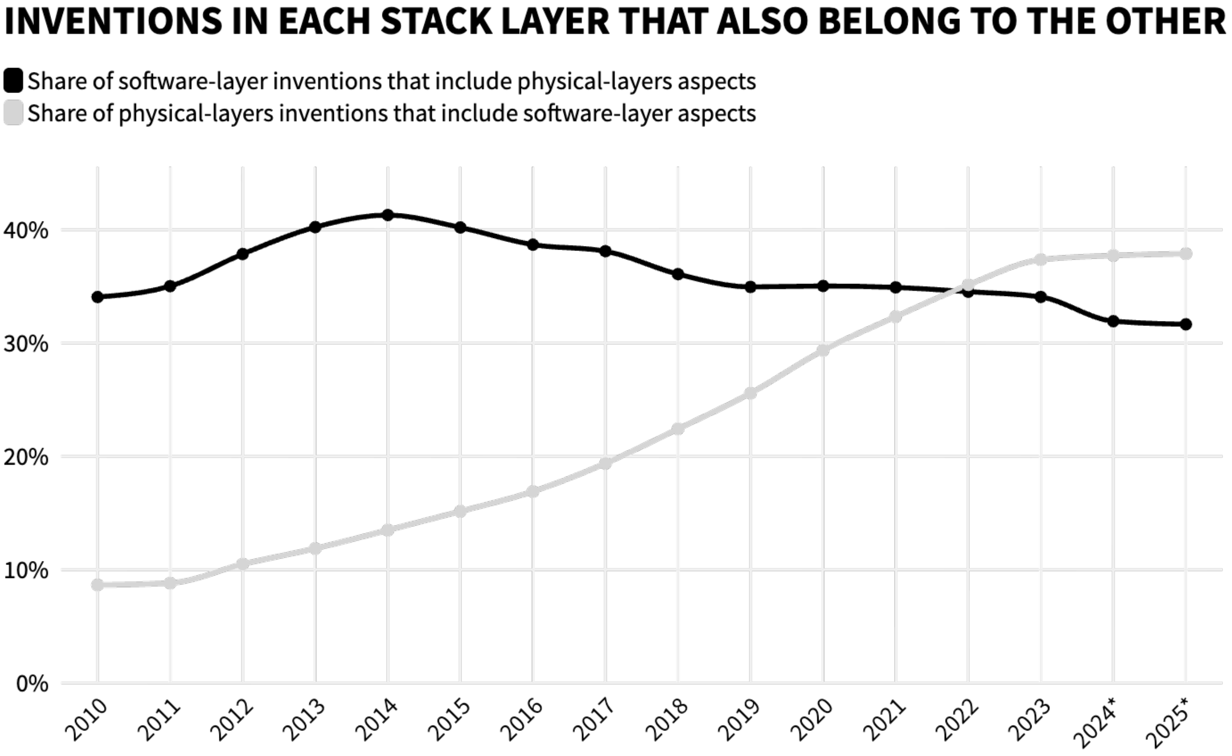
Source: Denizens LLC analysis of Lens data.

2.4.2 *Where maturation has not yet occurred*

Selective maturation does not mean broad readiness. Large parts of the quantum system remain technically unsettled, especially in the foundational layer. Multiple hardware, materials, and device pathways still coexist, and no dominant physical design has emerged across the field as a whole. Emergence scores in these areas remain uneven or volatile because influence is still shifting across competing approaches rather than consolidating around a settled industrial base.

This unsettled condition is clearest where progress still depends on hard-to-reproduce physical capabilities. Hardware architectures, materials systems, fabrication approaches, and device designs continue to show high diversity and low convergence. Progress at those layers remains slow because it depends on long development cycles, specialized facilities, and repeated engineering under tight physical constraints. The field is still trying to make promising physical capabilities reproducible, stable, and manufacturable enough to support broader system growth.

Figure 13. Physical layers increasingly entail software aspects



* Partial year data. • Source: Denizens LLC analysis of Lens data.

Application-specific development remains thin for the same reason. Quantum is discussed constantly in terms of navigation, sensing, communications, optimization, and other end uses, but the invention record still concentrates much more heavily in shared enabling layers than in finished application categories. The field is still building the conditions for deployment more often than it is scaling distinct products or services.

The funding structure points in the same direction. In the most fabrication-intensive and hardware-constrained parts of quantum, public and institutional support still absorb risks that a mature market would normally carry. Cost curves remain unstable, manufacturing yields remain inconsistent, and qualification standards remain incomplete. Those are not peripheral issues. They are signs that the lower layers of the system have not yet stabilized, and that large parts of the field remain in a formative rather than fully consolidating phase.

2.4.3 What selective maturation signals

Selective maturation means quantum will not become ready all at once. Readiness will appear first where a limited number of platforms can be assembled into repeatable systems, where interfaces are stable enough to manage calibration and validation burdens, and where performance can survive outside controlled settings. It will lag where progress still depends on unresolved physical design choices, bespoke fabrication, or difficult environmental constraints. In a field like quantum, maturity is therefore uneven by design.

That pattern changes how growth should be interpreted. Slower growth in one part of the system does not necessarily indicate weakening. It can signal hardening: a shift from exploratory proliferation toward infrastructural importance. Fast growth elsewhere does not necessarily indicate readiness. It may instead reflect continued experimentation in layers that still depend on unresolved bottlenecks below. Scale remains informative, but it is a poor guide to readiness on its own.

The same logic helps explain where commercialization pressure will emerge first. It will cluster around the parts of the system where integration can no longer be deferred—where devices must be calibrated, validated, and connected to existing workflows with tolerable levels of friction. Those thresholds will not be crossed uniformly across the field. They will appear unevenly, by platform and by quantum application area, as parts of the stack become dependable enough to support real use.

The central question, then, is no longer whether quantum is early or mature in the abstract. It is where the stack is hardening, where interfaces are becoming repeatable, and where unresolved bottlenecks still govern what can move from the lab into the world.

* * *

Chapter 2 shows that quantum progress is not simply a matter of rising scale. The system is differentiating. Some platforms are hardening into shared infrastructure, some are becoming more important as coordination layers, and others remain unsettled because the physical and engineering burdens of reproducibility, calibration, and integration have not yet been resolved. That is why growth alone is a poor guide to readiness. Faster expansion can still reflect experimentation, while slower growth can mark the hardening of capabilities the rest of the system increasingly depends on.

This is the practical meaning of selective maturation. Quantum will not become usable all at once, and it will not do so evenly across the stack. Readiness will surface first where interfaces become repeatable, validation burdens can be managed, and a limited number of platforms can be assembled into dependable systems under real operating conditions.

Sensing is the quantum application area where those pressures arrive earliest and most clearly. It is where the stack must first survive contact with noise, calibration demands, legacy infrastructure, and the practical requirements of users who need measurements they can trust. For that reason, sensing offers one of the clearest views of how the broader quantum system is moving from laboratory performance toward operational use.

3. Quantum sensing: reality, leverage, and limits

Quantum sensing is where the quantum technology system meets the world. In computing and communications, architectures can advance for long periods inside controlled environments and still defer some of the hardest questions of deployment. Sensing does not have that luxury. A sensor must hold performance under vibration, drift, thermal fluctuation, electromagnetic interference, and size, weight, and power constraints.[34] It must also deliver measurements that can be calibrated, validated, and used inside existing workflows. It is the first quantum application area in which stack integration is tested under operational conditions, and the first place where the system's bottlenecks become fully visible.

That role is easiest to see when sensing is treated less as a device category than as a deployable measurement stack. The relevant unit is not a stand-alone gravimeter, magnetometer, or clock. It is the assembled system that prepares and controls quantum states, extracts a signal, compensates for noise, maintains calibration, validates output against a reference, and embeds the result in software and decision routines that users can trust.[35] The invention record supports that reading. Since 2010, sensing accounts for 8,402 quantum-related inventions globally, well below computing and communications in raw volume. Yet 29.0 percent of sensing inventions overlap with computing, and 16.8 percent overlap with communications. Its smaller footprint understates its structural role because sensing advances only when multiple layers of the stack close at once.

That structure makes sensing strategically revealing. Several sensing modalities now have credible technical pathways, and some have moved beyond laboratory proof into field trials. Wider use remains constrained by harder problems: custom-built hardware, unstable calibration outside controlled settings, thin qualification pathways, and difficult interfaces with classical infrastructure. Most quantum sensing systems are still assembled for specific research or demonstration contexts. Shared performance benchmarks remain limited. Common interfaces remain sparse. Agreed calibration standards are still uneven. Integration work therefore must be redone from case to case. Commercial progress is slow for a precise reason: fragile measurement performance still must be made repeatable, certifiable, maintainable, and usable.

For advanced sensing and evironmental decision-making (or "ASCEND) technologies, that distinction matters. ASCEND applications do not sit outside the broader sensing story; they depend on the same photonics, optics, control, metrology, and integration layers that govern deployment across the field.[36] But ASCEND remains a bounded applied thread within a much larger quantum sensing universe. The strategic question is not whether isolated quantum devices can already transform environmental decision-making at scale. It is whether the underlying measurement stack is closing in ways that will make those ASCEND pathways credible over time, and whether the Mountain West is positioned in the technical layers where that closure is most likely to happen.

The chapter proceeds from that premise. It begins by examining sensing's role as a systems integrator across the three quantum application areas. It then turns to the enabling platforms that shape sensing performance, the bottlenecks that separate laboratory modality from deployed system, and the structural logic of dual-use pathways. It closes by identifying why ASCEND-relevant applications remain largely pre-invention and which signals matter most in judging whether that condition is beginning to change.

3.1 Quantum sensing as a systems integrator

In raw invention volume, sensing sits below the other two quantum application areas in the corpus used for this report. Since 2010, the global record contains 8,402 sensing inventions, compared with 13,370 in computing and 13,148 in communications. Read on its own, that gap can invite the wrong conclusion: that sensing is a narrower field whose importance will rise only after progress elsewhere diffuses into it. The evidence points in a different direction. Sensing is smaller because it reaches operational constraints earlier. It must convert fragile quantum effects into stable measurements under real-world conditions, which raises the threshold for useful progress.[37]

The overlap pattern makes that role visible. Of the 8,402 sensing inventions in the corpus, 2,440 also sit in computing, and 1,414 also sit in communications. That means 29.0 percent of sensing inventions overlap with computing, and 16.8 percent overlap with communications. These are not trivial spillovers. They show that sensing progress is frequently assembled through multi-layer systems in which measurement, control, signal extraction, and computation advance together. In practice, many quantum sensing pathways depend on the same enabling work that supports the other quantum application areas: photonics, precision optics, control electronics, readout, software, and calibration routines.[38] Sensing, therefore, reveals the degree to which the broader quantum system is integrating rather than merely expanding.

Sensing is best understood as a systems integrator precisely because it reveals whether the broader quantum system is integrating rather than merely expanding. Within the stack established earlier in the report, it occupies the position where quantum performance must hold inside legacy infrastructure, noisy environments, and user workflows. A sensing capability becomes meaningful only when several layers close at once: state preparation and control, readout and signal extraction, environmental compensation, calibration and validation, and the software needed to turn a measurement into a trusted output. The relevant unit is not an isolated device. It is a deployable measurement stack. When that stack fails, the problem is rarely confined to the sensor alone. It usually sits in the interfaces between hardware, photonics, metrology, software, and the operating context into which the system is being inserted.[39]

This also clarifies how maturity should be read. Sensing can be ahead in scientific and prototype maturity while still lagging in engineering and institutional maturity. The underlying measurement principle may be sound. A field trial may be credible. Yet deployment can still stall because the system is difficult to ruggedize, expensive to calibrate, hard to manufacture reproducibly, or unable to enter qualification and procurement channels. Those are not secondary frictions. They determine whether performance holds up outside controlled settings and whether users can trust the results enough to change practice. In sensing, the gap between demonstration and use often lies between a promising modality and a completed stack.[40]

The reciprocal overlaps reinforce the same point. Sensing appears in 18.2 percent of computing inventions and 10.8 percent of communications inventions. That pattern is consistent with a field in which measurement, control, and signal integrity shape performance ceilings across the wider quantum system. Sensing is where those ceilings become visible first, because it is where the system must deliver an output that can be calibrated, interpreted, and acted on. For that reason, sensing is one of the clearest early tests of whether quantum technologies are becoming usable in practice. It is also the most revealing place to judge whether application threads relevant to ASCEND technologies are moving beyond conceptual adjacency and toward systems that can be embedded in environmental measurement, geospatial workflows, and decision support.[41]

3.2 Enabling platforms shape sensing

The structure of quantum sensing becomes clearer when the analysis moves from quantum application-area totals to platform composition. Quantum sensing has fewer inventions than computing and communications. Platform composition shows why that smaller footprint understates its importance. The sensing portfolio is concentrated in photonics, precision optics, hardware, magnetometry, instrumentation, and a meaningful systems layer: the enabling platforms that make fragile quantum effects measurable, stable, and usable. That concentration matters because downstream pathways depend on whether the underlying measurement-and-control infrastructure is robust enough to support deployment.[42] Figure 14 points to that underlying structure. It shows a sensing portfolio built around photonics, optics, hardware, magnetometry, and a meaningful systems layer, rather than a thick field of isolated end-use applications.

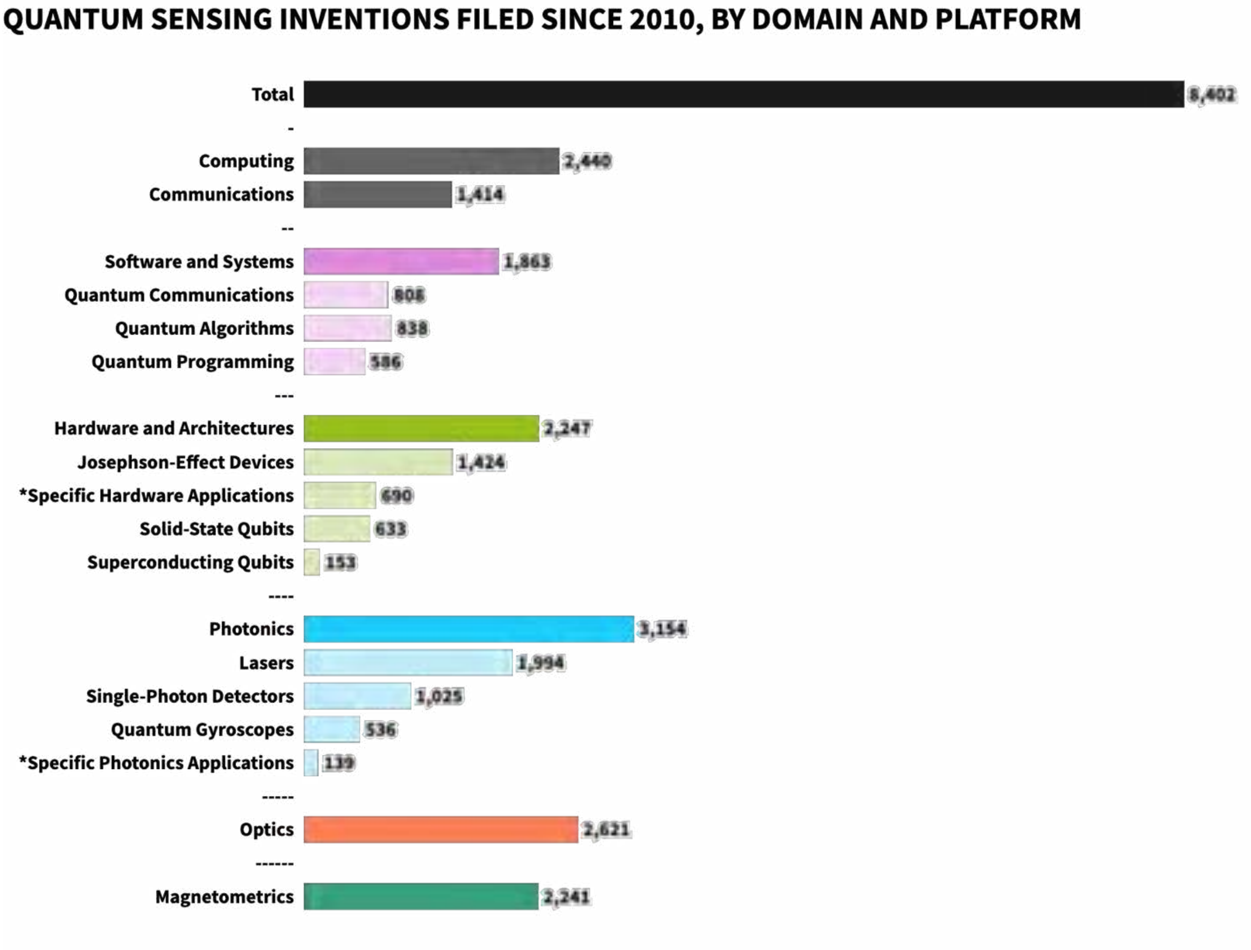
That distribution places the center of gravity of quantum sensing upstream, in the enabling and integration layers, where deployment capability is established. The field's strongest signals do not lie mainly in application-specific claims. They lie in the deeper platforms that determine whether sensing performance can survive outside the lab: photonics, precision optics, instrumentation, control, and the software needed to translate measurement into operational use.[43] For ASCEND technologies, that is the relevant read. The strongest signals do not sit only in application-specific claims about environmental measurement. They sit in the deeper layers—photonics, precision optics, instrumentation, control, and integration—that determine whether those applications can become fieldable.

3.2.1 Platform concentration evidence

Platform concentration within sensing is sharp. Photonics appears in 3,154 sensing inventions, or 37.5 percent of the sensing corpus. Optics appears in 2,621, or 31.2 percent. Hardware and architectures appear in 2,247, and magnetometry in 2,241; both account for 26.7 percent. Software and systems appear in 1,863 inventions, or 22.2 percent. Quantum gyroscopes appear in 536, or 6.4 percent. That distribution shows a field organized around the platforms required to generate, control, read out, and stabilize measurement. It does not show a field led primarily by downstream products.[44]

The largest clusters sit close to the measurement layer of the stack. Photonics and optics support interferometric measurement, frequency stabilization, high-performance detection, and the light-matter interfaces used in cold-atom and solid-state systems. Hardware and magnetometry reinforce the same pattern from another direction. They anchor sensing in the physical layers where signal quality, control fidelity, and environmental robustness are decided.[45] Figure 14 makes that structure visible by showing sensing's strongest nexus with measuring and hardware platforms rather than with a broad downstream applications layer.

Figure 14. Sensing has a strong nexus with measuring and hardware platforms



* These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens data.

Software and systems give the platform profile a second center of gravity. A 22.2 percent share is too large to treat as peripheral. It places control routines, signal processing, stabilization, validation support, and interoperability inside the inventive core of sensing rather than after it. Sensing is already doing the engineering work required to make measurement usable, not just the physics required to produce it.[46]

The platform mix, therefore, points to early system assembly. Quantum sensing still depends most heavily on enabling layers near signal generation and readout. But it is already pulling organizing layers into the same inventive space. That combination marks a field moving toward deployable capability through stack closure rather than through isolated device breakthroughs.[47]

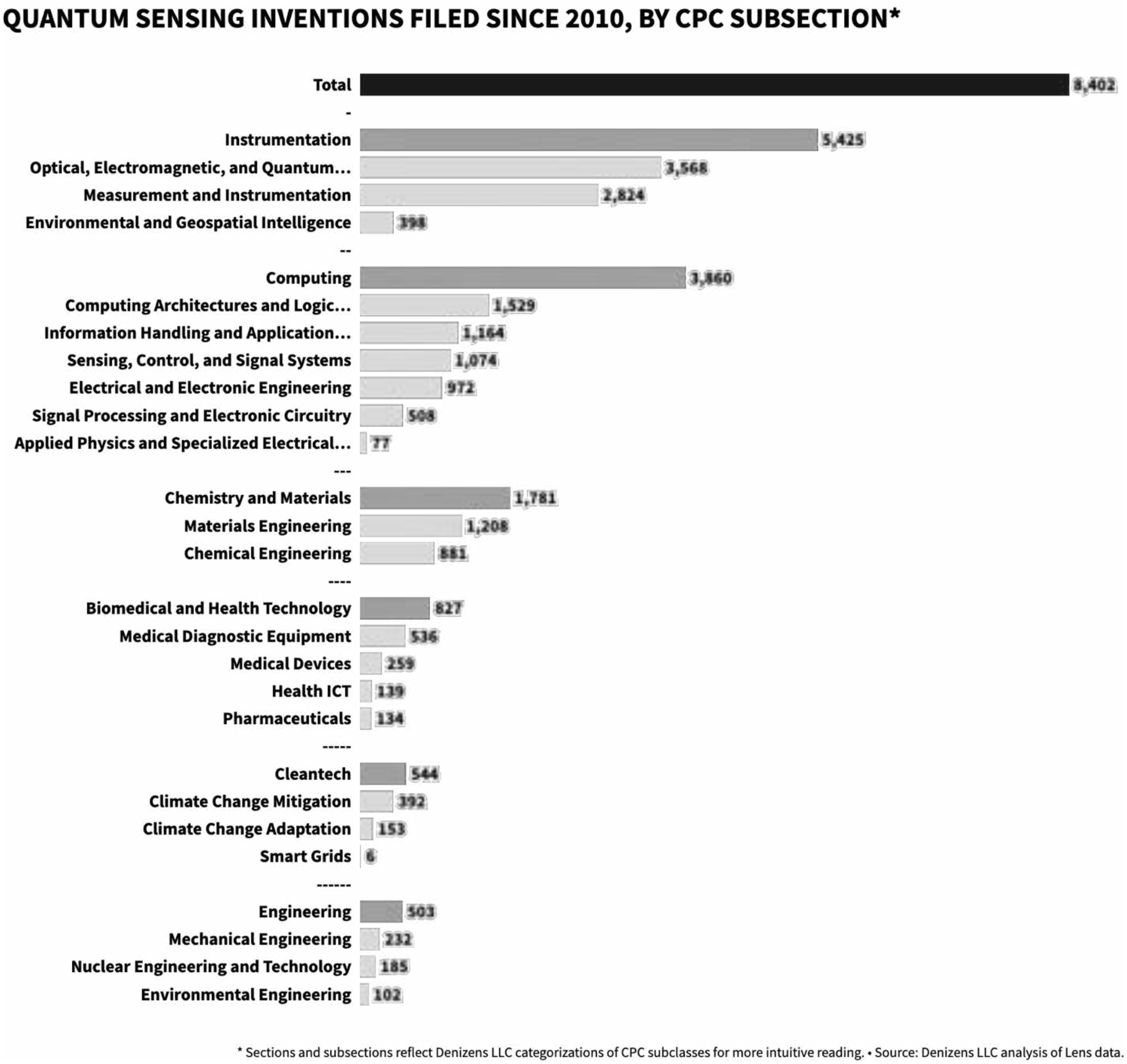
3.2.2 CPC composition evidence: sensing is stack-led

The CPC composition shows more precisely what quantum sensing inventions are doing. These counts are cumulative section- and subsection tallies rather than mutually exclusive bins, which makes them useful for identifying where inventive effort is concentrated within the stack. On that basis, sensing remains weighted toward instrumentation, computing, and chemistry and materials rather than toward a thick layer of downstream use cases. Instrumentation accounts for 12,215 CPC counts, or 41.7 percent of the sensing corpus. Computing accounts for 9,184, or 31.4 percent. Chemistry and materials account for 3,870, or 13.2 percent. By comparison, biomedical and health technology accounts for 1,895 counts, cleantech 1,095, and engineering 1,022. Figure 15, therefore, shows a field whose inventive center of gravity still sits in metrology, control, and component performance.[48]

Instrumentation is the clearest example. Within that cumulative total, Figure 15 shows 5,425 counts in the broader instrumentation section, alongside 3,568 in optical, electromagnetic, and quantum measurement, 2,824 in measurement and instrumentation, and 398 in environmental and geospatial intelligence. The emphasis is unmistakable. Much of what is being invented under the banner of quantum sensing remains concentrated in the means of measurement itself: readout architectures, metrology, calibration routines, and the technical systems required to convert fragile quantum effects into signals that can be trusted outside controlled settings.[49]

The computing composition points in the same direction. Figure 15 shows 3,860 counts in the broader computing section, plus 1,529 in computing architectures and logic, 1,164 in information handling and application, 1,074 in sensing, control, and signal systems, 972 in electrical and electronic engineering, 508 in signal processing and electronic circuitry, and 77 in applied physics and specialized electrical systems. Sensing progress is, therefore, already entangled with control loops, interpretation pipelines, and the electronic systems that stabilize and use the measurement. The relevant unit is not an isolated sensor. It is a measurement stack whose performance depends on how successfully quantum readout, classical electronics, and software control are made to work together.[50].

Figure 15. Sensing primarily relies on instrumentation and computing technologies


QUANTUM SENSING INVENTIONS FILED SINCE 2010, BY CPC SUBSECTION*

* Sections and subsections reflect Denizens LLC categorizations of CPC subclasses for more intuitive reading. • Source: Denizens LLC analysis of Lens data.

Chemistry and materials add a third constraint. Figure 15 shows 1,781 counts in chemistry and materials, 1,208 in materials engineering, and 881 in chemical engineering. Those numbers are smaller than instrumentation and computing, but they remain substantial because they point to manufacturability, component quality, and the specialized substrates on which many sensing pathways depend. Sensing cannot be scaled by software and systems work alone. It still depends on materials quality, fabrication control, and specialized optical and solid-state inputs that remain difficult to reproduce consistently. That aligns with the broader stack logic developed earlier in the report, where foundational materials and device architectures continue to act as binding constraints on higher-layer progress.[51]

The smaller application-facing categories matter precisely because they are smaller. Biomedical and health technology, cleantech, and engineering are present, but they remain far thinner than instrumentation and computing. The implication is straightforward. Quantum sensing is still doing the hard upstream work of stack completion. It is building the metrology, control, materials, and integration base that later application pathways will depend on. Adoption narratives should therefore be read cautiously. A field this heavily weighted toward instrumentation, computation, and materials remains closer to enabling and integration work than to broad downstream diffusion.[52]

3.2.3 Generativity through integration layers

The composition of inventions by technology platform shows where sensing activity concentrates. Generativity and emergence show which of those platforms do more work for the wider quantum system than size alone would suggest. As Figures 8 and 9 show, magnetometry, photonics, and optics all sit above the "contribution equal to scale" line on both measures. They are therefore not simply large parts of the sensing portfolio; they are disproportionately influential parts of the quantum stack.[53]

That pattern is consistent with the role these technologies play across the three quantum application areas. They recur wherever quantum systems need signals to be generated, stabilized, read out, calibrated, and interpreted under real operating conditions. In that sense, they behave as infrastructure. Advances in these layers do not stay confined to a single sensing modality. They propagate into computing and communications because they solve shared problems of measurement, control, and interface management.[54]

This is why sensing can remain smaller in invention volume while becoming more structurally important. Its leverage lies in the platforms the rest of the system repeatedly depends on to measure, trust, and translate quantum performance into usable information. The practical implication is that the strongest readiness signals in sensing will appear where these enabling platforms begin to close together with the organizing layers above them: where photonics, optics, hardware, and control systems support repeatable measurement; where calibration and validation become more routine; and where outputs can move into workflows that users can trust. For ASCEND-relevant pathways, that is the threshold that matters.[55]

3.3 From lab modality to deployed system

With the platform profile in view, the next question is practical: which sensing stacks are closing credibly enough to matter outside the lab? Progress is uneven because deployment burdens are not evenly distributed across modalities. Some pathways attach to established operational primitives such as timing, navigation, gravity, and magnetic-field measurement, which gives them clearer routes into existing systems. Others remain technically credible but more integration-heavy, which slows translation even when measurement performance is promising. The relevant test is therefore not whether a modality works in principle. It is whether the stack around it is closing far enough to support field use.

3.3.1 Leading modality pathways

The first pathway is precision timing and resilient position, navigation, and timing. Atomic clocks, quantum inertial sensors, accelerometers, and gyroscopes sit closest to established operational architectures in navigation, synchronization, and communications. That gives them unusually high deployment pressure because they can improve existing systems without requiring wholesale redesign. It also raises the validation bar because error costs are high in navigation and timing-dependent settings. In these pathways, progress depends less on discovering entirely new sensing concepts than on making systems smaller, more stable, and easier to package and certify. Ruggedization, calibration, and assurance are not secondary tasks here. They are the product.[56]

A second pathway is cold-atom interferometry for gravimetry and inertial measurement. This is one of the clearest examples of a technically credible but integration-heavy stack. The measurement principle is strong, but deployment depends on photonics, stabilization, vacuum control, environmental isolation, and control software operating together over long periods. Gravimetric and inertial systems, therefore, should not be read as stand-alone sensor products. They are assembled systems whose readiness depends on whether the underlying optical, control, and packaging burdens can be reduced enough for field conditions. That makes them strategically important, but it also means translation will remain selective until more of the supporting stack hardens.[57]

A third pathway is quantum magnetometry, including NV-center approaches in diamond and optically pumped magnetometers. These systems are attractive because they can, in principle, deliver high sensitivity in compact formats and support dual-use functions in navigation resilience, subsurface characterization, industrial inspection, and defense-relevant sensing. But compactness alone does not settle readiness. Performance remains tightly coupled to materials quality, readout engineering, and noise management. A magnetometer can demonstrate strong device-level performance yet still face slow deployment due to inconsistent fabrication, calibration drift under field conditions, or interfaces with existing data and control systems that remain bespoke. The constraint sits in stack closure, not in device sensitivity alone.[58]

A fourth pathway is quantum-enhanced optical and photonic sensing, including squeezed-light techniques and related photonic upgrades to existing measurement architectures. These are often best understood as enhancement layers rather than wholly separate device markets. That distinction matters because upgrade pathways can move through existing instrumentation and procurement channels faster than entirely new sensing classes can. Where a quantum technique improves a familiar architecture, the route to adoption may run through interface stabilization, calibration, and procurement qualification rather than through the creation of a new market category. That does not make deployment easy, but it often makes it more legible.

3.3.2 Deployment bottlenecks

Across these pathways, the binding constraints on deployment sit less in scientific feasibility than in engineering closure and system integration. The same bottlenecks recur because quantum sensing systems still depend on fragile measurement conditions being translated into repeatable operational performance, which is why commercially promising modalities can remain thin for extended periods even when the underlying physics is sound.

Miniaturization and portability remain the first bottleneck. Many leading sensing pathways still rely on optical benches, vacuum systems, specialized lasers, and precise alignment or isolation. Moving from that laboratory apparatus to fieldable form factors requires integrated photonics, microfabrication, packaging, and thermal management to improve together. The work is often incremental, but it is decisive: a system that cannot be packaged into an operational footprint is not yet deployable.[59]

Ruggedization and reliability are the second bottleneck. Field performance is tested over long duty cycles and across variable environments, not under controlled laboratory conditions. Vibration, temperature fluctuations, electromagnetic noise, maintenance burdens, and operator handling all matter because they determine whether performance holds up outside demonstration settings. In aviation, infrastructure, and defense-relevant use cases, reliability often governs adoption more than peak sensitivity does. A sensing advantage that cannot be sustained is not operationally meaningful.

Calibration, validation, and standards form the third bottleneck. As sensors become more sensitive, they also become more exposed to drift, systematic error, and environmental confounders. Readiness, therefore, depends on calibration regimes, cross-checking protocols, and qualification pathways that can establish trust in the output. Part of that work is technical, but a large part is institutional: standards bodies, test infrastructure, field-validation environments, and buyers willing to define qualification thresholds. Without those supports, performance claims remain difficult to compare and hard to procure against.[60]

Manufacturing and industrialization are the fourth bottleneck. Even when prototypes are credible, scaling requires repeatable fabrication, stable component supply, specialized materials, facilities, and workforce capabilities. Many sensing systems still behave like bespoke prototypes because each deployment carries its own materials, process, and integration history. That limits learning curves and keeps costs high. The shift that matters is not from invention to product launch in the abstract. It is from custom assembly to repeatable production.

Workflow embedding and classical integration are the fifth bottleneck, and often the decisive one. Measurement does not create impact on its own. It has to enter models, analytics, control systems, operational procedures, and procurement channels that were not designed around quantum subsystems. Interoperability is hard for a simple reason: most current sensing systems are still built to custom specifications for specific research or demonstration settings. Shared performance benchmarks remain limited, common interfaces remain sparse, and agreed calibration standards are uneven. Every deployment, therefore, requires expensive, from-scratch integration work, which is why promising modalities remain commercially thin even when the underlying physics is sound. Until outputs can move reliably through legacy infrastructure and decision workflows, measurement improvements will not convert cleanly into operational advantage.[61]

3.3.3 Interpreting readiness signals

These modalities and bottleneck patterns are often misread in public discussions of quantum sensing. The most common mistake is to treat laboratory sensitivity as field performance. Under controlled conditions, quantum sensors can show exceptional sensitivity. Field conditions introduce noise sources, drift mechanisms, reliability constraints, and maintainability burdens that can dominate effective performance. Timelines inferred directly from laboratory benchmarks, therefore, tend to overstate near-term deployability.

A second mistake is to treat demonstrations as deployable systems. Prototypes can validate a measurement principle without resolving the engineering and institutional requirements that govern use in the world: packaging, calibration, sustainment, cost, certification, manufacturability, and integration. Demonstrations matter because they narrow uncertainty. They do not settle readiness on their own because a valid principle still has to survive the full stack around it.

A third mistake is to treat measurement improvement as decision improvement. Even when a system produces a stronger or cleaner measurement, operational value depends on interpretation and use. Data must be fused with other sources, assimilated into models, routed through procedures, and trusted by institutions that have to act on it. The stack that matters therefore extends beyond the sensor and even beyond the immediate control system. It includes the workflow and institutional layers that allow a measurement to change practice.[62]

The strongest readiness signals are the ones that show stack completion rather than isolated performance. Calibration regimes, field-validation infrastructure, industrial integration capacity, qualification pathways, workflow embedding, and early procurement or testbed activity are more informative than sensitivity claims presented without a route through the systems layer. Those signals do not mean that broad diffusion is imminent. They mean that, in specific operational contexts, the work of system assembly is becoming unavoidable and therefore fundable. That is the threshold that matters for judging which sensing pathways are actually moving from technical plausibility toward deployment.

3.4 Dual-use sensing is structural, ASCEND is pre-invention

A stack-based reading of quantum sensing yields two strategic implications. In the near term, the sensing stacks closing most credibly create dual-use leverage by improving measurement primitives—time, motion, gravity, and magnetism—that operate within both civilian infrastructure and defense operations. Over a longer horizon, many climate and environmental pathways remain ASCEND-like and pre-invention: scientifically plausible, increasingly legible, but still constrained by thin invention density and by the systems-layer requirements that determine whether measurement can become a trusted capability.

3.4.1 Dual-use is structural

Dual-use in quantum sensing follows from the leading modalities themselves. Precision timing, inertial sensing, gravimetry, and magnetometry enhance operational functions foundational across domains. Positioning, navigation, and timing systems depend on more resilient measurement of time and motion. Subsurface and geospatial systems depend on better measurement of gravity and magnetic fields. Communications, infrastructure monitoring, logistics, and defense operations all rely on the same underlying primitives. Dual-use, therefore, does not appear at the end of the commercialization process as a secondary market option. It is built into the measurement problems the field is already solving.[63]

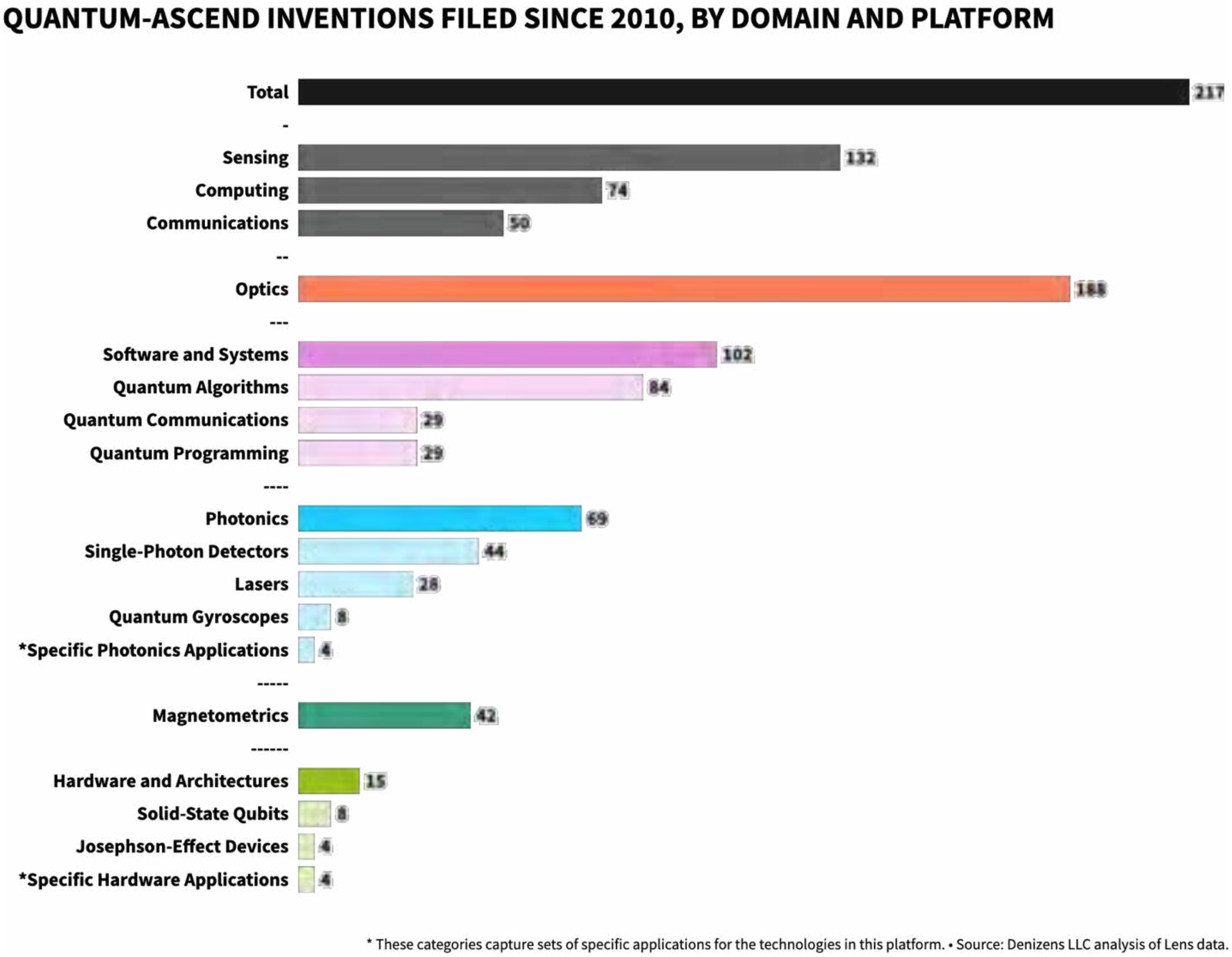
That logic becomes clearer when sensing is read as a stack-embedded capability rather than as a device category. Navigation resilience is not a component story. It depends on a larger architecture that links measurement to control systems, data fusion, and often communications. Gravimetry and magnetometry do not create value as isolated readings. They become consequential when embedded in survey systems, mapping workflows, and operational decision pipelines. The same stack logic that makes sensing diagnostic also makes dual-use structural. Once a measurement capability is tied to foundational operational functions, the boundary between civilian and defense relevance dissolves.

The consequence is that sensing can become materially important through gradual capability increments rather than through a dramatic break to entirely new deployed systems. Improvements in navigation reliability, detection performance, or mapping fidelity can shift operational thresholds without requiring a discontinuous market transition. Decision-makers should therefore assess sensing trajectories as improvements to system-embedded capabilities, not as a search for standalone quantum sensor markets.[64]

3.4.2 ASCEND remains pre-invention

The ASCEND-relevant promise of quantum sensing is real. Plausible pathways exist across subsurface and hydrological inference, geospatial measurement, remote sensing, and detection methods relevant to environmental and infrastructure intelligence. In that sense, the field is conceptually and scientifically adjacent to ASCEND technologies. The question is whether the invention base and the surrounding systems layer are robust enough to support an emerging application frontier. On that test, the evidence still reads as pre-invention.[65]

Figure 16. Quantum applications to ASCEND remain limited



QUANTUM-ASCEND INVENTIONS FILED SINCE 2010, BY DOMAIN AND PLATFORM

* These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens data.

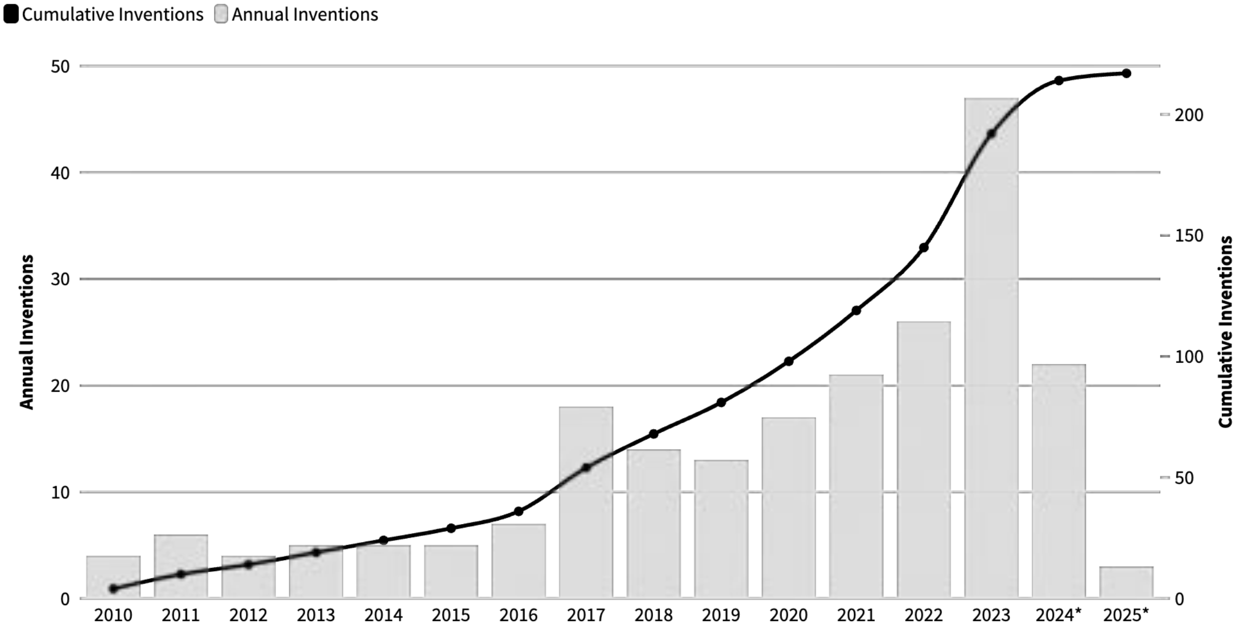
Figure 16 makes that pattern visible. The full quantum-ASCEND technology overlap surface contains 217 inventions filed since 2010. Within that set, 132 sit in sensing, 74 in computing, and 50 in communications. The platform profile is even more revealing. Optics accounts for 188 of those inventions, software and systems for 102, photonics for 69, magnetometry for 42, and hardware and architectures for only 15. That is not the profile of a thick application frontier. It is the profile of a space in which enabling science and system-adjacent platforms are present, but application buildout remains sparse and uneven.

Figure 17 points in the same direction, but with an important nuance. New quantum-ASCEND inventions have risen in recent years, and the strongest annual uptick arrives only very recently. That matters because it suggests growing legibility around the intersection. It does not yet indicate mature readiness. Growth from a small base is still growth from a small base. The recent rise is best read as a sign that the overlap space is becoming more visible, not as proof that climate and environmental pathways have crossed into broad deployability.

Figure 17. New quantum applications to ASCEND have risen in recent years

GLOBAL GROWTH IN QUANTUM-ASCEND INVENTIONS SINCE 2010

Number of new quantum inventions filed by year of first filing that contain ASCEND-related technology codes



* Partial year data. • Source: Denizens LLC analysis of Lens data.

In system terms, pre-invention means something precise. The enabling science is advancing. Adjacency to high-value use cases is visible. But the mechanisms that convert measurement capability into climate and environmental impact remain immature or fragmented: deployment networks, long-run validation regimes, calibrated baselines, interoperability standards, data assimilation pipelines, and institutional uptake. The opportunity set should therefore not be judged only by whether a quantum sensor can, in principle, detect a relevant signal. It should be judged by whether the systems layer required to trust, scale, and operationalize that measurement is being assembled.[66]

3.4.3 Signals to monitor

The most informative leading indicators are not isolated demonstrations or additional invention counts in isolation. They are signs that the connective tissue of deployment is forming. For decision-makers building, funding, or partnering around ASCEND-relevant pathways, that connective tissue matters more than headline performance claims because it determines whether measurement can move into trusted operational use.

The first signal is standards and calibration infrastructure. Deployment readiness often hinges on calibration protocols, reference baselines, and the institutions capable of maintaining them. Progress in this area can be low-visibility, but it is decisive. A field begins to move beyond bespoke prototypes when measurements can be compared, validated, and reproduced against shared standards.[67]

The second signal is field trials connected to operations. Device-only demonstrations matter less than trials that embed sensing into navigation architectures, survey systems, mapping environments, or environmental monitoring workflows and quantify performance under operational noise, sustainment, and maintenance constraints. These trials reveal whether a promising modality can withstand real-world conditions.

The third signal is qualification and procurement pathways. Adoption accelerates when sensing capabilities can enter recognizable certification regimes and procurement channels. Repeatable qualification processes matter as much as marginal performance gains because they tell potential users how to compare, absorb, and sustain the technology.[68]

The fourth signal is platform industrialization and integrator capacity. Reliable component supply, yield improvements in specialized materials and optics, better packaging, and the emergence of subsystem integrators all indicate that the platform base is shifting from bespoke to industrial. That transition matters because it is the clearest sign that stack closure is no longer being attempted one prototype at a time.

The fifth signal, and the one most specific to ASCEND technologies, is linkage to modeling and data assimilation. For environmental-facing pathways, impact depends on whether sensing outputs can be absorbed into decision systems with uncertainty quantification, operational interpretation, and institutional trust. Measurement becomes decision support only when it can move through models, analytic workflows, and operating procedures designed to use it.[69]

These signals support a disciplined strategic posture. Dual-use pathways should be treated as near-term opportunities for systems integration around capabilities that are already becoming operationally legible. ASCEND-relevant sensing should be treated as a pre-invention frontier whose progress will depend on deliberate investment in the connective tissue of the stack: standards, testbeds, qualification pathways, integration pipelines, and the institutions that translate measurement into trusted environmental decision support.

* * *

Quantum sensing is best understood as system assembly. Its strategic importance lies less in raw invention totals than in where it forces the quantum technology system to confront operational reality. Sensing can remain a smaller application while underpinning progress throughout the stack. It is where fragile quantum effects must become repeatable measurements, and where the field's bottlenecks become visible earliest. The chapters that follow widen the frame from sensing itself to the larger competitive, commercial, and regional systems through which these stacks are assembled, validated, and scaled.

For ASCEND technologies, the implication is disciplined rather than expansive. The most important signals are not isolated environmental use cases or headline device claims. They are signs that the deeper measurement stack is hardening: shared standards, field validation, industrialization, and the ability to move sensing outputs into modeling and decision systems that users can trust. That is the threshold that will determine whether climate and infrastructure-relevant pathways remain promising adjacencies or begin to mature into a real frontier for deployment in the Mountain West.

4. Global competition: scale, control, and interdependence

Chapter 3 showed where the quantum system meets operational reality first. Sensing forces quantum hardware, photonics, control systems, calibration, validation, and workflow integration to function together under real constraints. That same pressure now shapes global competition. Countries are not contesting a single technical milestone. They are competing to control the bottlenecks, interfaces, and deployment pathways through which quantum capabilities become usable, trusted, and repeatable.[70]

That competition is unfolding inside a partially assembled, internationally interdependent system. Quantum computing, communications, and sensing remain useful quantum application areas, but no country advances them independently or controls every enabling layer beneath them. Progress still depends on shared bottlenecks in materials, photonics, precision measurement, software, calibration, and systems integration. Influence therefore flows through position inside the system: who controls critical platforms, who can validate performance, who can integrate subsystems across organizations, and who can shape the standards others must meet.

China and the United States anchor two different approaches to that problem. China reduces uncertainty through coordinated scale, sustained state direction, and early commitment to deployment-facing pathways. The United States works through a looser but more adaptive model tied to universities, firms, national laboratories, venture-backed experimentation, and dense collaboration with allied specialists.[71] These systems do not produce the same advantages at the same points in the stack. China is better positioned where infrastructure rollout, manufacturing coordination, and rapid convergence matter most. The United States and its allies are stronger where enabling-platform depth, systems integration, standards-setting, and architectural flexibility determine what can be stabilized and exported.

The distinction matters because quantum does not mature evenly. Higher-level deployments can reward speed, coordination, and the ability to commit resources at scale. Movement across bottleneck layers rewards something else: the ability to combine specialist capabilities, compare competing technical paths, absorb setbacks, and adapt before standards harden. A country can therefore lead in raw invention or visible deployment and still remain dependent on capabilities developed elsewhere. It can also hold less aggregate activity while occupying the layers through which much of the rest of the field must pass.

Collaboration follows from that structure. In quantum, collaboration is part of the innovation system. It distributes risk across more architectures, exposes performance claims to more validation settings, and links specialist capabilities that no single institution or country holds on its own.[72] Dense collaboration networks can therefore confer real power. More internally consolidated systems can move faster once priorities are set, but they also face greater lock-in risk if they commit heavily to architectures that later prove harder to adapt, qualify, or diffuse.

That comparison matters for ASCEND technologies, but only in a bounded way. Sensing, navigation resilience, and other validation-heavy pathways are among the first places where these system differences become visible, because they force quantum capabilities into operating environments where reliability, standards, and integration matter more than laboratory performance alone. The sections that follow examine how global activity is distributed, how collaboration shapes system position, why the language of races obscures the structure of competition, and how the Chinese and U.S.-allied systems derive power from different parts of the same quantum field. Chapter 5 then turns to the commercial consequences of those differences, where competition becomes system assembly under real constraints.

4.1 The global landscape: scale, specialization, and dependence

Global quantum competition is already concentrated, but totals alone do not tell us who controls the system. A small number of countries account for most invention activity, yet they occupy different positions in the stack. China dominates by volume. The United States anchors a broader base across quantum application areas and enabling platforms. A smaller group of specialist countries holds capabilities that neither major power fully internalizes. The global field turns on three things at once: scale, stack position, and dependence on capabilities held elsewhere.

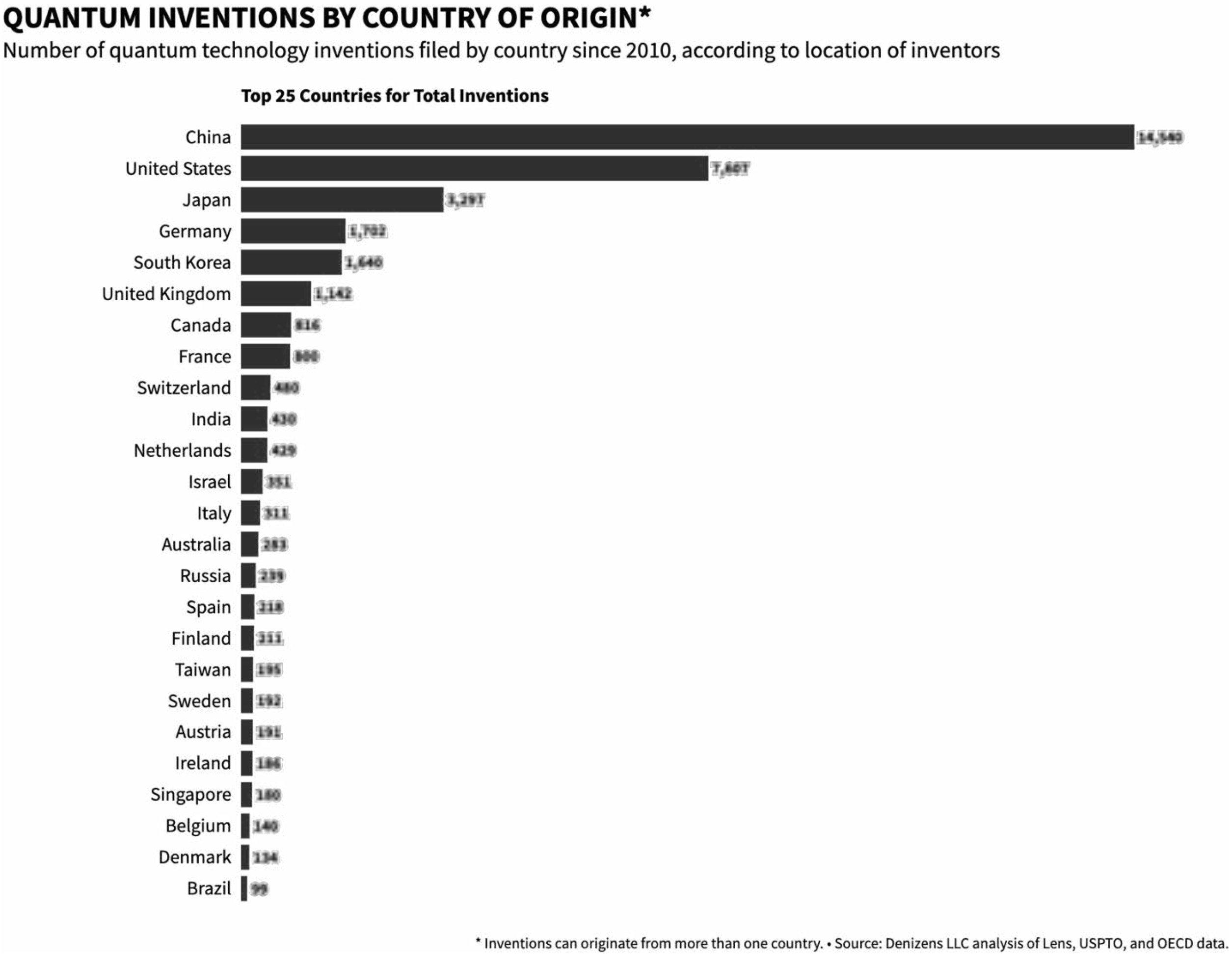
4.1.1 Scale and concentration across countries

Figures 18 through 20 show the degree of concentration clearly. China and the United States are the two principal poles of global quantum invention, with Japan, Germany, South Korea, the United Kingdom, Canada, and France forming a second tier at much lower volumes. That distribution matters because, in a field this unsettled, scale buys more than prestige. It buys more technical bets, more learning cycles, and more chances to push promising pathways into infrastructure and deployment.[73]

China's lead is now large enough to shape the global picture on its own. Figure 19 shows Chinese quantum invention growing from a modest base in the early 2010s to a level that surpasses the rest of the world in annual filings by 2024. That trajectory reflects more than strong research output. It reflects a national system willing to commit resources across a wide front for long enough to force convergence in selected pathways.

Figure 20 shows what kind of system produced that scale. China's leading sponsors span universities, state-linked companies, telecommunications firms, grid-related organizations, specialist quantum companies, and defense-adjacent institutions. This is a coordinated national base, not a narrow corporate cluster. It is built to reduce uncertainty through breadth, then move quickly once priorities are set.[74]

Figure 18. The U.S. and China compete for quantum leadership

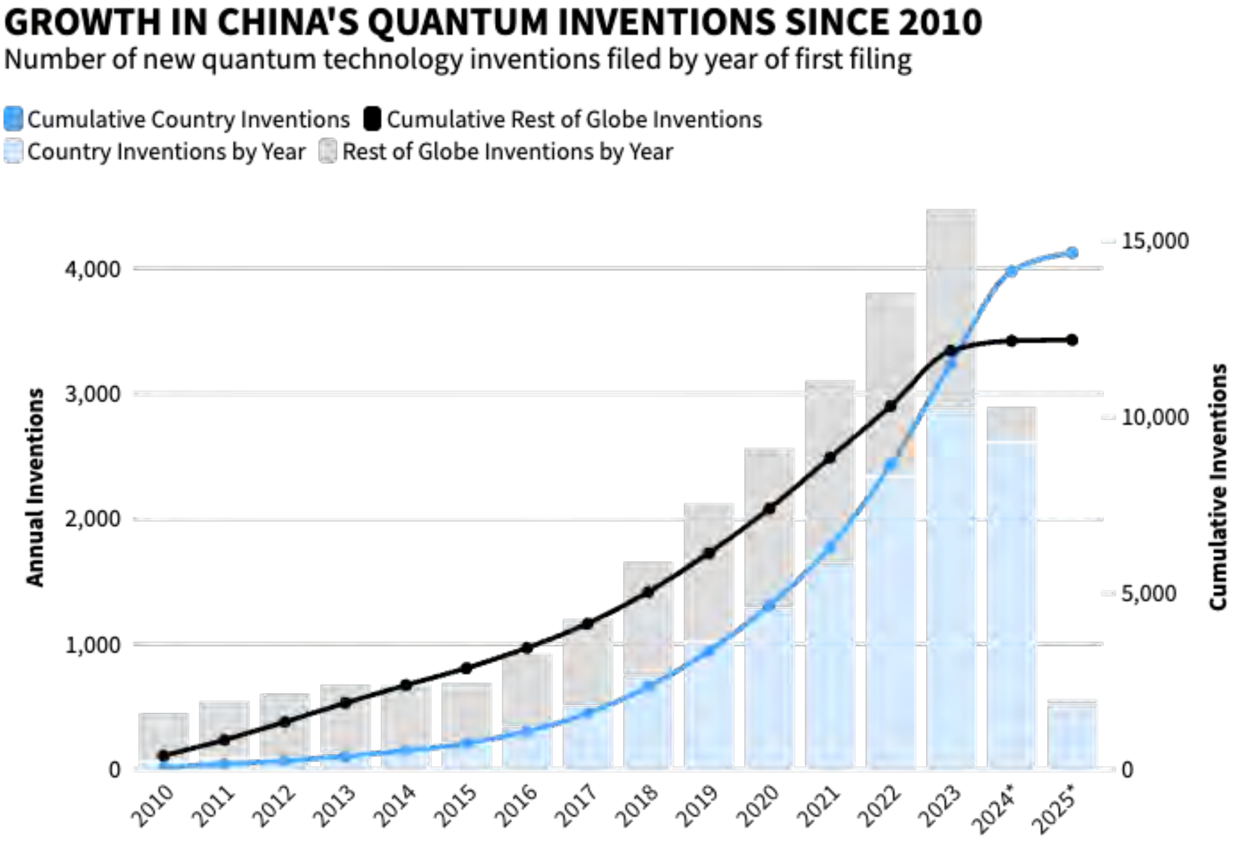


QUANTUM INVENTIONS BY COUNTRY OF ORIGIN*

Number of quantum technology inventions filed by country since 2010, according to location of inventors

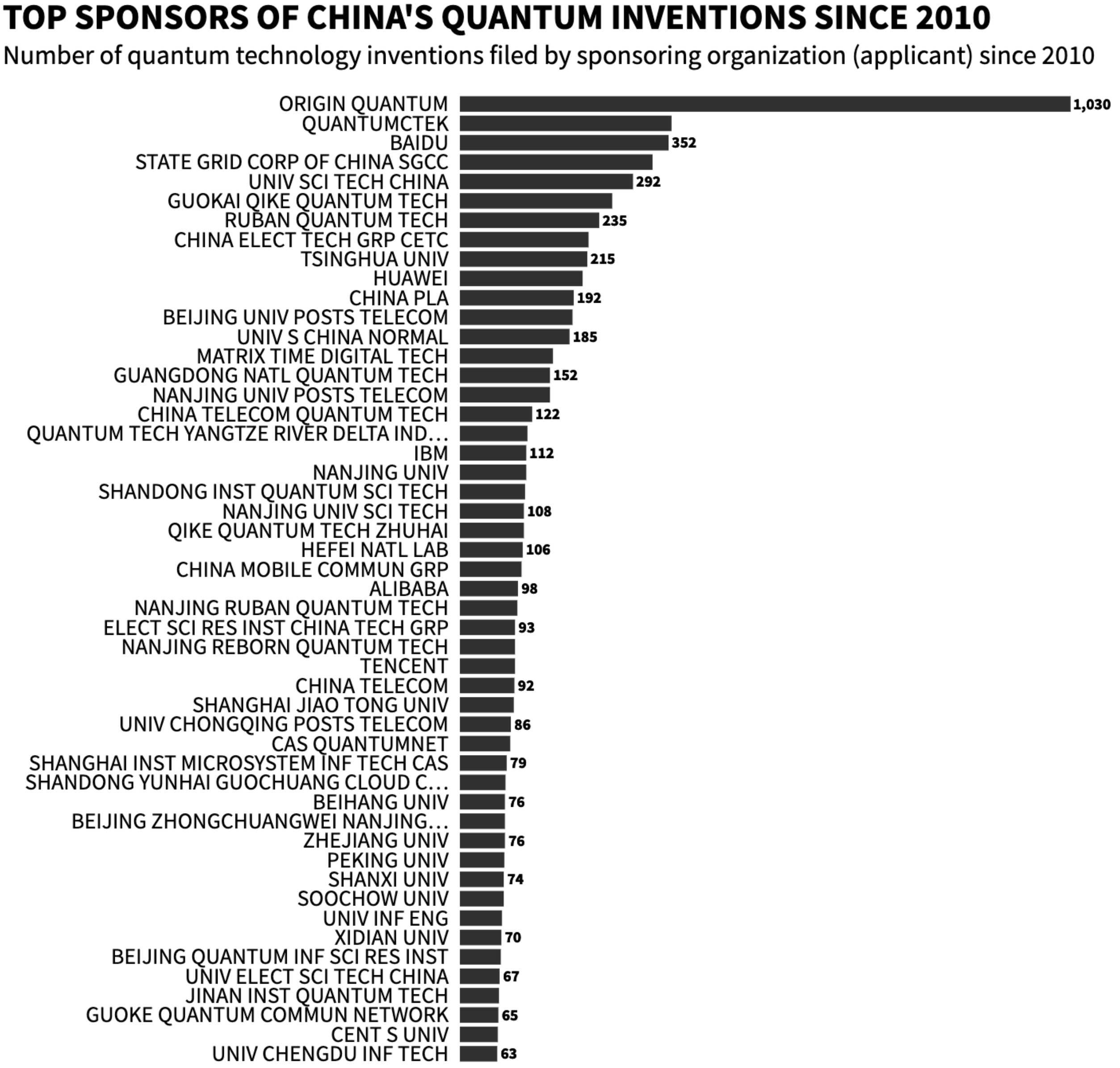
* Inventions can originate from more than one country. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

Figure 19. China surpassed the rest of the globe in quantum invention in 2024



* Partial year data. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

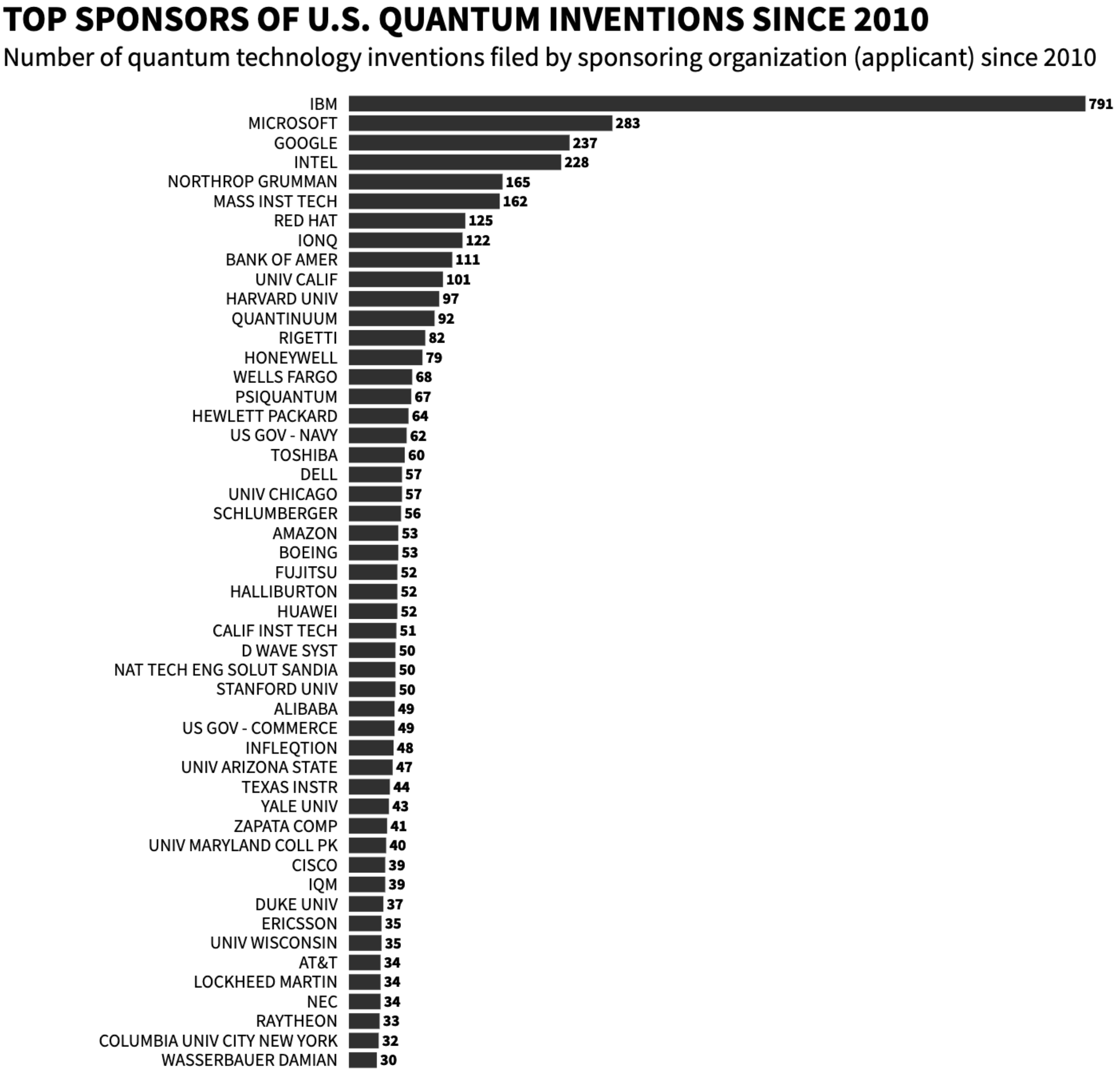
Figure 20. China's list of top invention sponsors suggests a "whole of nation" approach



Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

The United States occupies a different position. Its total output is lower, but its sponsor base is broader across large technology firms, universities, defense contractors, specialized quantum companies, and a smaller public-sector presence. That mix matters because it supports a different model of progress. China's system is built to converge and scale rapidly once it commits. The U.S. system is built to explore multiple technical paths simultaneously and recombine them across sectors before settling on one.[75]

Figure 21. U.S. quantum invention is driven by companies and universities

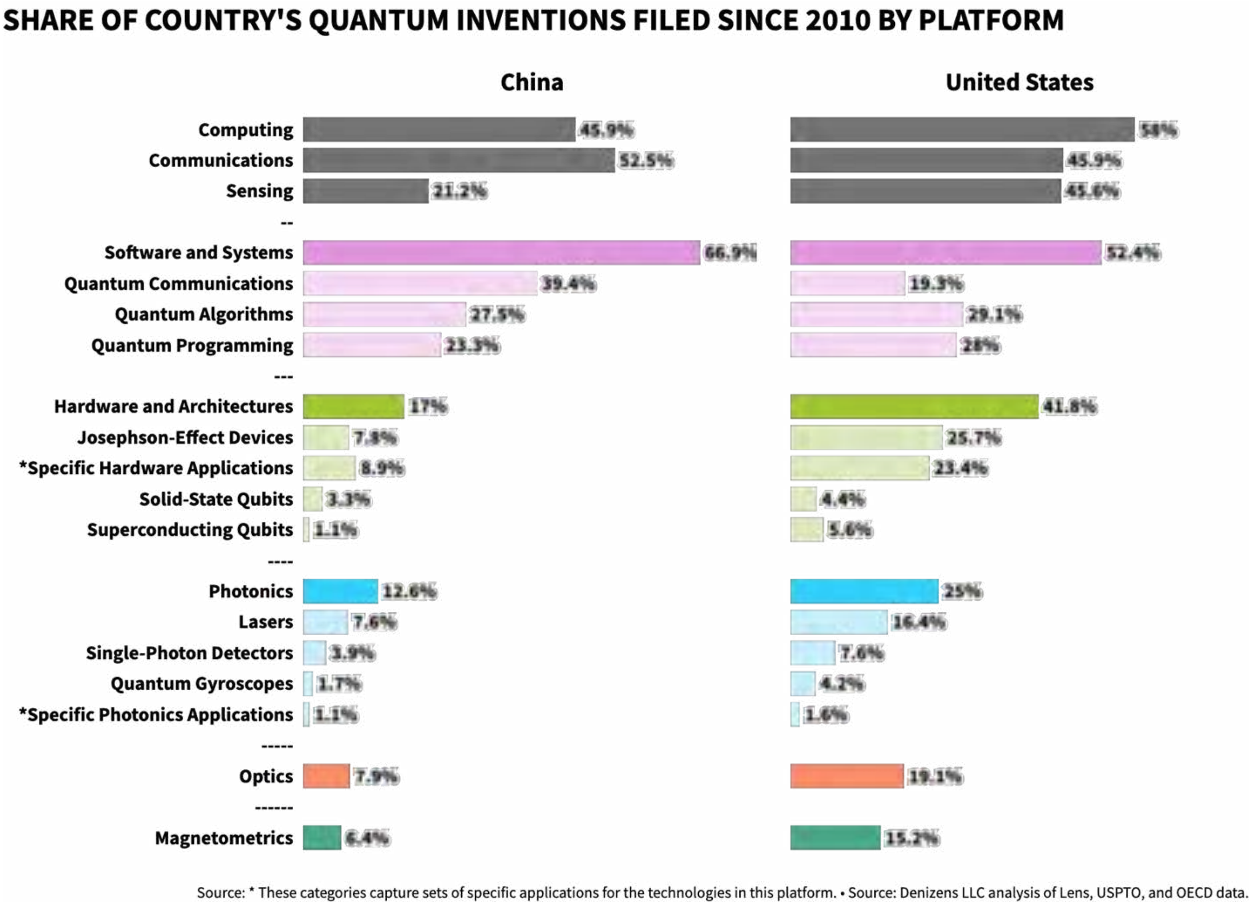


Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

4.1.2 Differences in technological emphasis across the quantum stack

Total volume hides the more important distinction. Different layers of the stack reward different competitive models. Deployment-adjacent pathways in communications and sensing reward coordination, infrastructure buildout, and fast convergence. Enabling platforms and unsettled architectures reward breadth, specialist inputs, and tolerance for parallel experimentation. The U.S.–China comparison becomes more revealing once activity is broken out that way.

Figure 22. Compared to China, the U.S. specializes in "high-leverage" platforms



Source: * These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

Figure 22 makes that divergence visible. China is more concentrated in software-and-systems and communications-heavy activity. The United States is stronger in hardware and architectures, photonics, optics, magnetometry, and a more distributed sponsor base led by companies and universities. China's profile fits a system built to move chosen pathways toward deployment at speed. The U.S. profile fits a system that retains more architectural optionality and more depth in the enabling platforms other pathways depend on.

The three quantum application areas bring those differences into sharper focus. Sensing is the clearest case. The United States leads global quantum sensing innovation because its strengths align closely with the parts of the stack that sensing stresses first: photonics, precision measurement, control software, data fusion, and integration with aerospace and defense systems. That profile fits the central problem of sensing as defined earlier in the report. Sensors only matter when fragile measurements can be stabilized, interpreted, and trusted in real environments. China remains active in sensing, but the U.S. position is stronger where measurement systems must be integrated across heterogeneous platforms and operating conditions.[76]

Communications show the opposite pattern. China's concentration is strongest here, especially in secure communications architectures and quantum key distribution. That emphasis fits a system designed to scale through centralized rollout, long planning horizons, and tight alignment between state priorities and network infrastructure. The U.S. and allied profile is broader and less centralized. It spans quantum networking, cryptographic resilience, and hybrid classical-quantum security approaches rather than one dominant physical architecture. China's model moves faster when deployment depends on coherence and infrastructure control. The allied model is better suited to standards, interoperability, and adaptation across mixed technical environments.[77]

Computing remains the least settled of the three. No hardware path has won. Superconducting systems, trapped ions, neutral atoms, photonics, silicon spin, and more speculative approaches all remain in play. China is still a major force, but its activity is more concentrated around superconducting systems and clearer engineering roadmaps. The U.S. and allied cluster is more dispersed across competing modalities, with strong positions in trapped-ion, neutral-atom, photonic, and error-correction research. That diversity preserves more room to adjust as the field evolves, but it also slows convergence. China's model is better suited to committing hard once a path appears viable. The U.S.-allied model is better suited to fluid phases in which the main advantage lies in exploring multiple architectures simultaneously.

These patterns show that different stack layers do reward different competitive models. Foundational and deployment-adjacent layers favor systems that can quickly coordinate capital, infrastructure, and engineering effort. Integration-heavy and architecturally unsettled layers favor systems that can combine specialist knowledge, test competing designs, and adapt without having to rewrite the whole system. China's strengths are greatest where scale and convergence matter most. The United States and its allies are strongest where enabling platforms, systems integration, and architectural flexibility decide what becomes durable.[78]

4.1.3 The role of specialist and second-tier countries

Aggregate output obscures another defining feature of the global system. A small group of second-tier countries holds capabilities that neither China nor the United States fully internalizes. Germany, the United Kingdom, Japan, and a wider circle of advanced industrial economies appear less dominant in top-line counts, but they matter because they control hard-to-substitute inputs in the enabling layers of the stack. Those inputs shape how quickly progress elsewhere can move.

Germany's position is anchored in photonics, optics, and precision measurement. German firms and research institutions supply stabilized laser systems, frequency combs, and calibration tools that recur across quantum sensing, atomic clocks, and neutral-atom computing. These are not flashy end applications. They are the technical substrate on which many end applications depend. When they lag, downstream systems stall with them.[79]

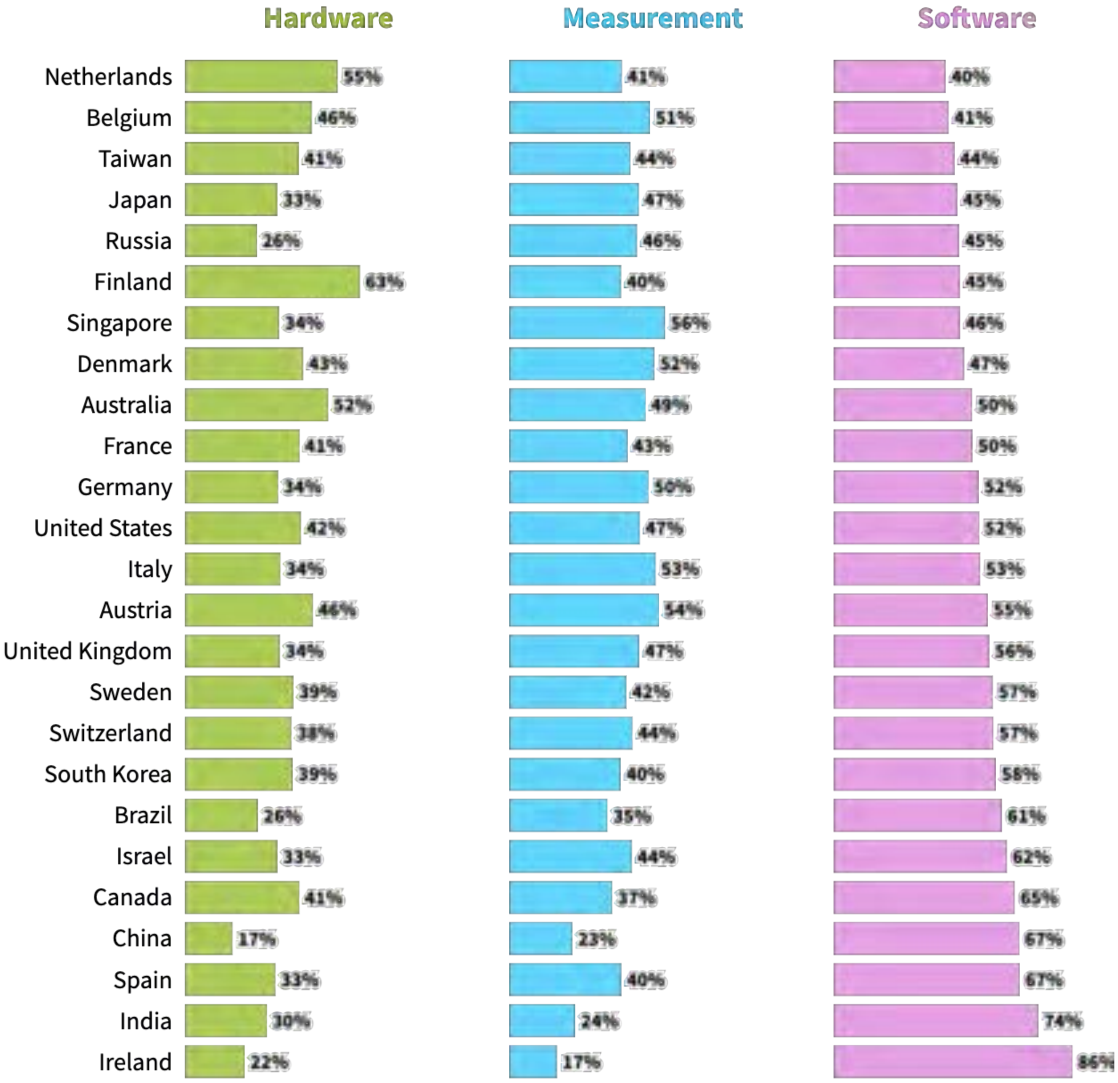


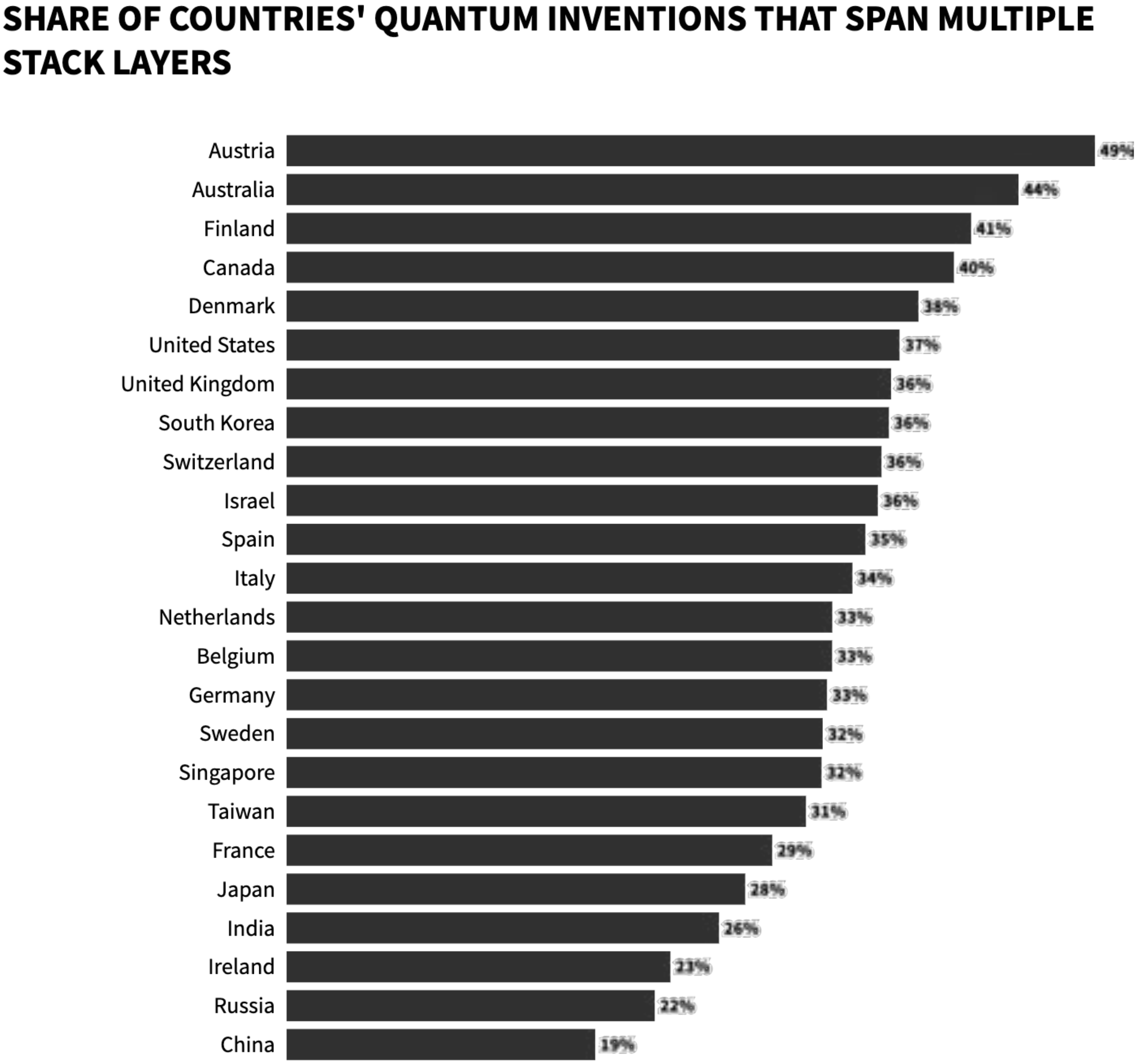
Figure 23. Countries like Japan, Germany, and U.K. over-index in enabling platforms

STACK LAYER'S SHARE OF COUNTRIES' QUANTUM INVENTIONS

Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

The United Kingdom occupies a different but equally important role. British activity is weighted toward sensing, control software, and field-deployable prototypes that bridge laboratory systems and ruggedized operating environments. That makes the UK especially important in validation, testing, and integration.[80] Japan sits farther upstream still. Its strengths in precision manufacturing, materials, optoelectronics, detectors, packaging, and specialized electronics tie quantum progress to capabilities that also align closely with the classical semiconductor supply chain.[81] These components look ordinary in isolation. They become decisive when systems scale and substitution slows or becomes expensive.

Figure 24. Specialist countries tend to integrate the quantum technology stack layers



Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

The wider specialist group matters as well. France and the Netherlands contribute strongly in trapped-ion systems, software, and photonics research. Canada and Australia recur in sensing and control systems, often with defense or environmental applications. South Korea and Israel add selective strengths in electronics, materials, and security-adjacent technologies. None of these countries defines the global field alone. Collectively, they anchor a meaningful share of the upstream and integrative capacity that the two major powers still rely on.

Quantum remains internationally interdependent because critical capabilities are still distributed across specialist countries and hard-to-substitute layers of the stack. No country controls the full set of inputs required to move cleanly from research through validation to deployment. Network position, therefore, matters for reasons more concrete than diplomacy alone. It determines who can access specialist capabilities early, who can absorb technical shocks, and who can influence the standards and reference architectures through which the field consolidates.[82] Collaboration is, therefore, a source of system power.[83]

4.2 Collaboration, network position, and system power

The distribution of quantum activity shows where invention is occurring. It does not show how the system resolves uncertainty or who becomes indispensable to others' progress. In quantum, collaboration is part of the innovation system. No country controls every enabling platform, validation environment, or specialist capability required to move from promising device to usable system. Network position determines who can combine capabilities, compare architectures, and shape standards around which the field consolidates.

Collaboration is not a soft virtue in this setting. It is how distributed systems manage technical risk when architectures remain unsettled, and integration costs are high. Dense co-production exposes performance claims to more validation settings, links specialist capabilities that no single country holds on its own, and keeps more technical paths alive for longer. More internally consolidated systems can move faster once priorities are set, but they rely more heavily on domestic judgment about which paths to back. That difference is one of the clearest ways the U.S.-allied system and China diverge.[84]

4.2.1 A hierarchical collaboration network

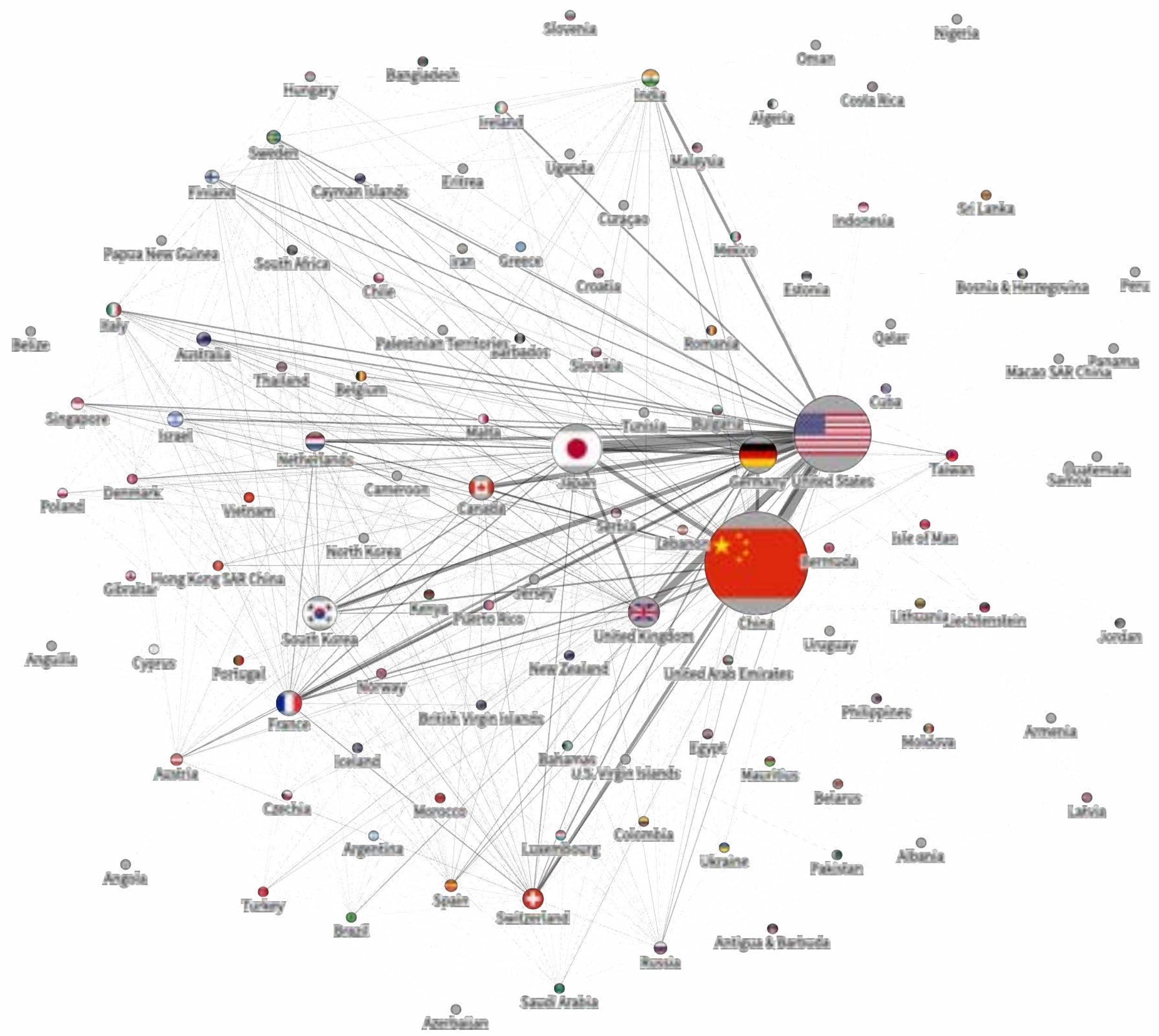
The global quantum collaboration network is not flat. A small number of countries sit at the center, while most others attach to the system through those hubs rather than through broad mutual collaboration. That pattern reflects the structure of the field itself. When progress depends on shared platforms, costly integration, and scarce specialist inputs, countries gravitate toward partners that can connect them to the widest range of capabilities.

Figure 25 shows that hierarchy clearly. Collaboration clusters around a limited set of nodes with repeated co-invention ties, high connectivity, and strong reciprocity. Most countries do not collaborate broadly across the full field. They connect through a smaller core that routes knowledge, talent, and technical practice across otherwise weakly linked national systems.

This structure gives central nodes an advantage that raw output cannot capture. In a hierarchical network, influence flows through brokerage as much as through scale. Countries at the core do not simply contribute more work. They help determine which technical problems are worked on jointly, which benchmarks circulate widely, and which assumptions become normal across the system. Peripheral countries may still matter greatly in specialist niches, but they enter the wider field through standards and relationships shaped at the core.[85]

Figure 25. The U.S. is at the center of global collaboration on quantum invention

MULTINATIONAL COLLABORATION ON QUANTUM TECH. INVENTIONS BY COUNTRY
Collaboration among nations on quantum inventions



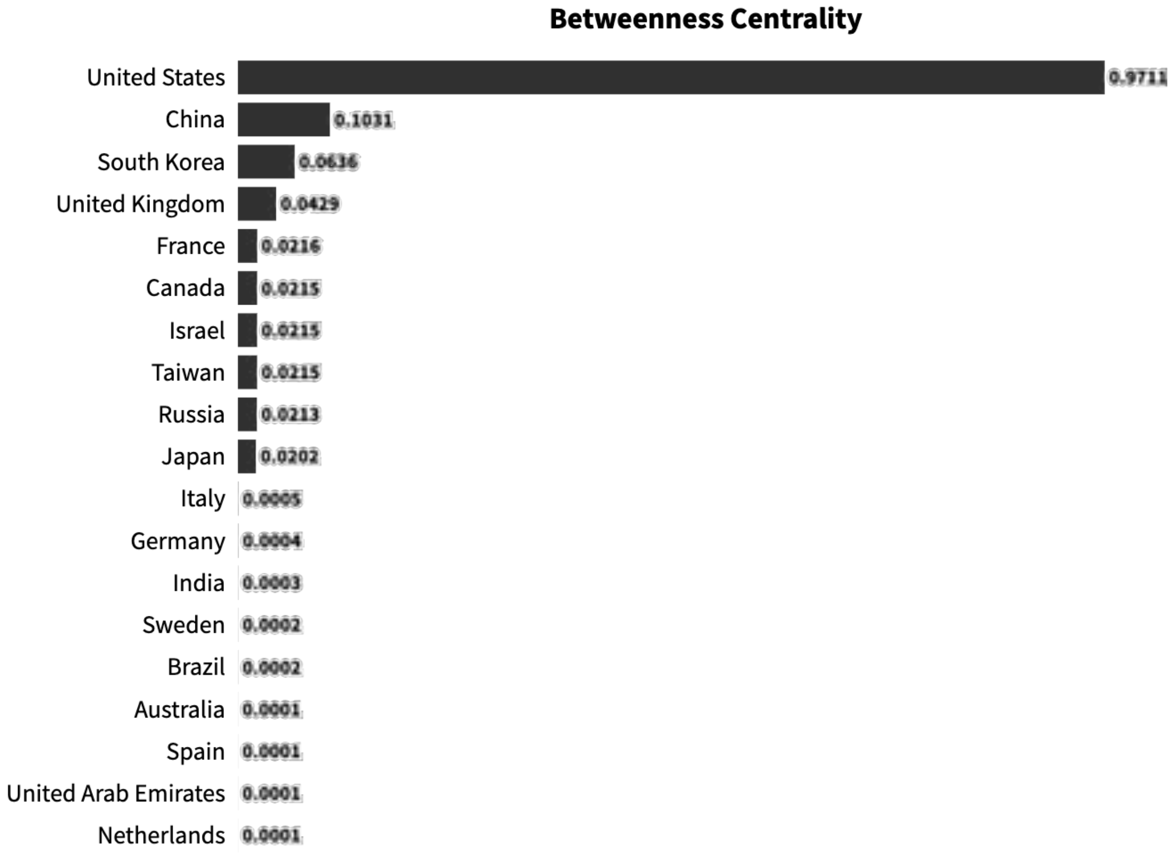
Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

4.2.2 The United States as system integrator

Within that hierarchy, the United States occupies a singular position. It is not only a large producer and frequent collaborator. It is the system's primary integrator. Across the current network measures, the United States shows the highest overall collaboration weight, the strongest inbound collaboration, and an outsized bridging role between countries that are not directly connected.

Figure 26. The U.S. plays an outsized integrative role in the quantum invention network

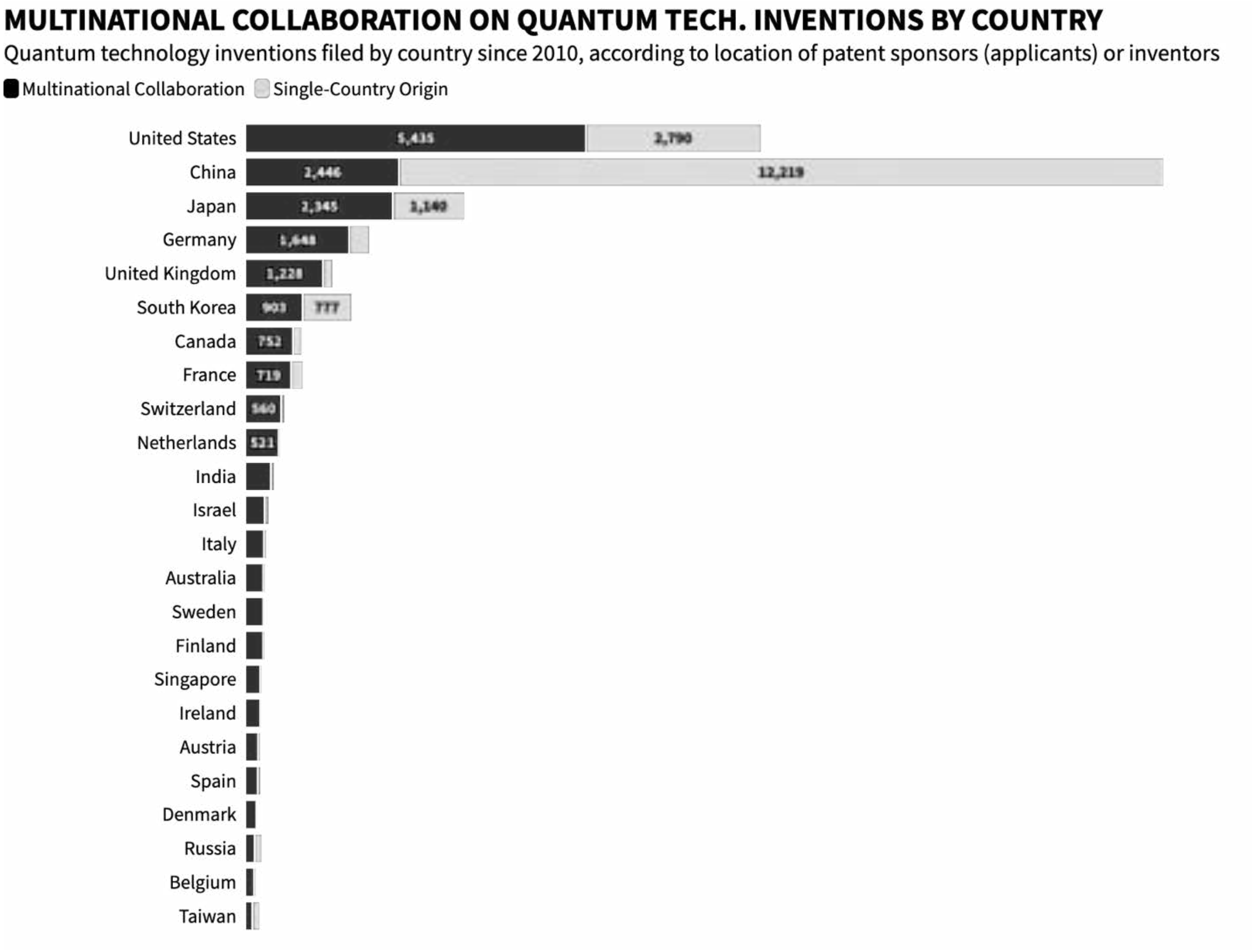
COUNTRIES' STRENGTH AS CONNECTORS IN INTERNATIONAL QUANTUM COLLABORATION



Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

That position matters because it turns the United States into a practical coordinator of distributed experimentation. Other countries co-produce disproportionately with U.S. institutions, while U.S. institutions collaborate across a wider range of partners. The result is a bridging function that reduces duplication and accelerates recombination across the field. In practice, this can mean British validation work, German photonics depth, Canadian or Dutch control expertise, and U.S. systems integration capacity entering a shared development pathway faster than any one national system could assemble on its own. The example is illustrative, but the underlying pattern is exactly what a brokerage-centered network enables.[86]

Figure 27. The U.S. is the global leader in collaborative quantum invention



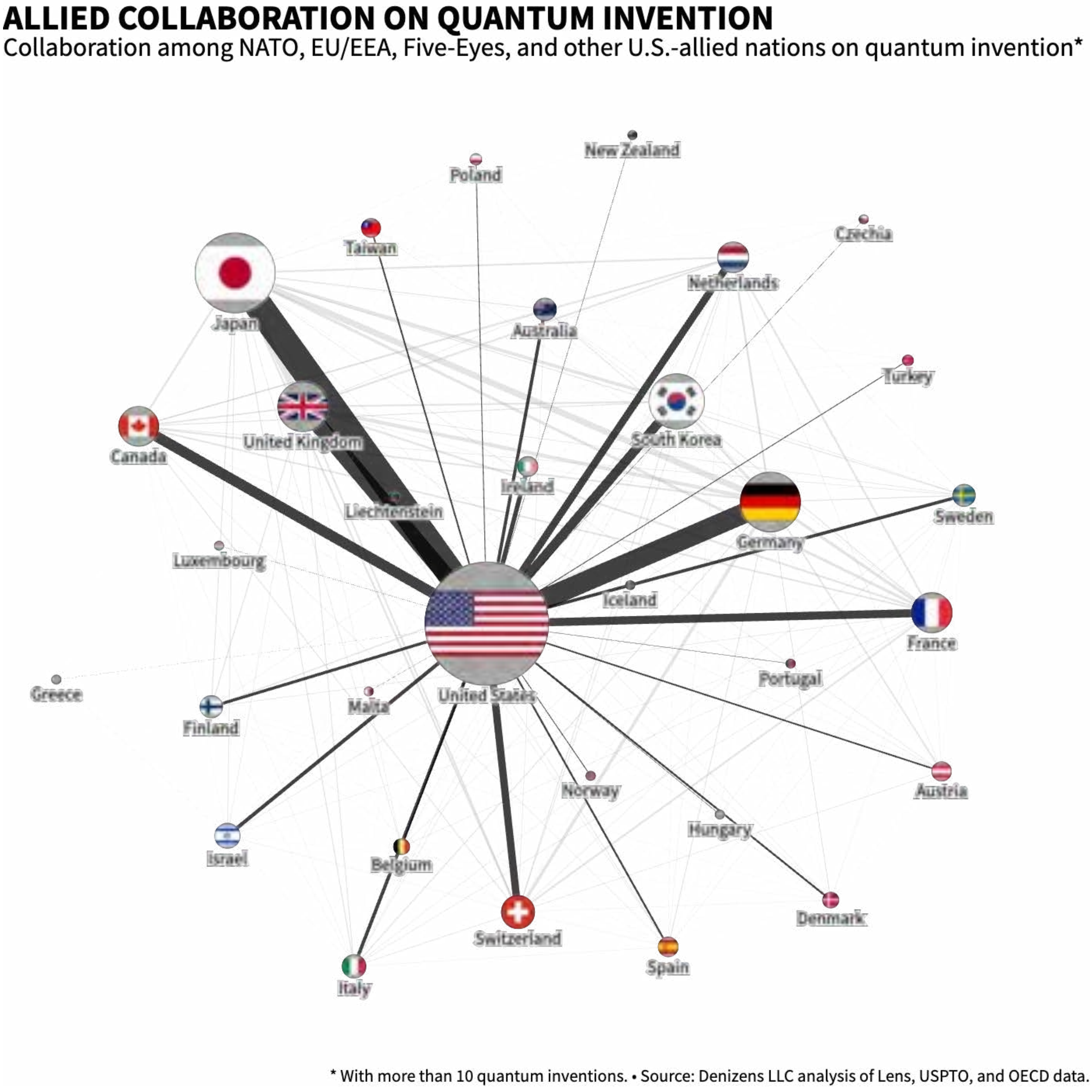
Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

This role confers a form of influence that simple invention counts miss. A country that repeatedly connects otherwise separate clusters gains earlier visibility into emerging problems, access to a broader range of specialist capabilities, and a stronger hand in shaping shared research agendas, validation practices, and interoperability norms. The U.S. advantage here does not depend on dominating one quantum application area or one platform. It depends on repeated integration across sensing, communications, computing, and the enabling layers beneath them. That is why U.S. influence persists even where aggregate output does not lead: leadership in a hierarchical network accrues to the actor that helps turn dispersed technical effort into a more coherent system.[87]

4.2.3 The allied cluster as a shared system

The United States does not occupy this position alone. It sits inside a denser allied collaboration cluster that includes the United Kingdom, Germany, France, the Netherlands, Switzerland, Canada, and Australia. These countries do not matter because they rival the United States or China in aggregate scale. They matter because they repeatedly co-produce high-value work and connect specialist capabilities across the system. Many of them record multinational collaboration shares close to or above four-fifths of total invention activity, far above the U.S. share of 66 percent and far above China’s 17 percent. Their most consequential work is often designed to be joint from the start.

Figure 28. The U.S. and allies form an especially dense quantum collaboration network



ALLIED COLLABORATION ON QUANTUM INVENTION

Collaboration among NATO, EU/EEA, Five-Eyes, and other U.S.-allied nations on quantum invention*

* With more than 10 quantum inventions. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

That pattern produces a denser and more redundant network than a hub-and-spoke model. These countries do not connect only through the United States. They collaborate with one another in overlapping constellations, which allows knowledge, personnel, and technical standards to circulate through multiple pathways. Redundancy matters in a field where architectures remain unsettled and integration costs are high. It keeps more technical options alive, accelerates recombination across institutions and borders, and reduces the chance that one early bet hardens too quickly into a dead end.

The allied advantage is therefore not just openness. It is shared system-building.[88] Repeated co-production helps allied countries validate approaches across different settings, align around practices that prove robust, and strengthen the credibility of the benchmarks and interfaces they use. Smaller countries matter here for reasons that output counts miss. They anchor upstream capabilities such as precision instrumentation, control systems, and validation expertise that recur across multiple quantum application areas. The allied cluster behaves like a distributed system because it links those specialist strengths into a wider process of co-production and refinement.[89]

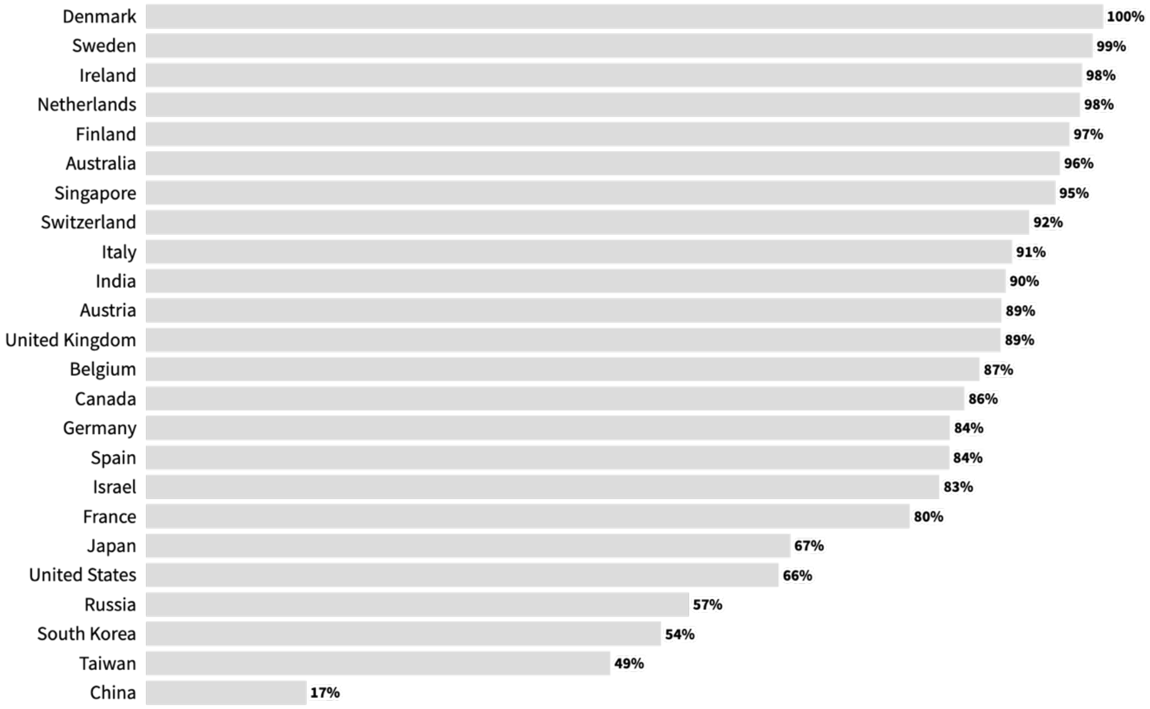
4.2.4 China’s network position

China occupies a different network position. In absolute terms, it is a major collaborator and an essential part of the global field. But collaboration is not the organizing principle of its system. China’s multinational co-production share is just 17 percent, the lowest among leading quantum countries shown in the report. External collaboration supports the system, but the system is built to resolve uncertainty primarily at home.

The structure of China’s collaboration reinforces that pattern. Chinese co-production is concentrated among a narrower set of partners and exhibits less reciprocity than the dense allied cluster. Its international ties extend outward more like spokes from a domestic core than like a web of overlapping peer relationships. That structure supports internal coherence and fast diffusion once priorities are set. It is well suited to a system that wants to scale chosen pathways quickly and keep core capabilities under tighter sovereign control.

That same structure narrows the range of architectures explored in parallel. Dense collaboration networks expose a system early to weak-tie spillovers, alternative technical approaches, and problems discovered elsewhere. China’s model gets less of that benefit because external collaboration plays a more instrumental role. It helps acquire knowledge, benchmark progress, or validate selected pathways, but it does not distribute technical uncertainty across a broad co-productive network in the same way. The result is a system that is coherent and fast, but less diversified. If an early technical commitment proves wrong, the cost of adjustment is higher because fewer alternative pathways have been developed in parallel. That is the core tradeoff in China’s network position.[90]

Figure 29. China ranks last in collaborative invention among leading quantum nations



MULTINATIONAL COLLABORATION ON QUANTUM TECH. INVENTIONS BY COUNTRY

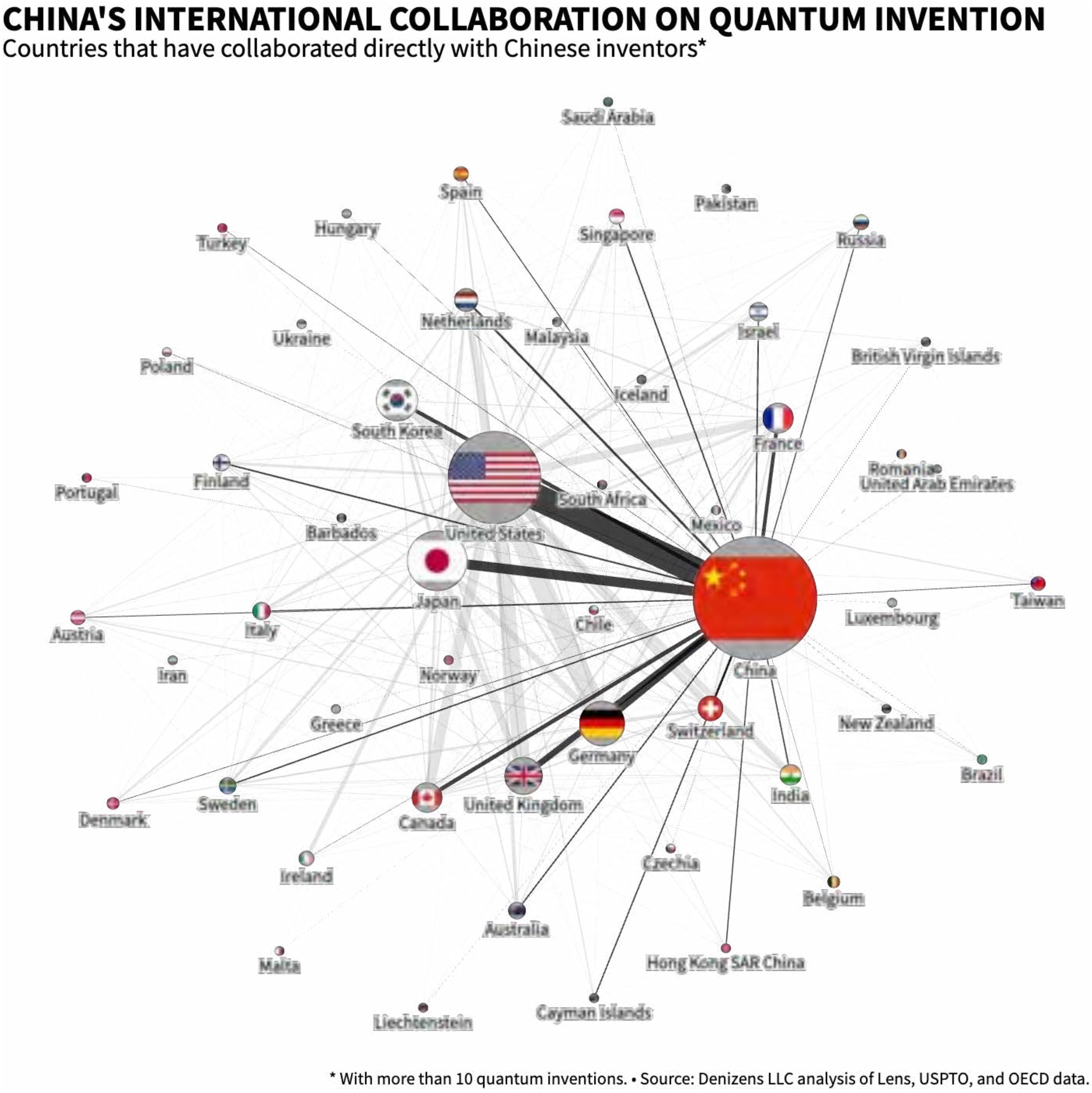
Share of quantum technology inventions that involve inventors or sponsors in other countries

Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

China is therefore not outside the global quantum system, nor marginal to it. It is adjacent to the dominant collaboration cluster while operating a parallel system optimized for coherence, speed, and sovereignty rather than brokerage and agenda-setting. That position can be powerful in domains where technical pathways are relatively clear and large-scale rollout matters most. It is less powerful where adaptability, repeated cross-context validation, and broad exposure to alternative architectures determine who shapes the field.

The contrast is now clear. The U.S.-anchored allied cluster gains strength by distributing uncertainty across a dense network of co-production, validation, and specialist inputs. China gains strength by resolving uncertainty more internally and moving rapidly once priorities are fixed. One model is more adaptable and more resilient to technical dead ends. The other is more coherent and often faster at deployment.

Figure 30. China plays a less-central role in its own quantum collaboration network



CHINA'S INTERNATIONAL COLLABORATION ON QUANTUM INVENTION

Countries that have collaborated directly with Chinese inventors*

* With more than 10 quantum inventions. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

4.3 Why "the quantum race" is the wrong metaphor

The reality of interdependence in quantum innovation makes the race metaphor for describing geopolitical contest unhelpful. Nations do compete for quantum primacy on the grounds of security, economic growth, and technological prestige. That competition is easy to read as a "race" because it fits the most visible signals in the field. Patent counts, funding totals, qubit milestones, national strategies, and headline demonstrations all lend themselves to scorekeeping. They make quantum competition look like a contest on a shared track, with a leader, a pursuer, and a clear finish line. That picture is simple, legible, and wrong.

Quantum technologies do not advance toward one finish line, however. Different countries lead in different application areas, and the most important advantages sit at different points in the stack. China's scale is strongest where coordinated infrastructure, manufacturing alignment, and rapid convergence matter most. The United States and its allies are stronger where enabling platforms, control layers, systems integration, and standards-setting determine what becomes durable. Those positions are not commensurable on a single scoreboard, and strength in one part of the system does not erase weakness in another.[91]

Race language also misses the constraint that matters most once a capability leaves the lab: integration. Quantum technologies do not scale as isolated devices. They scale as systems built from bespoke components that still lack shared interfaces, common benchmarks, stable calibration routines, and repeatable validation pathways. That is why early demonstrations and rapid scaling do not settle the competition. A country can move first and still struggle if the resulting system is hard to qualify, hard to integrate, or costly to adapt.

The strategic distinction is sharper than the metaphor permits. Different layers of the stack reward different competitive models. Foundational and deployment-adjacent layers favor systems that can quickly coordinate capital, infrastructure, and engineering effort. Integration-heavy and architecturally unsettled layers favor systems that can compare approaches, absorb error earlier, and adjust without having to unwind the whole system. The question is not who is ahead in a race. It is which system is better positioned under uncertainty, which one controls the bottlenecks, and which one can adapt more cheaply.[92]

4.4 Two systems, one quantum landscape

China and the U.S.-anchored allied cluster occupy different positions within the same quantum landscape. China derives strength from coordinated scale, early commitment, and the ability to rapidly move chosen pathways from research to sovereign deployment. The allied system derives strength from distributed experimentation, upstream platform depth, and dense collaboration that keeps more technical options alive for longer. As quantum technologies move from laboratory progress to operational use, the contrast is clearest in four areas: commitment, integration, reach, and resilience.

4.4.1 China's system: coherence, scale, and early commitment

China's quantum system is built to resolve uncertainty quickly. It accounts for the largest share of global invention activity, but its scale matters less as a headline number than as an organizational fact: the invention base is overwhelmingly domestic, anchored by universities, state laboratories, telecoms, infrastructure-linked firms, specialist quantum companies, and defense-adjacent institutions, with only 17 percent of activity involving multinational collaboration. That structure is well suited to quantum application areas in which architectures are clearer, infrastructure rollout matters, and operational learning can be accelerated through repeated deployment. In quantum communications, navigation-resilient sensing, and other deployment-adjacent pathways, China can align research, engineering, procurement, and fielding more directly than more distributed systems.[93]

That coherence is a real advantage, but it comes with a narrower design space. Because China collaborates internationally far less intensively than the U.S.-anchored allied cluster, it is less exposed to weak-tie recombination, alternative validation environments, and competing technical approaches as they emerge elsewhere. When early bets prove sound, this model compresses timelines and builds sovereign capability quickly. When they do not, revision is harder because capital, infrastructure, and institutions have already been organized around a chosen path. China's advantage, then, is speed through coherence; its vulnerability is that a more undiversified system pays more when it is wrong.[94]

4.4.2 The allied system: distributed control, optionality, and integration

The allied system resolves uncertainty differently. It does not try to settle the field early through centralized commitment. Instead, it distributes experimentation across the United States and a dense cluster of allied specialists with strong positions in photonics, precision metrology, control software, validation, and other enabling platforms. The United States itself collaborates on roughly two-thirds of its quantum invention activity, and many allied partners are more international still. This structure keeps more hardware modalities, sensing approaches, and integration pathways viable for longer. It is less efficient in the short run, but it is especially strong in the parts of the stack where architectures remain unsettled and where influence depends on setting benchmarks, validating performance, and making heterogeneous components work together.[95]

That strength is concentrated upstream and across interfaces rather than in raw volume of invention or rapid domestic deployment. Because the allied system is built through repeated co-production, it tends to generate technologies and practices that are more interoperable across institutions, geographies, and operating environments. It also gives the United States a distinct role as a system integrator: not the sole source of capability, but the main node through which distributed capabilities are combined into something coherent. The cost is slower convergence, messier coordination, and a weaker ability to scale a single pathway on command. The advantage is cheaper course correction and greater control over the standards, validation regimes, and integration pathways that others must navigate.[96]

4.4.3 System reach: exportability, interoperability, and standard-setting

Those structural differences shape not only how quantum technologies develop at home, but how they travel. China's system is optimized for sovereign deployment. Tight coupling among research, engineering, procurement, and infrastructure enables selected solutions to diffuse quickly across national boundaries once priorities are set. That same tight coupling can limit external reach, because technologies built around domestic standards, operating conditions, and procurement regimes are harder to fit into heterogeneous environments abroad.[97]

The allied system gains a different advantage. Repeated cross-border co-production forces technologies to work across institutions, regulatory settings, and legacy infrastructures from the start. That slows early rollout, but it produces interfaces, benchmarks, and validation practices that are easier to adapt elsewhere. In platform-dependent technologies, this matters because quantum sensors, communications systems, and computing components rarely operate in isolation. They have to connect to classical hardware, software stacks, data systems, and operating procedures that vary by user and geography.[98]

4.4.4 System resilience: fragility, correction, and the cost of being wrong

Every innovation system pays for how it resolves uncertainty. Systems built on early commitment concentrate risk. When assumptions hold, they gain speed because research, engineering, and deployment are aligned early. When assumptions fail, correction arrives later and costs more because infrastructure, procurement, and workforce capabilities have already been organized around a chosen path. That is China's core tradeoff.

Systems built on distributed experimentation spread risk across more institutions, technical paths, and validation settings. The allied cluster pays for that structure with slower convergence, messier coordination, and a reduced ability to scale a single pathway rapidly. It gains something different: earlier error detection and cheaper revision. Alternative approaches remain alive longer, problems surface in more settings, and standards or interfaces can be adjusted without unwinding the whole system.[99]

The difference is not which system makes mistakes. Both do. The difference is which system absorbs the cost of error more cheaply once quantum technologies leave controlled environments and encounter mixed infrastructures, regulatory scrutiny, and adversarial conditions. China's system is stronger when coherence and speed matter most. The allied system is stronger when the field is still learning what will prove robust, interoperable, and durable under real-world conditions.

Taken together, the comparison is clear. China is optimized for coherence, sovereignty, and deployment speed. The U.S.-anchored allied cluster is optimized for optionality, interoperability, and cheaper course correction. Neither system dominates at every layer. Chapter 5 turns to the practical consequence of that fact: commercialization in quantum is the work of assembling systems whose bottlenecks, interfaces, and validation burdens reflect those same structural differences.

* * *

The implications of this chapter are clearest when translated from the sovereign level to the regional one. For a region seeking a durable role in quantum innovation, the relevant lesson is not how to replicate a scale-first national model. It is how to become indispensable inside a distributed allied system. In quantum, durable influence does not come only from producing more activity locally. It comes from occupying roles others need: reducing integration friction, helping validate performance under real conditions, and contributing capabilities that make wider systems more deployable, trusted, and interoperable.[100]

That distinction matters because regional strengths in sensing and measurement do not become economically or strategically meaningful in isolation. They become more consequential when they are paired with complementary capabilities elsewhere in the stack: fabrication, controls, software, standards participation, deployment partners, and institutional demand. The practical implication is that regional advantage in quantum should be understood as selective system assembly through collaboration. The goal is not broad connectivity for its own sake. It is outward-facing collaboration that makes local strengths harder to substitute and more valuable in national and allied pathways to deployment.

Read this way, the chapter's global findings point toward a more disciplined regional ambition. A region does not need to lead in every quantum application area to matter. It needs to become a trusted node in the parts of the system where bottlenecks are resolved and capability becomes usable. That means the next chapters should be read with a specific question in mind: where does the Mountain West appear strongest in the enabling layers, validation environments, and integrative functions that allow quantum technologies to move from promising technical achievement to repeatable operational systems?[101]

The same logic gives a bounded but important reading for ASCEND technologies. Applications tied to environmental intelligence, infrastructure, navigation, and decision systems are exactly where this chapter's argument matters most, because they depend on trusted measurement, validation across real operating conditions, and integration with classical infrastructure. If the region is to press those ambitions effectively, it will have to do so as part of a broader allied system in which local strengths are combined with complementary capabilities elsewhere. That is the strategic implication of Chapter 4: long-run regional advantage will depend less on trying to build a self-contained quantum sector than on becoming a place where collaborative system assembly turns technical strengths into deployable use.

5. Commercialization as systems assembly

Competition in quantum does not stop at invention, scale, or geopolitical position. It extends into commercialization: the process through which fragile technical capabilities become usable, trusted, and durable in the world. That process is harder to read in quantum than in many earlier technologies because the field is still consolidating its enabling platforms and because progress remains uneven across the stack. Some layers are moving quickly. Others remain constrained by unresolved questions in architecture, fabrication, calibration, validation, and integration. Commercialization, in this setting, does not look like the straightforward diffusion of finished products into ready markets. It looks like the assembly of systems capable of surviving outside the laboratory.[102]

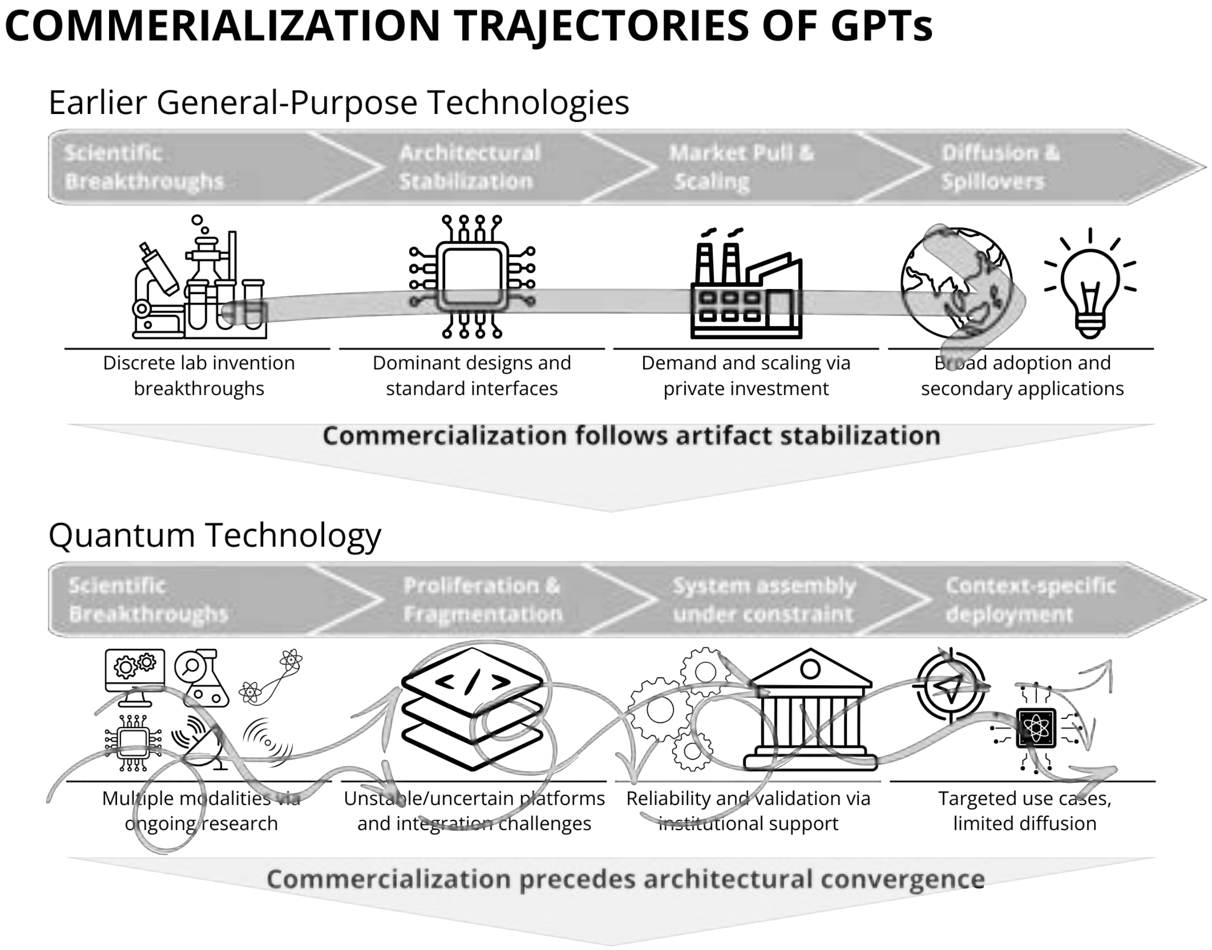
That difference changes how progress should be interpreted. Familiar indicators such as startup formation, venture investment, product announcements, and early revenue remain useful. They do not, on their own, establish that the underlying system has matured. Quantum technologies are commercialized when multiple layers can function together reliably enough to support real use: physical platforms, readout and measurement interfaces, control electronics, software, verification, and maintenance. The key question is whether those layers can be stabilized under operational conditions and connected to larger technical and institutional environments at acceptable cost. Commercial traction, therefore, emerges unevenly. It appears first where integration cannot be deferred, where failure is costly, and where buyers are willing to pay for trust, resilience, and validation.

This chapter examines commercialization on those terms. It begins by explaining why quantum commercialization differs from earlier general-purpose technologies. It then defines commercialization as system assembly, identifies where pressure is emerging first, and shows why large portions of the field remain commercially distant. The chapter also shows that institutions are not peripheral to this process. In many quantum application areas, they are the mechanism through which commercialization occurs: funding shared infrastructure, setting standards, validating performance, and acting as early buyers. That matters for advanced sensing and computing for environmental decision-making (or “ASCEND”) pathways, but Chapter 5 is not about ASCEND alone. It is about the broader structure that will determine which quantum capabilities become deployable, credible, and repeatable.

5.1 Why quantum commercialization differs from earlier GPTs

Policymakers and investors often approach quantum through a familiar commercialization template drawn from earlier general-purpose technologies such as semiconductors, high-performance computing, and the internet. In those cases, the sequence was broadly recognizable. Public funding helped establish the scientific base. Technical architectures converged early enough for supply chains and standards to form around a stable core artifact. Commercialization then accelerated through scale, cost reduction, and widening demand. The transistor, the supercomputer, and the packet-switched network each gave firms and users a clear object around which markets could organize.

Figure 31. Quantum's commercialization pathways are more varied than earlier GPTs



Quantum does not follow that sequence. It still lacks a stable core artifact around which production, standards, and adoption can reliably converge. The field remains organized around interdependent platforms—hardware architectures, sensing modalities, photonics, control systems, and software layers—that must work together before any application can function dependably at all.[103] Table 2 captures the break clearly: earlier GPTs stabilized around convergent architectures and diffused through broad product adoption; quantum remains fragmented, co-evolving, and dependent on system deployment and validation as its real commercial signal. Figure 31 makes the same point visually. In earlier GPTs, commercialization followed artifact stabilization. In quantum, commercialization begins before architectural convergence because the pressure to assemble workable systems arrives first.

Table 2. Quantum exhibits commercialization trends that differ from earlier GPTs

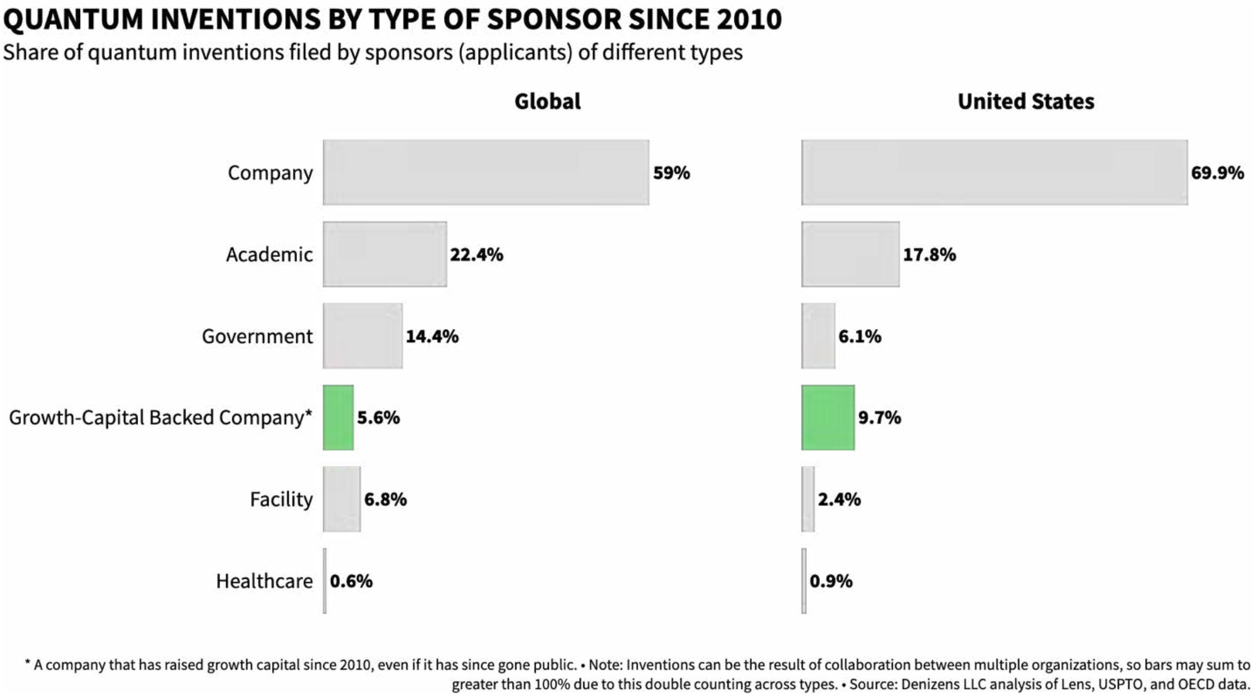
Dimension	Earlier GPTs	Quantum Technologies
Core artifact	Stabilized early	Not yet stabilized
Architecture	Convergent	Fragmented, co-evolving
Primary driver	Market pull + cost curves	System reliability + strategic risk
Role of government	Early funder, then recedes	Persistent integrator & risk absorber
Role of firms	Scale production	Assemble and control stacks
Commercial signal	Product adoption	System deployment & validation
Diffusion pattern	Broad, rapid	Uneven, domain-specific

Source: Denizens LLC.

Market formation also works differently. Earlier GPTs benefited from strong commercial demand well before their technical limits were reached. Semiconductor markets expanded because performance gains translated directly into cheaper and more powerful products. High-performance computing moved from government-backed missions into industry once faster computation created obvious value for defined users. Quantum faces a different demand structure. Much of its early commercial urgency comes from strategic risk and operational vulnerability rather than from broad discretionary demand. Concerns about cryptographic exposure, secure communications, and resilient navigation create pressure to act even where near-term mass markets remain uncertain. In quantum, the earliest buyers are often not consumers or even ordinary enterprises. They are governments, regulated industries, defense organizations, and infrastructure operators that will pay for trust, resilience, and risk reduction before they pay for scale.[104]

That difference changes how commercial signals should be read. Startup formation, venture rounds, product announcements, and early revenue remain useful. They do not measure system-wide maturity. The current sponsor record shows why. Growth-capital-backed companies account for only 5.6 percent of quantum invention sponsorship globally and 9.7 percent in the United States. Those firms matter because they show where private capital sees a plausible translation pathway. But they still represent a narrow slice of the broader quantum innovation system. Venture investment, therefore, tracks commercialization in a subset of firms and stack layers, not the maturity of the field as a whole. It shows where translation and scale-up are beginning to look credible. It does not show that the underlying system has stabilized.[105]

Figure 32. Startups drive a small but meaningful portion of quantum invention



QUANTUM INVENTIONS BY TYPE OF SPONSOR SINCE 2010

Share of quantum inventions filed by sponsors (applicants) of different types

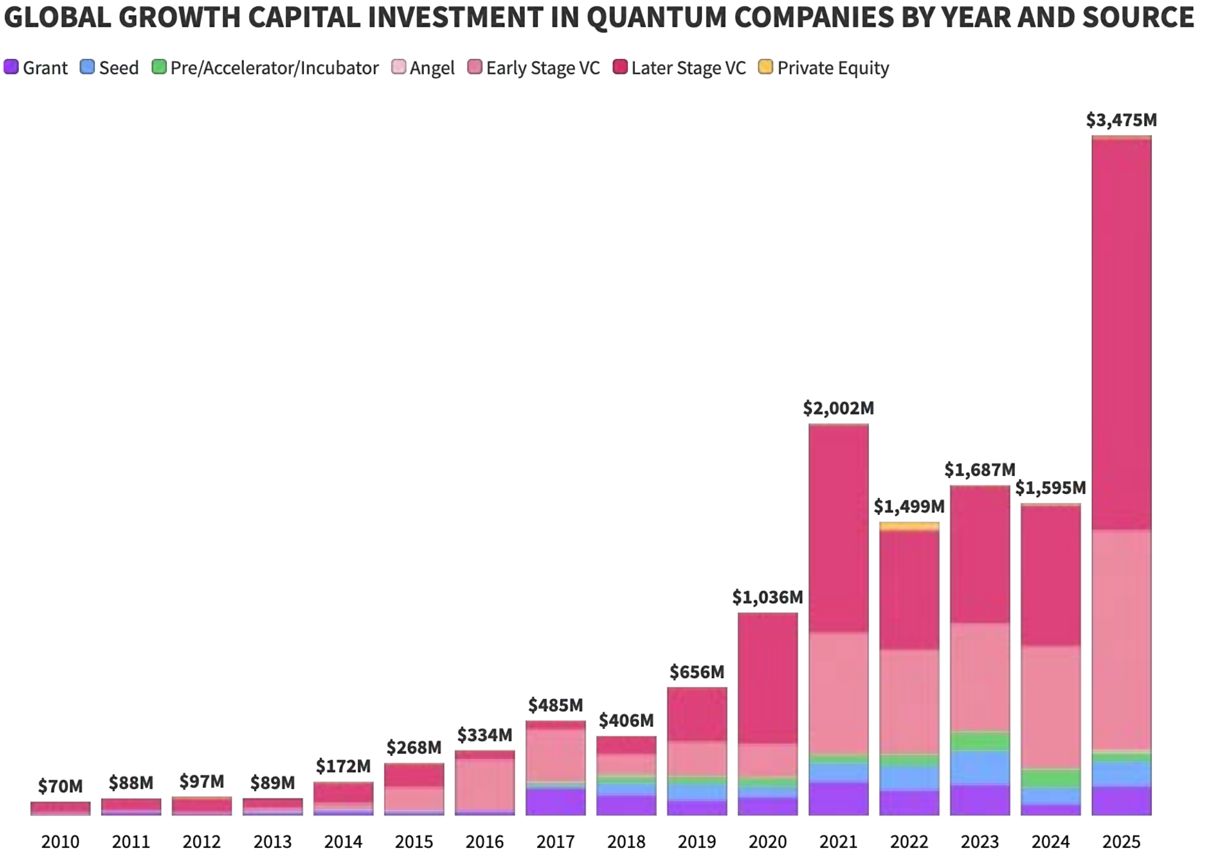
* A company that has raised growth capital since 2010, even if it has since gone public. • Note: Inventions can be the result of collaboration between multiple organizations, so bars may sum to greater than 100% due to this double counting across types. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

To describe commercialization structurally, this analysis distinguishes between (i) the universe of invention sponsors (who are producing quantum inventions) and (ii) the subset of growth-capital-backed firms (where private capital underwrites translation). The latter is not the whole quantum innovation system—but it is a window into market-facing system assembly.

Quantum also differs from earlier GPTs in that it will not commercialize uniformly across its own quantum application areas. Computing, communications, and sensing do not follow a single commercial timeline, and they do not face the same integration burdens. Some sensing systems can enter narrow operational use without the massive overhead required for fault-tolerant computing. Some communications pathways advance through standards, migration, and infrastructure coordination before frontier hardware matures. Some computing pathways may commercialize first as access and orchestration models rather than as broadly deployed machines. Treating "quantum" as one market obscures those differences and encourages false comparisons with technologies that matured more uniformly. Quantum is not one adoption story. It is a set of uneven commercialization pathways tied together by shared platforms and bottlenecks.

A final difference is that quantum is developing against a moving classical frontier. Earlier GPTs often expanded into environments where the incumbent baseline improved more slowly or had already stabilized, making the new technology's distinctiveness obvious. Quantum faces stronger competition. Classical computing keeps advancing. Artificial intelligence continues to improve what classical systems can do. Specialized hardware keeps narrowing the set of problems for which quantum can claim clear near-term superiority. Quantum has to prove distinctive value against a baseline that keeps shifting upward. That raises the threshold for commercial adoption and delays the emergence of application markets.[106]

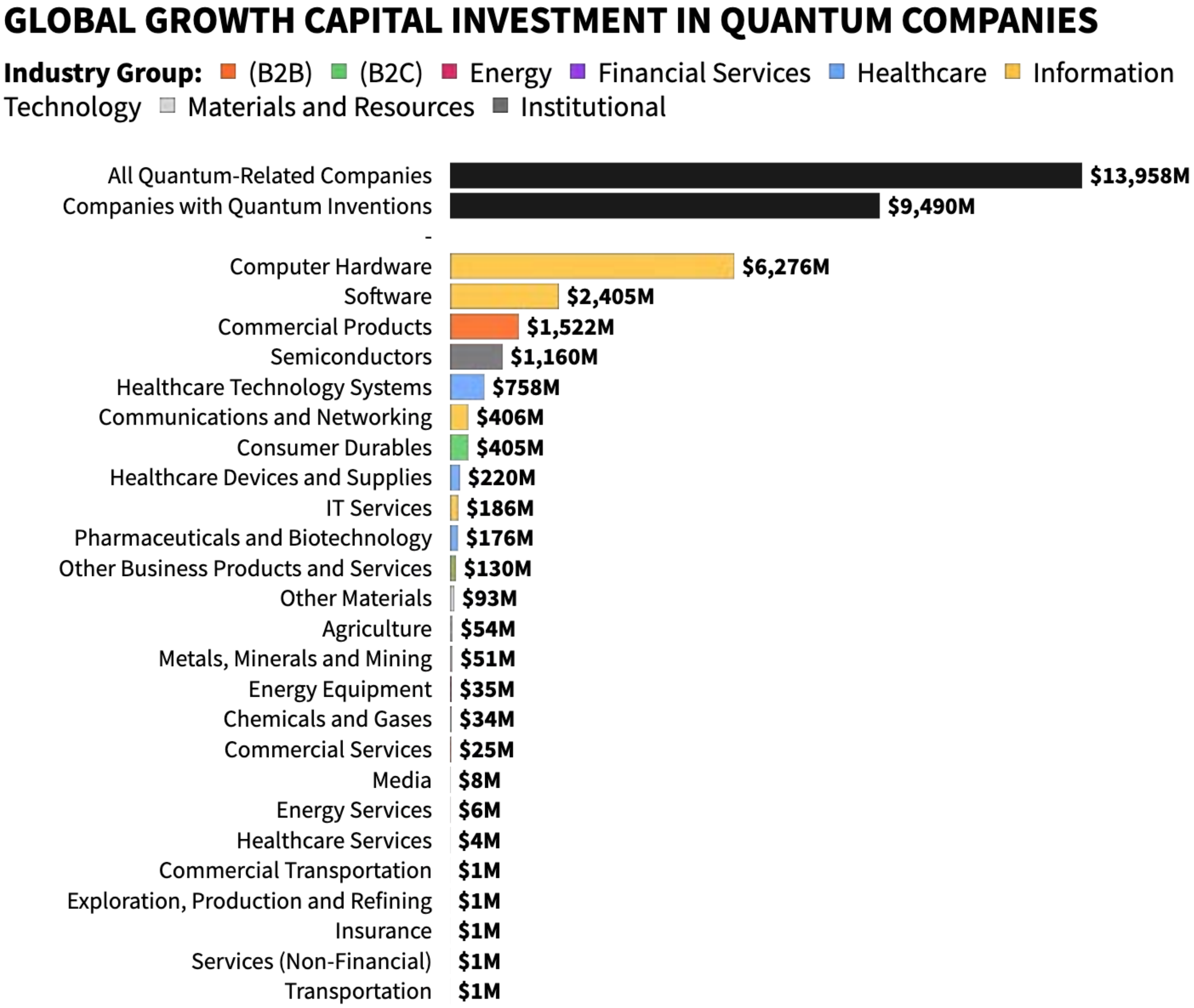
Figure 33. Global investment in quantum startups has accelerated in recent years



* Partial year data. • Note: Deals missing a value were assigned an investment value of $1 Million. • Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data

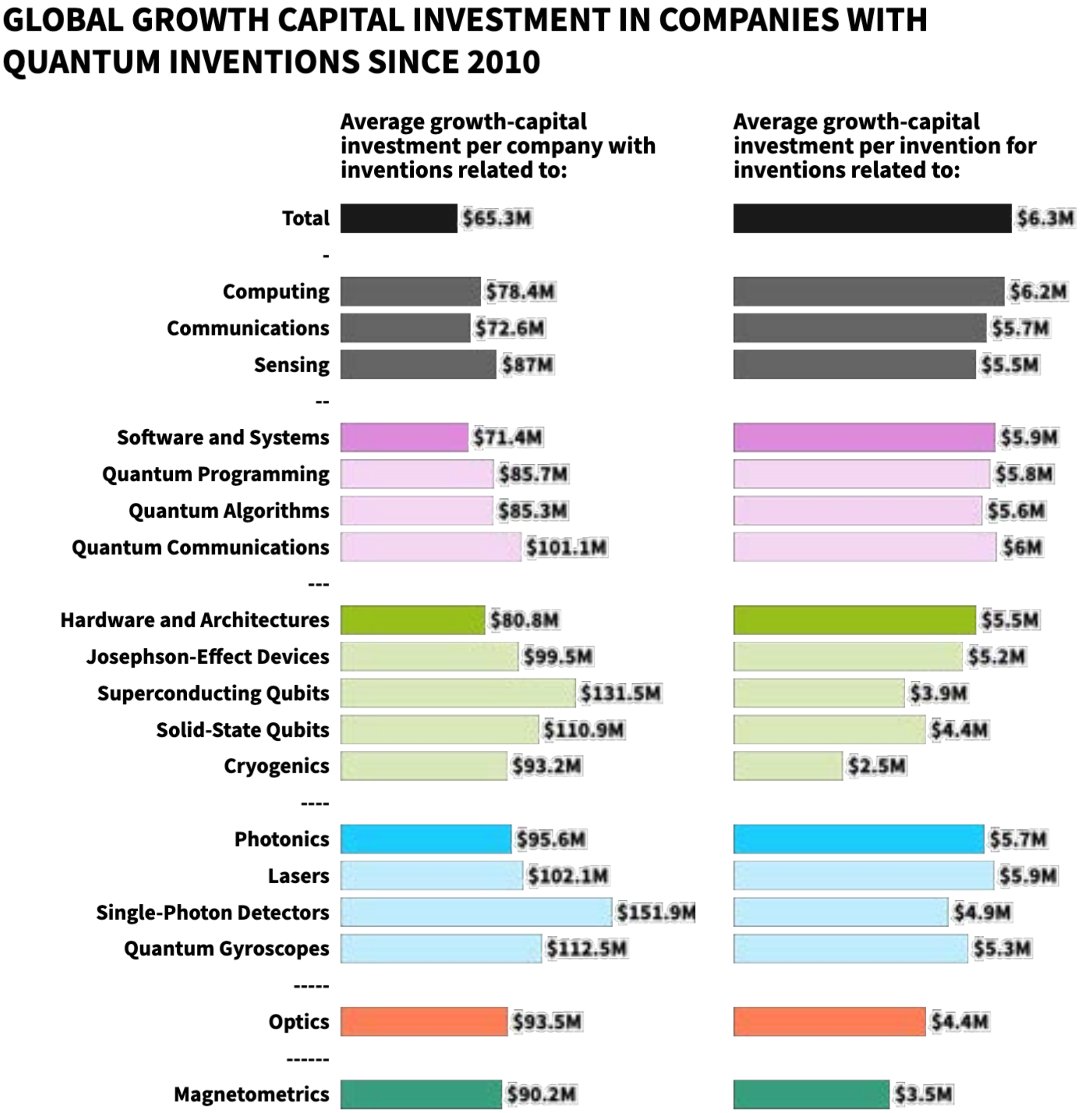
These differences explain why the familiar commercialization narrative fails here. Quantum is not simply earlier on the same path traveled by semiconductors or the internet. Its architectures remain unsettled. Its earliest demand is often institution-led. Its strongest commercial signals appear in translation, validation, and integration rather than in broad product adoption. The field is doing a different kind of work: assembling interdependent systems that can operate reliably under real-world constraints. That is why the right unit of analysis is not the quantum market. It is the assembled system.

Figure 34. Startups with quantum inventions raised 68% of growth capital investment



Note: Deals missing a value were assigned an investment value of $1 Million. • Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data

Figure 35. Relatively uniform average investment in quantum platforms suggests convergence within inventions and the startups that sponsor them



GLOBAL GROWTH CAPITAL INVESTMENT IN COMPANIES WITH QUANTUM INVENTIONS SINCE 2010

Note: Deals missing a value were assigned an investment value of $1 Million. • Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data

5.2 Quantum commercialization as system assembly

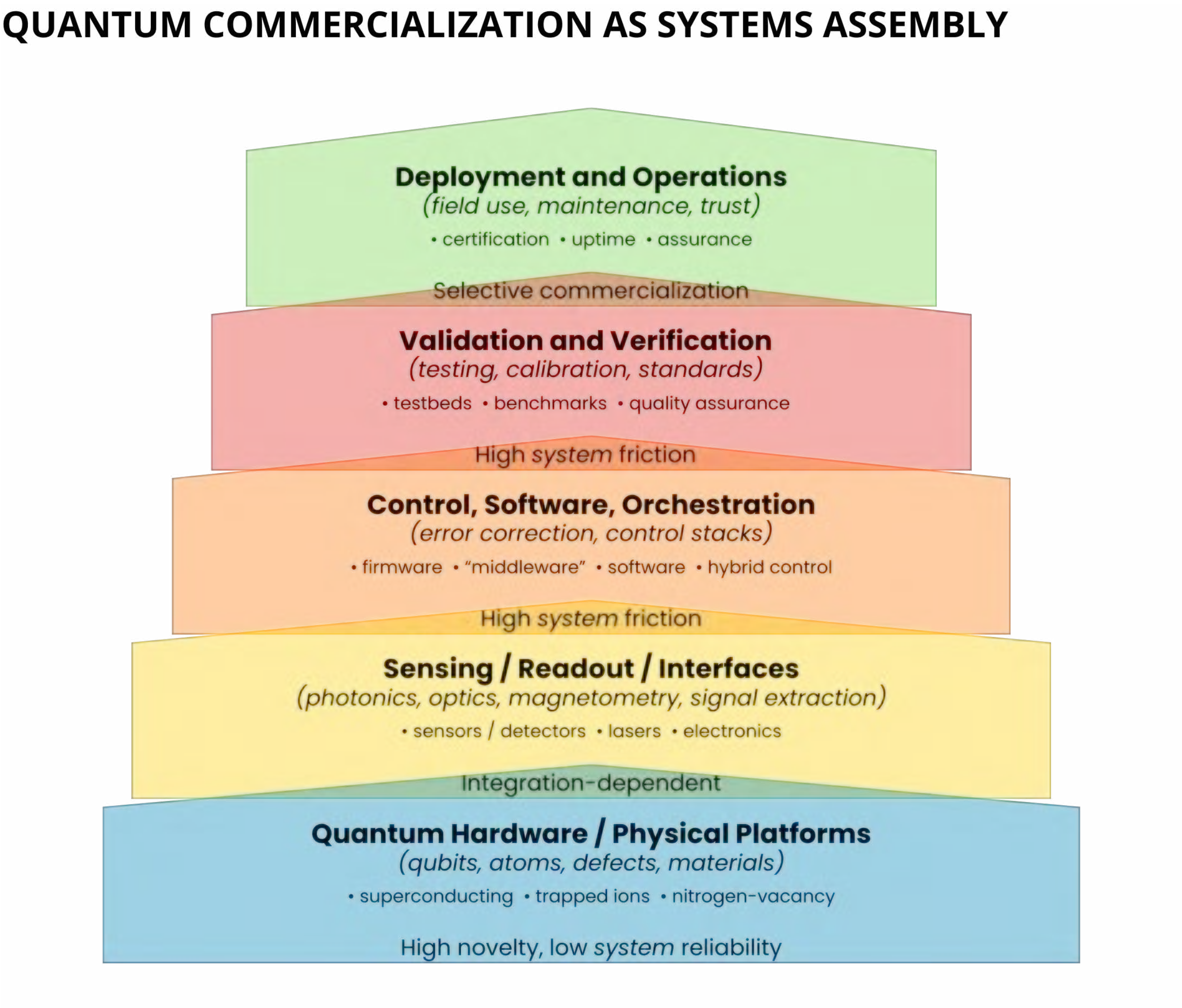
Quantum commercialization is the assembly of reliable systems under real-world constraints. It does not begin when a single device posts an impressive laboratory result. It begins when fragile quantum effects can be converted into repeatable, trusted capability inside an operating system that users can actually adopt. The relevant unit is therefore the assembled system: the combination of hardware, sensing and readout, control electronics, software, calibration, validation, and operational support required to make performance hold outside controlled environments.[107]

That distinction matters because the field's inventive center still sits in enabling layers rather than finished products. Since 2010, software and systems account for 16,131 quantum-related inventions globally, compared with 6,956 in hardware and architectures and 4,819 in photonics. Those are not downstream market categories. They are the layers that generate, control, read, stabilize, and interpret quantum effects. Commercial progress, therefore, depends less on the appearance of a single dominant product than on whether these layers can be made to function together with tolerable levels of error, cost, and maintenance.

Seen through the stack, commercialization is a cumulative engineering problem. Physical platforms must first generate and preserve the relevant quantum states. Sensing and readout layers must then extract a usable signal. Control electronics, firmware, and software must translate that signal into something stable enough to interpret and operate. Validation and verification must establish whether performance is comparable, repeatable, and credible. Deployment adds another burden: the system must keep working under real operating conditions, often for long periods, and often inside legacy infrastructures that were not designed around quantum subsystems. Progress in one layer often exposes unresolved constraints in another because the stack commercializes through alignment rather than isolated breakthroughs.[108]

No layer commercializes independently for long. A quantum sensor with remarkable sensitivity still fails commercially if its calibration drifts in the field, if its output cannot be benchmarked against a shared standard, or if the rest of the workflow cannot absorb the measurement. A computing architecture with promising qubit performance remains commercially limited if its control overhead, error burden, and classical integration costs remain too high. A communications system with strong security properties still struggles if its interfaces, deployment requirements, and network dependencies remain bespoke. Commercial value appears when the assembled system becomes dependable enough to be used, maintained, and trusted. Until then, even real technical progress can remain commercially thin.

Figure 36. Integration pressures compound between layers of the system



This also explains why familiar indicators can mislead if they are treated as system-wide measures of maturity. Growth-capital-backed firms account for only 5.6 percent of global quantum invention sponsorship and 9.7 percent in the United States. Private capital is therefore tracking translation in a subset of the field, not the development of the full system. Capital clusters around firms that control key points of integration: hardware-control interfaces, photonics, software, orchestration, and access layers that make fragile systems easier to use. That pattern is not evidence of confusion about what quantum is for. It is evidence that the hard commercial work sits in binding the stack together.[109]

Table 3. The quantum industrial-base imposes commercialization constraints

Element	Primary Role	Where It Binds	Resulting Friction	Implication
Research	Expands the feasible design space; resolves foundational physics limits	Hardware platforms; sensing modalities	Architectural instability; competing approaches; uncertain scaling	Prevents early convergence; delays product definition
Workforce	Translates prototypes into operable systems	Control systems; calibration; deployment	Bottlenecks in integration, maintenance, and scale-up	Limits deployment capacity even where technology exists
Materials	Enables performance, stability	Hardware, sensing, cryogenics	Yield variability; supply chain risk; cost volatility	Raises uncertainty and capital intensity of scaling
Fabrication	Converts laboratory devices into repeatable components	Hardware–control interface	Low yields; bespoke processes; lack of standardization	Prevents cost curves from forming
Software	Makes quantum systems usable and interoperable	Control layers; hybrid classical–quantum systems	Fragile orchestration; limited abstraction	Restricts access to expert users and controlled environments
Testing	Establishes trust, reliability, and comparability	System integration; deployment	High cost of assurance; lack of shared benchmarks	Slows adoption outside government and mission-critical use

Source: Denizens LLC.

Quantum-as-a-Service is a good example. These offerings do not signal that a broad, mature market for quantum computing has already arrived. They commercialize access to partially assembled systems while centralizing the burdens that most users cannot absorb themselves: infrastructure, calibration, orchestration, maintenance, and expert control. The provider hides fragility and complexity behind an access model. Users can experiment, prototype workflows, and begin integrating quantum resources into larger technical environments without owning the full system. That is a real commercialization pathway. It is also selective, because it depends on centralizing expertise and shielding users from unresolved lower-layer constraints, rather than solving those constraints for everyone at once.[110]

The criterion for commercial progress, therefore, has to shift. The important question is not whether quantum technologies have reached end users at scale. The important question is whether systems can be deployed, maintained, calibrated, verified, and trusted outside laboratory settings. Reliability, repeatability, interoperability, certification, and assurance become the operative thresholds because they determine whether a promising capability can survive contact with the world. The same logic makes the industrial base central to commercialization. Research, workforce, materials, fabrication, software, and testing each bind at different points in the stack because each determines whether a prototype can become an operable system rather than a one-off achievement.

Interoperability is especially important because it reveals why commercialization remains slow and uneven, even where the underlying science is strong. Most quantum systems are still built for specific research or demonstration settings. Shared interfaces remain thin. Common performance benchmarks remain limited. Calibration standards are still incomplete across much of the field. Connecting subsystems from different developers, or connecting quantum subsystems to classical infrastructure, therefore requires repeated, expensive integration work. The field is still turning custom technical achievements into repeatable systems.

For ASCEND-relevant pathways, that distinction is decisive. The issue is not whether a quantum device can register an interesting environmental, infrastructure, or navigation-related signal. The issue is whether the full measurement stack can deliver outputs that field users, models, and decision systems can trust. Once commercialization is understood in those terms, the next question is: where do these system pressures first emerge, and in which parts of the field does deployment force the stack to harden sooner?

5.3 Where quantum commercialization pressure is emerging first

Quantum commercialization pressure does not emerge where novelty is highest or where forecasts promise the largest eventual markets. It emerges when systems must work outside the laboratory, where failure is costly, and integration cannot be deferred. In these settings, the central question is not whether a quantum device can outperform a classical one under ideal conditions. It is whether a quantum-enabled system can be deployed, calibrated, maintained, and trusted under real operating constraints. Three arenas bring that pressure into view early and clearly: resilient navigation and timing, secure communications and cryptographic transition, and infrastructure-adjacent sensing. They differ technically, but they share the same commercial logic. The value proposition is immediate. The operating environment is unforgiving. Adoption depends more on validation than on novelty.[111]

5.3.1 Resilient navigation and timing: deployment forces integration

Positioning, navigation, and timing sit at the heart of modern economic and security infrastructure. GPS-enabled timing supports financial transactions and critical-infrastructure synchronization. GPS-enabled positioning supports aviation, maritime logistics, and defense operations. That makes GPS's vulnerability to jamming and spoofing far more than a technical curiosity. It is already an operational problem. As interference becomes more common in contested environments, the value of alternatives rises even when those alternatives remain partial, expensive, or technically demanding. Commercialization pressure appears here because the underlying need is already real. The system being protected already exists. The cost of failure is obvious.

Quantum sensing enters this arena as a resilience layer, not as a wholesale replacement for satellite navigation. That distinction matters. The relevant commercial opportunity is not a consumer-facing navigation product. It is the assembly of trusted PNT stacks that can preserve function when satellite signals degrade or disappear. That pushes commercialization upstream into ruggedization, calibration, reliability, packaging, and integration with existing control and data-fusion systems. In this arena, those elements are not ancillary engineering tasks. They are the product because they determine whether a measurement advantage can be trusted in situ. PNT, therefore, becomes a leading edge of system assembly: deployment forces the stack to harden sooner because navigation resilience is only meaningful when the full system holds together under operational stress.[112]

5.3.2 Security transition: commercialization via standards

Secure communications reveals a different path, but the same structural pattern. Quantum communications is often associated with quantum key distribution and longer-term visions of quantum networking. The most immediate commercialization pressure, however, does not sit there. It sits in the transition to post-quantum cryptography. That transition is being driven by the expectation that future quantum computers will eventually threaten today's widely used encryption standards. The commercial work is therefore not the rollout of a fully quantum network. It is the migration of large installed systems across sectors and supply chains: updating protocols, validating implementations, hardening interfaces, and maintaining compatibility while reducing systemic risk. The binding challenge is coordination, not frontier quantum performance. The clearest signal of progress is not revenue or user growth. It is interface stabilization across standards bodies, regulated industries, government procurement channels, and cybersecurity mandates.[113]

5.3.3 Infrastructure-adjacent sensing: validation-driven adoption

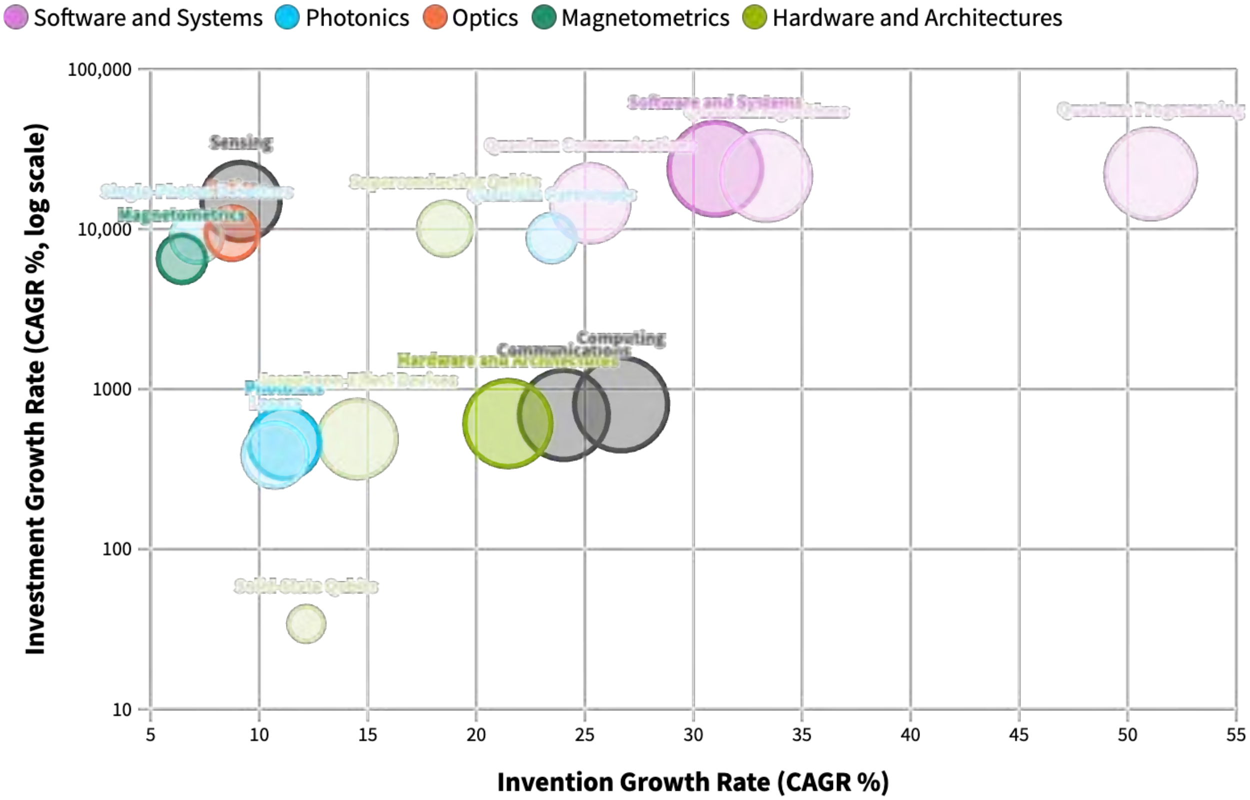
A third commercialization arena appears in sensing applications tied to infrastructure and other high-value operations. These include underground imaging and subsurface mapping, environmental and geophysical monitoring, and sensing that supports aviation, defense, or industrial systems. What makes these settings commercially important is not that they promise the largest long-run markets. It is that small measurement improvements can create meaningful operational gains if the system can be trusted in place. These deployments already have institutional buyers. They already use pilots, testbeds, and validation-heavy procurement pathways. They do not need a polished consumer product to begin adoption. They need evidence that a system can operate reliably in situ and that its outputs can be integrated into an existing workflow without introducing unacceptable uncertainty. That is why sensing can appear commercially ahead even when invention growth is slower. The commercial frontier lies in deployment and maintenance, not in the laboratory sensitivity benchmark.[114]

These three arenas share a common structure. Commercialization pressure arrives early where systems must function outside controlled environments, where reliability and calibration determine value, where integration with legacy systems cannot be deferred, and where institutions can absorb uncertainty through pilots, procurement, and test environments. None of those conditions guarantees rapid scale. They do something more important. They force the work of system assembly into the foreground. In each arena, the field advances only when interfaces stabilize, assurance regimes form, and the stack becomes trustworthy enough to support use under constraint.

These early pressure points do not prove that a broad, unified quantum market is imminent. They show where system assembly has become unavoidable and therefore fundable. That is why they matter. They reveal the contexts in which commercialization ceases to be a speculative future question and becomes a present engineering, validation, and coordination problem. Once those pressures are visible, the next question becomes institutional rather than purely technical: who reduces integration risk, funds shared infrastructure, defines validation pathways, and helps assembled systems cross from promising performance into usable capability? That is the work of institutions, and it is the subject of the next section.

Figure 37. Commercialization is highly uneven across quantum platforms

GROWTH OF INVENTION VERSUS INVESTMENT ACROSS QUANTUM TECHNOLOGY PLATFORMS, 2010 – 2023



Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data.

5.4 The binding constraints on system assembly

If commercialization pressure emerges first where integration cannot be deferred, then large portions of the quantum field will still appear commercially distant. That distance is not evidence of failure. It reflects a simpler fact: in many parts of the stack, the binding constraints still sit below the level of the visible application. They sit in architectures, manufacturing, calibration, validation, and integration. In those conditions, a breakthrough can be scientifically meaningful and remain commercially inert because it cannot yet be turned into a repeatable, reliable system under real operating conditions.

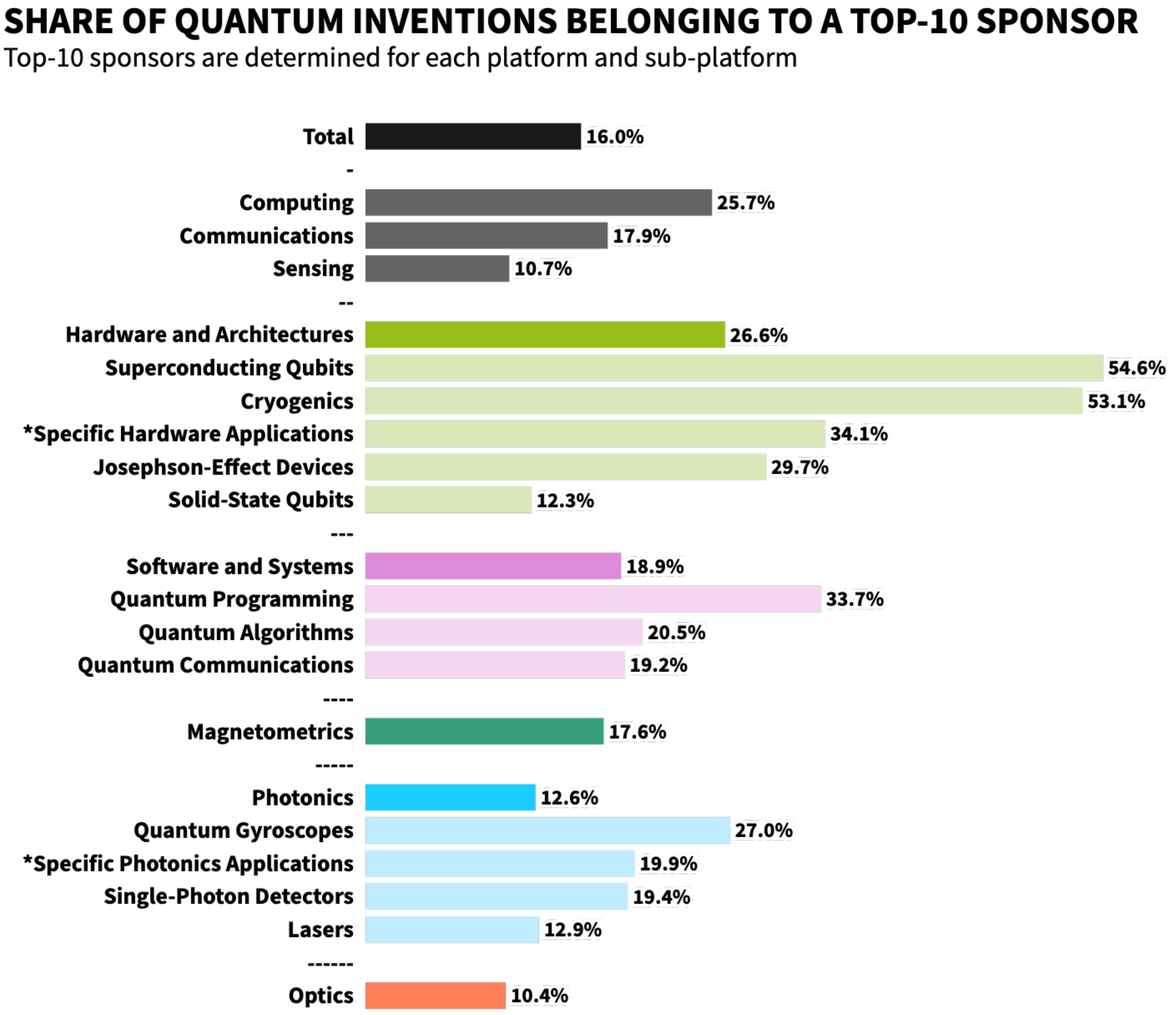
The first constraint is architectural fragmentation. Earlier general-purpose technologies accelerated once architectures converged and interfaces stabilized. Quantum has not reached that point. Multiple hardware modalities still coexist, each with distinct advantages, control requirements, and engineering burdens. That keeps downstream investment expensive because every choice propagates through the rest of the stack. Control systems stay bespoke. Validation protocols resist standardization. Suppliers hesitate to scale around uncertain demand. Adopters hesitate because they cannot yet tell which design path will remain durable enough to justify deep integration.[115]

The second constraint is manufacturing immaturity. Quantum commercialization depends not only on what can be shown in principle, but on what can be made reliably and repeatedly. Many systems still rely on exotic materials, highly specialized fabrication processes, and demanding operating environments. That keeps the field stuck between laboratory prototypes and production-grade systems. Figure 38 underscores how thin the industrial base remains in some sub-platforms: the top-10 sponsors collectively account for 54.6 percent of superconducting-qubit inventions and 53.1 percent of cryogenics inventions, compared with 16.0 percent across the full corpus. That concentration matters because it signals low supplier depth, weak learning curves, and fragile scale-up pathways. Packaging and miniaturization compound the problem. Broad deployment in most civilian settings will require advances in quantum system-on-chip or analogous packaging, not simply better standalone devices.[116]

The third constraint is calibration and metrology. Quantum systems derive their value from extraordinary sensitivity, but that same sensitivity makes them vulnerable to environmental noise, drift, and performance degradation outside controlled settings. In sensing, the challenge is distinguishing real signals from environmental confounders while maintaining stable performance across varying operating conditions. In computing, the same problem manifests as noise accumulation, thermal management burdens, and escalating error-correction overhead. In communications, it appears as photon loss, device imperfections, and fragile network performance. Commercialization becomes harder when a system is expected to operate continuously rather than perform only once in a demonstration. The question shifts from can it work to can it keep working.[117]

The fourth constraint is validation. Many quantum application areas still lack established qualification pathways, shared benchmarks, and agreed field standards. That leaves buyers in a difficult position. They may believe the underlying science is sound and still be unable to compare claims, define thresholds, or procure with confidence. Each deployment then has to invent too much of its own validation regime: what counts as acceptable performance, how drift will be detected, how outputs will be cross-checked, and what evidence is sufficient for certification or mission use. That slows procurement cycles and raises adoption risk because trust must be rebuilt case by case instead of being carried by common protocols and institutions.[118]

Figure 38. Invention concentration suggests a thin industrial base in some platforms



SHARE OF QUANTUM INVENTIONS BELONGING TO A TOP-10 SPONSOR

Top-10 sponsors are determined for each platform and sub-platform

* These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens data.

The fifth constraint is classical integration, and in many cases it is the decisive one. Measurement or computation does not create impact on its own. Outputs have to move into models, analytics, control systems, operational procedures, and procurement environments that were not designed around quantum subsystems. Interoperability remains hard for a simple reason: most current systems are still built to custom specifications for specific research or demonstration settings. Shared performance benchmarks remain limited. Common interfaces remain sparse. Agreed calibration standards remain uneven. Every deployment, therefore, requires expensive integration work again.

These structural constraints define the pace and shape of quantum system assembly. They sit in the enabling conditions that make systems repeatable, interoperable, and trustworthy. Private capital can help translate some parts of the stack, but it cannot substitute for missing architectures, thin supply chains, incomplete standards, or absent validation infrastructure. The commercialization challenge is therefore broader than inventing better devices. It is about building the technical and organizational conditions that enable those devices to become durable systems, which is why institutions, not markets alone, are the mechanism through which quantum commercialization occurs.

5.5 The role of institutions in quantum commercialization

The constraints described in Section 5.4 explain why quantum commercialization cannot be left to markets alone. Where architectures remain unsettled, manufacturing is immature, validation regimes are incomplete, and integration into classical systems is expensive, private firms face risks that are difficult to price and harder to absorb. In that environment, institutions do more than “support” commercialization. Public agencies, national laboratories, standards bodies, defense and infrastructure buyers, and regional intermediaries reduce the costs of system assembly and enable early deployment. In many quantum application areas, they commercialize the system before the market can. They fund shared infrastructure, absorb qualification risk, define credible performance thresholds, and create deployment conditions in which trust can be built rather than merely claimed.

5.5.1 Institutions reduce integration risk through funding and infrastructure

System assembly requires capabilities that are expensive, specialized, and often uneconomic for any single firm to build in isolation. Shared-use fabrication facilities, cryogenic infrastructure, photonics labs, metrology equipment, and calibration environments sit beneath multiple quantum application areas, yet they rarely fit the business model of an early-stage company facing uncertain demand and long development cycles. Institutions fill that gap by underwriting the physical environments in which experimentation, iteration, benchmarking, and failure can occur at workable cost.[119]

That function extends beyond funding basic research. Shared infrastructure shortens iteration cycles, lowers capital barriers, and makes performance more comparable across teams and platforms. It also helps reduce one of the field's most stubborn problems: bespoke integration. When multiple firms, labs, and users test systems in the same physical and metrological environment, interfaces begin to stabilize and performance claims become easier to verify. Shared infrastructure is therefore commercialization work in a literal sense. It creates the conditions under which prototypes can become components, components can become systems, and systems can begin to earn trust outside isolated demonstrations.

5.5.2 Institutions create early markets by acting as anchor customers

Institutional buyers also do work that conventional markets cannot yet do. In sectors where failure is costly—defense, aviation, critical infrastructure, secure communications, and other mission-driven settings—buyers are often willing to procure early systems, sponsor pilots, and fund long validation cycles before broad commercial demand exists. They do not behave like consumer early adopters. They behave like qualification partners. They purchase capability under uncertainty, tolerate long testing and certification periods, and invest in training, sustainment, and integration because reliability is itself the requirement being purchased.[120]

That is why early commercialization pressure appears first in arenas such as resilient navigation and cryptographic transition. Institutional buyers are not simply adding demand at the margin. They are helping define the adoption pathway. They specify requirements, fund demonstrations, support certification processes, and establish interoperability expectations. In quantum, that role is decisive because early deployments are rarely plug-and-play. They have to be connected to existing legacy systems, operating procedures, and maintenance routines. Buyers with the patience and authority to support that work become part of the commercialization mechanism itself.

5.5.3 Institutions stabilize through standards, benchmarking, and assurance

Commercialization also accelerates when interfaces stabilize, and performance claims become comparable. In quantum, neither condition emerges automatically. Standards bodies, public programs, and metrology institutions define benchmarks, test protocols, calibration procedures, and assurance frameworks that let buyers, investors, and integrators distinguish a laboratory demonstration from a deployable system. Without those mechanisms, information asymmetry remains high. Firms can show progress, but outsiders cannot easily judge what the progress means or how portable it is.

Post-quantum cryptography offers an example of standards-led commercialization. Adoption advances because standards processes create a migration pathway before fully mature quantum computing arrives. The same dynamic extends beyond cryptography. In sensing and hardware, calibration standards, certification thresholds, shared test protocols, and traceable measurement practices determine whether performance can be trusted outside bespoke pilots. Institutions create those rules. They turn isolated technical achievements into interoperable capabilities and make system assembly legible.[121]

5.5.4 Institutions shape where commercialization happens

Because institutions host shared infrastructure and coordinate validation pathways, they also shape the geography of commercialization. Regions and countries that control testbeds, standards work, early deployment programs, and mission-facing qualification environments gain disproportionate influence over the direction of quantum markets. That influence does not always appear as firm-level market dominance. It appears as control over interfaces, interoperability requirements, certification regimes, and the practical terms under which systems can be deployed.

That is why competition for quantum leadership extends beyond invention counts and beyond the location of high-profile firms. It includes the race to build and host the institutional infrastructure that enables system assembly. Places that can convene researchers, suppliers, standards-setting functions, mission buyers, and validation environments become harder to route around. They shape whose benchmarks become default, whose platforms become easier to integrate, and whose supply chains become more strategically important. In quantum, commercialization is therefore also a governance function. It determines where trust is built, where interoperability is defined, and where the wider system learns how to deploy.

These institutional functions help explain why commercialization in quantum will not unfold along a single path. Shared infrastructure, anchor customers, standards work, and qualification environments are unevenly distributed across sectors and geographies. Some pathways will harden quickly because institutions are already in place to absorb risk and establish trust. Others will remain slow because those institutional conditions are absent or thin. Commercialization is therefore uneven not only because the technologies differ, but also because the institutions that make them usable differ.[122]

5.6 Quantum commercialization is inherently uneven

The preceding sections point to a simple conclusion: quantum commercialization is inherently uneven because the field itself is being assembled unevenly. Progress does not move through a single market, a single product category, or a single adoption curve. It moves through a layered technical system whose components mature at different speeds, under different cost structures, and with different institutional supports. That unevenness is structural. It does not reflect weak interest, inadequate ambition, or a temporary pause before a broad commercial takeoff. It reflects the fact that quantum capabilities become valuable only when heterogeneous layers can function together reliably enough to survive outside the laboratory.

That unevenness follows the stack. Upper layers, such as control software, orchestration, programming, and hybrid interfaces, can advance quickly because they benefit from faster iteration cycles and from adjacent digital capabilities. They generate visible commercial momentum: new tools, new access models, new developer environments, and expanding claims about usability. Lower layers move more slowly because they remain constrained by materials quality, fabrication reproducibility, calibration burdens, packaging, and environmental sensitivity. Commercialization, therefore, appears first where upper-layer gains can be anchored in physical systems that are already stable enough for deployment. Where that anchoring is weak, momentum remains real but selective. It produces narrow pathways rather than broad market readiness.[123]

The same pattern appears across the major quantum application areas. Sensing often commercializes earlier because some sensing stacks can be qualified and deployed without the full burden of fault-tolerant computation. Even there, commercialization is usually narrow, validation-heavy, and institution-led, concentrated in settings where measurement resilience matters more than mass-market diffusion.[124] Communications occupies an intermediate position. Some pathways advance through standards, migration, and secure-link deployment before frontier hardware matures, while larger networking ambitions remain constrained by losses, memory, repeater, and systems-integration problems. Computing remains the most commercially constrained area because useful commercialization depends on reliable, scalable systems with manageable error burdens and tolerable operating overhead. Its earliest commercial forms, therefore, center on access, orchestration, and hybrid experimentation rather than broadly deployed machines. These are different commercialization pathways, not stages on a single shared clock.

Unevenness also follows institutions. Commercialization proceeds fastest where shared infrastructure exists, where early demand is real, and where standards or validation pathways reduce adoption risk. Public agencies, national laboratories, defense buyers, critical-infrastructure operators, and standards-setting bodies matter because they absorb integration costs that markets alone still struggle to bear. They fund fabrication and testing environments, define qualification thresholds, and create early procurement pathways for systems that remain expensive, fragile, or technically specialized. In much of quantum, the first real market is therefore institutional. That is not a temporary deviation from commercialization. It is the mechanism through which commercialization occurs.[125]

There will be no single commercialization finish line for quantum. Some capabilities will enter narrow operational systems years before the broader field converges. Some layers will scale through access and standards before hardware stabilizes. Others will remain research-intensive even as adjacent layers become commercially legible. The right question is therefore no longer whether quantum is commercializing in general. The right question is where system assembly is becoming reliable enough to support deployment, trust, and repeatability—and what that reveals about who is positioned to shape the next stage of the stack's consolidation.

* * *

The preceding chapters have advanced a single claim about quantum technology: the relevant unit of progress is not the "quantum market," but the quantum system. Quantum capabilities become consequential only when enabling platforms, measurement layers, control systems, software, and validation regimes can be assembled into reliable, interoperable capability. Chapters 1 through 3 showed why progress concentrates in shared platforms and why sensing matters as the point where stack integration is tested against operational reality. Chapter 4 showed that competition is not only a matter of scale, but of who controls bottlenecks, interfaces, and integrative roles inside an interdependent system. Chapter 5 showed that commercialization follows the same logic. It proceeds through system assembly under real-world constraints, mediated by institutions and uneven by design.

That changes how progress should be read. Startup counts, venture funding, product announcements, and early revenues remain useful, but they are partial indicators. They reveal movement in specific parts of the stack, not maturity of the system as a whole. The stronger signals are harder and more structural: reliability hardening under operational conditions; shared testing and validation regimes; stabilizing interfaces and performance benchmarks; institutions able to absorb early deployment risk; and evidence that fabrication, supply chains, and workforce capabilities are becoming repeatable rather than bespoke. These are the conditions under which market pull emerges as an outcome of system consolidation rather than as its starting point.

It also changes how advantage should be understood. Scale still matters. But in a field where bottleneck platforms, validation environments, standards processes, and deployment pathways remain decisive, scale is not the only axis that matters. Influence accrues to places that help determine how quantum systems become usable: where interfaces are set, where performance is qualified, where integration risk is reduced, and where fragile capabilities are turned into trusted operational systems. That is as true for regions as it is for nations.[126]

As the report turns from the global scan to the Mountain West, the central question is not whether the region participates in quantum research. It is whether the region holds assets that shape how system assembly happens. A practical way to judge that is to ask five questions.

- **Bottleneck-layer position:** Does regional activity concentrate in enabling layers close to performance constraints — sensing, photonics, control, packaging, validation — or mainly in downstream applications?
- **Assembly and validation capacity:** Does the region host the integrators, shared facilities, testbeds, and qualification environments needed to reduce integration risk and move systems beyond one-off demonstrations?
- **Institutional anchoring and early demand:** Are there mission-driven partners, early buyers, and operating contexts that can absorb uncertainty and force deployment under real conditions?

- **Industrial and workforce depth:** Can the region build, maintain, calibrate, and certify systems, or does it still depend on missing suppliers, fabrication pathways, or translation talent?
- **Outward network position:** Is the region connected to the collaborative, standards-setting, and deployment networks through which quantum systems become interoperable and widely usable, or is it largely isolated?

Chapters 6 and 7 apply this rubric to Colorado and the wider Mountain West. The purpose is not to stage a promotional argument or to compare the region against an abstract finish line. It is to judge whether the Mountain West occupies positions that make wider quantum systems easier to validate, integrate, and deploy — and therefore whether regional advantage is best understood not as scale alone, but as influence over the conditions under which quantum becomes real, reliable, and usable.

6. The Mountain West's quantum advantage

Chapter 5 established a practical standard for assessing whether a place can influence the assembly of quantum systems. The question is not simply whether a region produces quantum research or attracts startup activity. It is whether it holds meaningful strength in the parts of the stack that determine whether quantum effects become usable systems: enabling platforms close to measurement, control, validation, and deployment; organizations capable of integrating across layers; institutions that can absorb long qualification cycles; and pathways that connect invention to repeatable use.

This chapter applies that standard to the Mountain West, understood here as Colorado, New Mexico, and Wyoming. The objective is diagnostic. The chapter asks whether the region is large enough, sufficiently concentrated, and positioned in the right parts of the quantum stack to matter for system assembly rather than merely for participation. That question matters because quantum advantage does not arise from activity in the abstract. It arises where regions help reduce the frictions that still slow the field: unstable interfaces, difficult calibration, limited validation capacity, and the challenge of integrating fragile quantum components into real operating environments.

Read through that lens, the Mountain West should be assessed as part of a broader U.S. and allied quantum system, not as a self-contained cluster. The region does not need to dominate every quantum application area to be consequential. A more relevant test is whether it shows unusual strength in the enabling layers where performance becomes trusted, systems become deployable, and institutions can shape qualification and adoption pathways.[127] That is also where the chapter's bounded ASCEND relevance sits. Environmental and infrastructure-relevant sensing pathways rely on the same measurement, photonics, control, and validation layers that are increasingly important across the broader quantum field. The chapter, however, remains broader than ASCEND technologies. Its purpose is to assess the region's position in the quantum system as a whole.

The analysis proceeds in five steps. Section 6.1 establishes the region's invention footprint and internal structure, asking whether the Mountain West has a material presence across the stack and across quantum application areas. Section 6.2 tests whether that presence reflects real comparative advantage by examining employment-normalized concentration and platform specialization. Section 6.3 turns to momentum, assessing whether recent growth is occurring in the layers most likely to shape future system assembly. Section 6.4 evaluates commercialization signals through sponsor structure and capital flows, treating them as selective indicators of translation rather than proof of full system maturity. Section 6.5 then asks what regional role the evidence actually supports. The goal throughout is to provide a grounded reading of what is real, what is emerging, and what remains conditional before Chapter 7 turns from diagnosis to implications.

6.1 The Mountain West's scale leverage in the quantum stack

The Mountain West has a quantum invention footprint large enough to treat as a real regional system rather than a scattering of isolated efforts. That footprint is anchored by a distinctive institutional base: NIST and its jointly operated institute JILA in Boulder, and Sandia and Los Alamos in New Mexico. Those anchors help explain why the region's invention record reaches across multiple layers of the stack, especially in precision measurement, photonics, hardware, and control.[128]

6.1.1 The Mountain West's scale advantage

Inventors and patent sponsors in Colorado, New Mexico, and Wyoming have produced 594 quantum inventions since 2010. Colorado accounts for 439, New Mexico 144, and Wyoming 19. That places the region in the upper tier of U.S. quantum geographies outside the handful of very large coastal concentrations and gives it enough scale for composition and structure to matter analytically, not just descriptively.

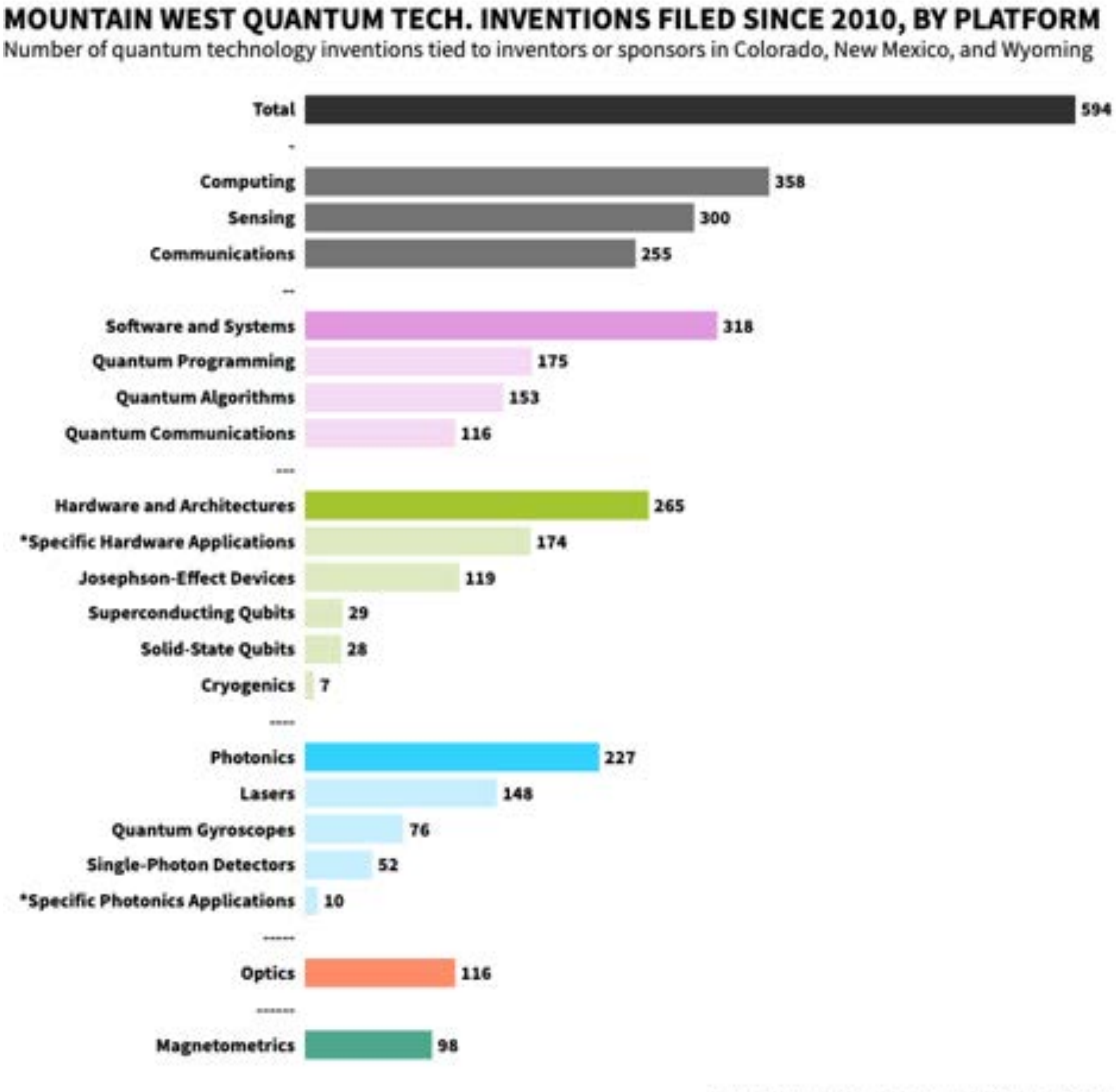
The internal distribution is uneven, but the pattern is clear. Colorado carries most of the regional volume, New Mexico supplies a meaningful second anchor, and Wyoming contributes a small tail that should be interpreted cautiously. Because inventions can be linked to more than one state through inventor locations, sponsor locations, and collaborative filings, these counts are best read as structural signals rather than additive shares. Even on that basis, the Mountain West already registers as a two-anchor invention system rather than an aspirational one.

6.1.2 Scale and convergence in the quantum technology stack

By quantum application area, the Mountain West shows substantial activity in computing, sensing, and communications, with 358 inventions in computing, 300 in sensing, and 255 in communications. That breadth matters because it shows that the region is not participating only through a single narrow specialty. Its invention base reaches across the major application areas of the field.

The stronger result is the overlap among those application areas. The region records 186 inventions jointly tagged to computing and communications, 124 that overlap computing and sensing, and 59 that overlap sensing and communications. Those overlaps do not prove integrated products or fielded systems, but they do show that Mountain West invention is not neatly partitioned into separate silos. In a field organized around shared enabling platforms, that degree of coupling is one of the earliest empirical signs that system-assembly pressures are already shaping the regional record.

Figure 39. The region invents across platforms in the quantum technology stack

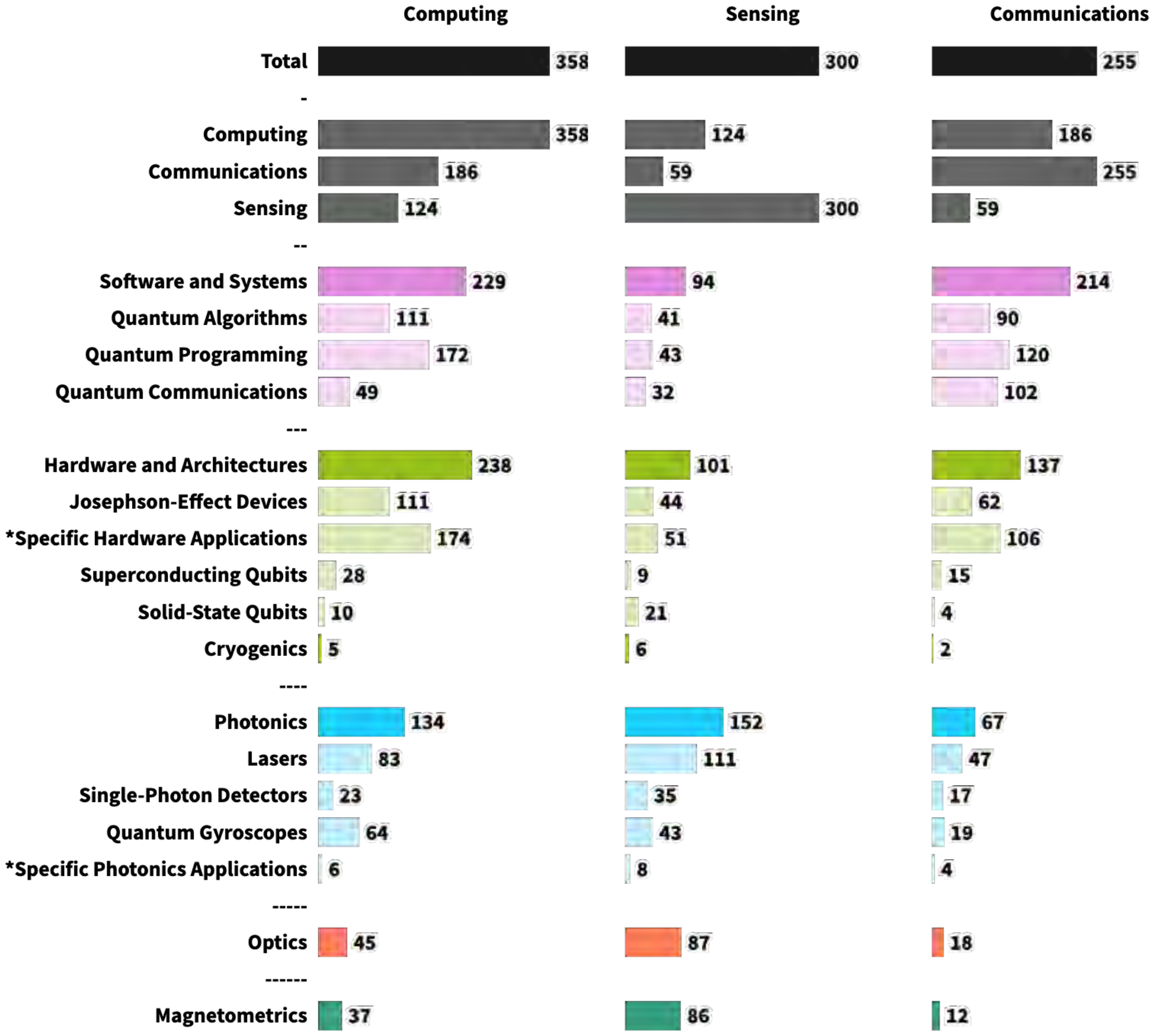


Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

6.1.3 The Mountain West's distinctive domain x platform fingerprint

At the platform level, the regional footprint concentrates in software and systems, hardware and architectures, and photonics, with additional weight in optics and magnetometry. The Mountain West records 318 inventions in software and systems, 265 in hardware and architectures, 227 in photonics, 116 in optics, and 98 in magnetometry. That is not the profile of a region active only in downstream claims or only in abstract software. It is a mixed stack footprint that spans orchestration, physical embodiment, and measurement-heavy enabling layers close to readout, stability, and calibration.

Figure 40. The region's quantum inventions converge across domains



MOUNTAIN WEST QUANTUM TECH. INVENTIONS FILED SINCE 2010, BY DOMAIN AND PLATFORM

Number of quantum technology inventions tied to inventors or sponsors in Colorado, New Mexico, and Wyoming

* These categories capture sets of specific applications for the technologies in this platform. • Source: Denizens LLC analysis of Lens data.

The subclusters sharpen that picture. Within software and systems, the region records 175 inventions in quantum programming, 153 in quantum algorithms, and 116 in a communications-oriented software cluster. Within hardware and architectures, it records 174 inventions in specific hardware applications and 119 in Josephson-effect devices. Within photonics, it records 148 inventions in lasers, 76 in quantum gyroscopes, and 52 in single-photon detectors. The region's invention base is therefore not only broad across platforms; it is materially present in the subclusters that determine how quantum systems are controlled, measured, and embodied.

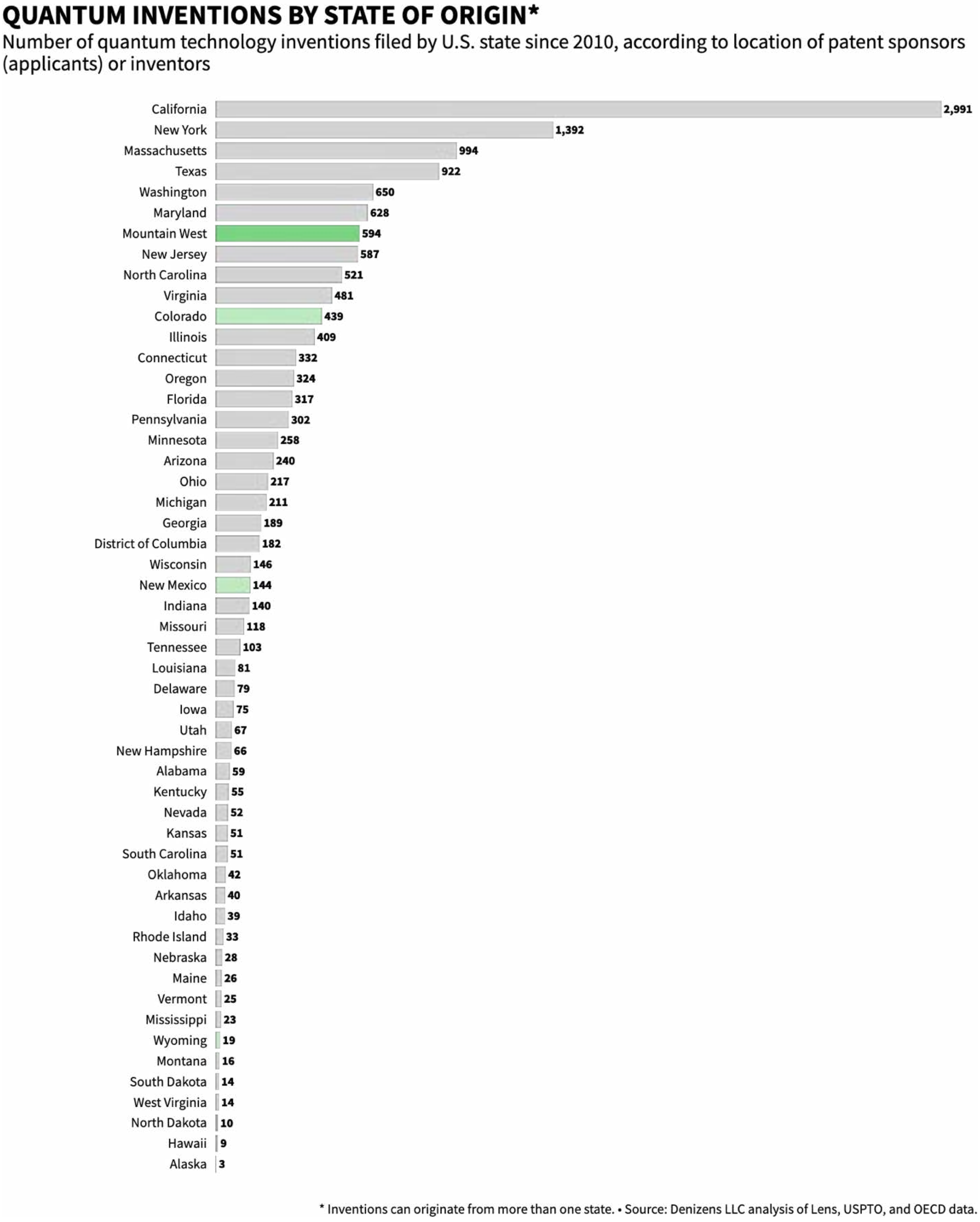
The application-area × platform view is the most revealing cut because it shows that the same regional system expresses different stack signatures in different parts of quantum. Computing is mainly a hardware-and-software story, with 238 inventions in hardware and architectures, 229 in software and systems, and 134 in photonics. Communications is overwhelmingly software-and-systems dominant, with 214 inventions in software and systems, 137 in hardware and architectures, and 67 in photonics. Sensing looks different. There, photonics leads with 152 inventions, while optics at 87 and magnetometry at 86 remain unusually prominent alongside hardware and architectures at 101 and software and systems at 94. That sensing profile places a meaningful share of the region’s activity close to the measurement layer of the stack rather than only at the edge of downstream application.[129]

That differentiated fingerprint is consistent with the region’s institutional shape. Boulder’s metrology base has long concentrated capability in atomic clocks, quantum measurement, and optics, while New Mexico’s national-lab infrastructure reinforces mission-oriented engineering, testing, and system-relevant development. The result is not a monolithic quantum cluster. It is a regional invention system whose sensing-linked work is weighted toward photonics, optics, and magnetometry, whose communications work skews toward software and systems, and whose computing work remains anchored in hardware plus control.

6.1.4 What the scale evidence establishes

The scale evidence supports three bounded conclusions. The Mountain West has presence at a material scale large enough to treat as a real regional system. Its invention record shows cross-area breadth with meaningful coupling, especially between computing and communications. And its sensing-linked footprint is weighted toward measurement-heavy enabling layers where stack constraints tend to surface earliest. Those results do not yet establish comparative advantage, commercialization readiness, or durable regional control. They do establish that the region’s quantum position is real, structured, and close enough to the stack to warrant the stricter test taken up in the next section.

Figure 41. The Mountain West ranks high among U.S. states in quantum inventions



QUANTUM INVENTIONS BY STATE OF ORIGIN*

Number of quantum technology inventions filed by U.S. state since 2010, according to location of patent sponsors (applicants) or inventors

* Inventions can originate from more than one state. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

6.2 The Mountain West’s comparative quantum advantage

Section 6.1 established that the Mountain West has a material quantum invention footprint and a distinctive application-area × platform signature. The next question is whether that footprint is merely present, or whether it is unusually concentrated relative to the U.S. baseline. This section answers that question using an employment-normalized concentration measure similar to a location quotient. A value of 1.0 means a state’s quantum invention intensity is roughly in line with the national average; values above 1.0 indicate above-average intensity. This is a stricter test than raw counts because it asks how unusual the activity is given the size of the state’s workforce and economy. For the Mountain West, that is the right test. If the region’s advantage truly lies in precision measurement and sensing-adjacent layers, it should appear not only as activity, but as unusually high concentration in those parts of the stack.[130]

6.2.1 The Mountain West punches above its weight on quantum

On an employment-normalized basis, the Mountain West is a highly concentrated quantum region. Its overall concentration is 2.88x the U.S. average, or nearly three times the national baseline. That places the region in the same upper cohort as many of the most visible quantum states despite being far smaller than the largest coastal economies. The regional result is carried by two strong anchors with different profiles: New Mexico at 3.27x, Colorado at 2.96x, and Wyoming at 1.33x. The combined picture matters. New Mexico’s concentration is unusually high by any U.S. standard, while Colorado’s is similarly strong and paired with far greater absolute invention volume. The result is a region that is not simply active, but structurally dense in quantum invention relative to its economic base.

A further nuance sharpens that interpretation. The Mountain West’s inventor-linked concentration is 2.70x, while its sponsor-linked concentration is 1.79x. New Mexico remains highly concentrated even on a sponsor-linked basis at 2.32x. That difference suggests that Colorado’s strength is expressed even more clearly through inventor presence, while New Mexico’s is more tightly tied to sponsoring institutions. The underlying point is simpler and more important: the region’s concentration is not an illusion of size. It appears robustly in normalized data and aligns with a real concentration of federally backed quantum assets in Colorado and New Mexico.

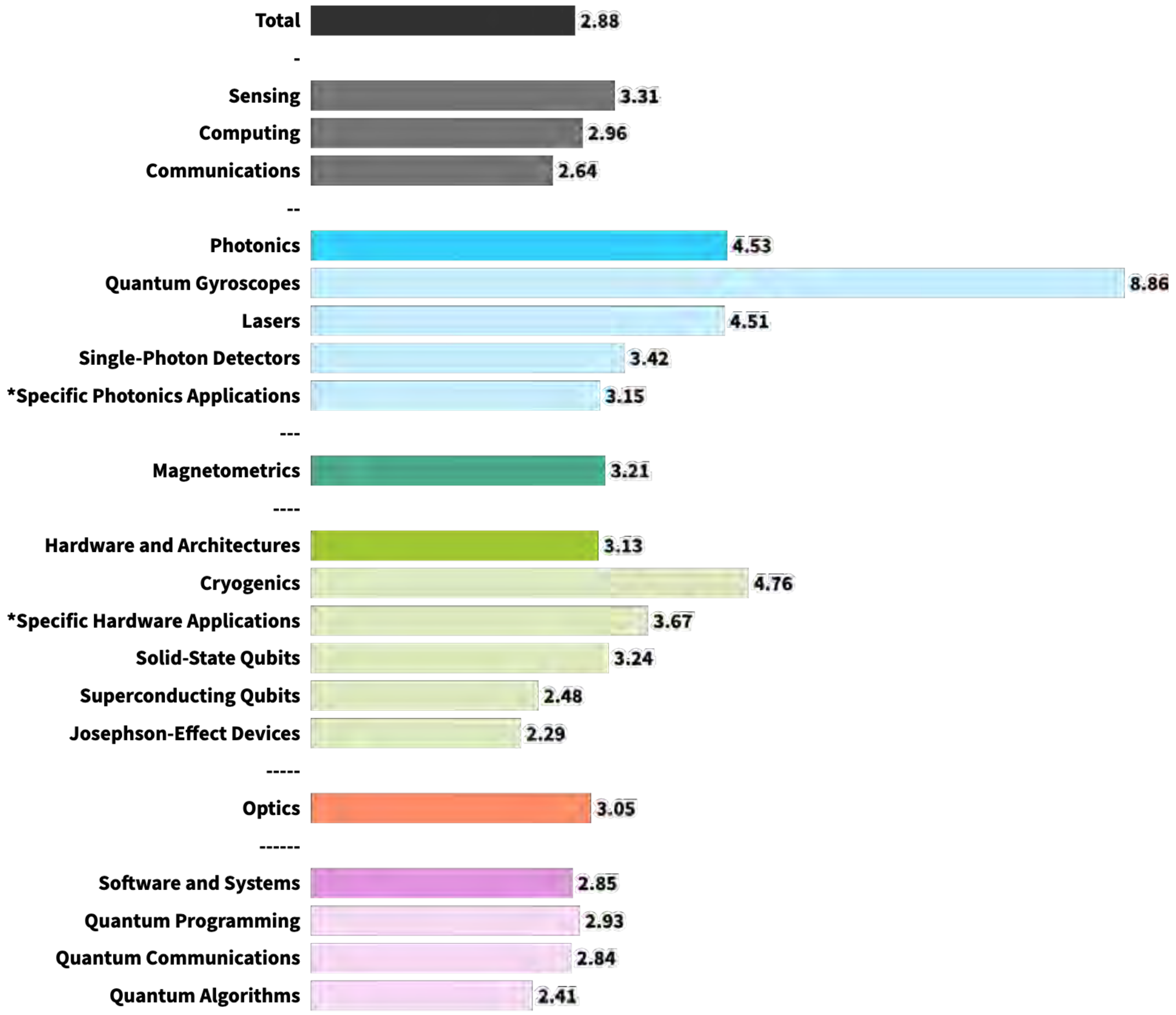
6.2.2 Concentration by quantum application area: sensing is distinctive

When concentration is disaggregated by quantum application area, the Mountain West’s strongest position is in sensing at 3.31x the U.S. average. Computing reaches 2.96x, and communications 2.64x. That is a consequential result because it is not a claim about future markets or hypothetical deployment. It is an empirical statement about where the region’s invention intensity is unusually concentrated today. The Mountain West’s most distinctive application-area signal sits in sensing, where performance is often constrained by readout fidelity, noise, calibration, and integration with operational environments.

Figure 42. The Mountain West punches above its weight on quantum invention

CONCENTRATION OF MOUNTAIN WEST QUANTUM INVENTIONS, BY PLATFORM

Number of quantum technology inventions per job compared to the U.S. average



This is a comparison of two ratios, similar to a location quotient (LQ) or "revealed comparative advantage" (RCA).
Denizens LLC analysis of Lens, USPTO, and OECD data.

Colorado and New Mexico reinforce that interpretation in different ways. Colorado is also strongly concentrated in computing, consistent with its deeper base in hardware and software invention. New Mexico is more concentrated in sensing and measurement-adjacent work, consistent with its role as a mission-oriented R&D anchor through Sandia and Los Alamos. Read together, the regional signature is sensing-weighted rather than computing-led. It aligns closely with the long-standing precision-measurement and optics strengths anchored in Boulder's NIST and JILA complex and in New Mexico's national-lab infrastructure.[131]

6.2.3 Concentration by platform: specialized in the measurement layer

The clearest evidence of stack position comes from platform-level concentration. The Mountain West is strongly specialized in several enabling technologies that are closely tied to sensing, readout, and precision system performance. Photonics reaches 4.53x the U.S. average. Lasers reach 4.51x. Quantum gyroscopes reach 8.86x. Single-photon detectors reach 3.42x. Magnetometry reaches 3.21x, optics 3.05x, specific hardware applications 3.67x, and hardware and architectures overall 3.13x. That is not the profile of a region concentrated in generic downstream use cases. It is the profile of a region unusually dense in measurement- and control-adjacent enabling layers.

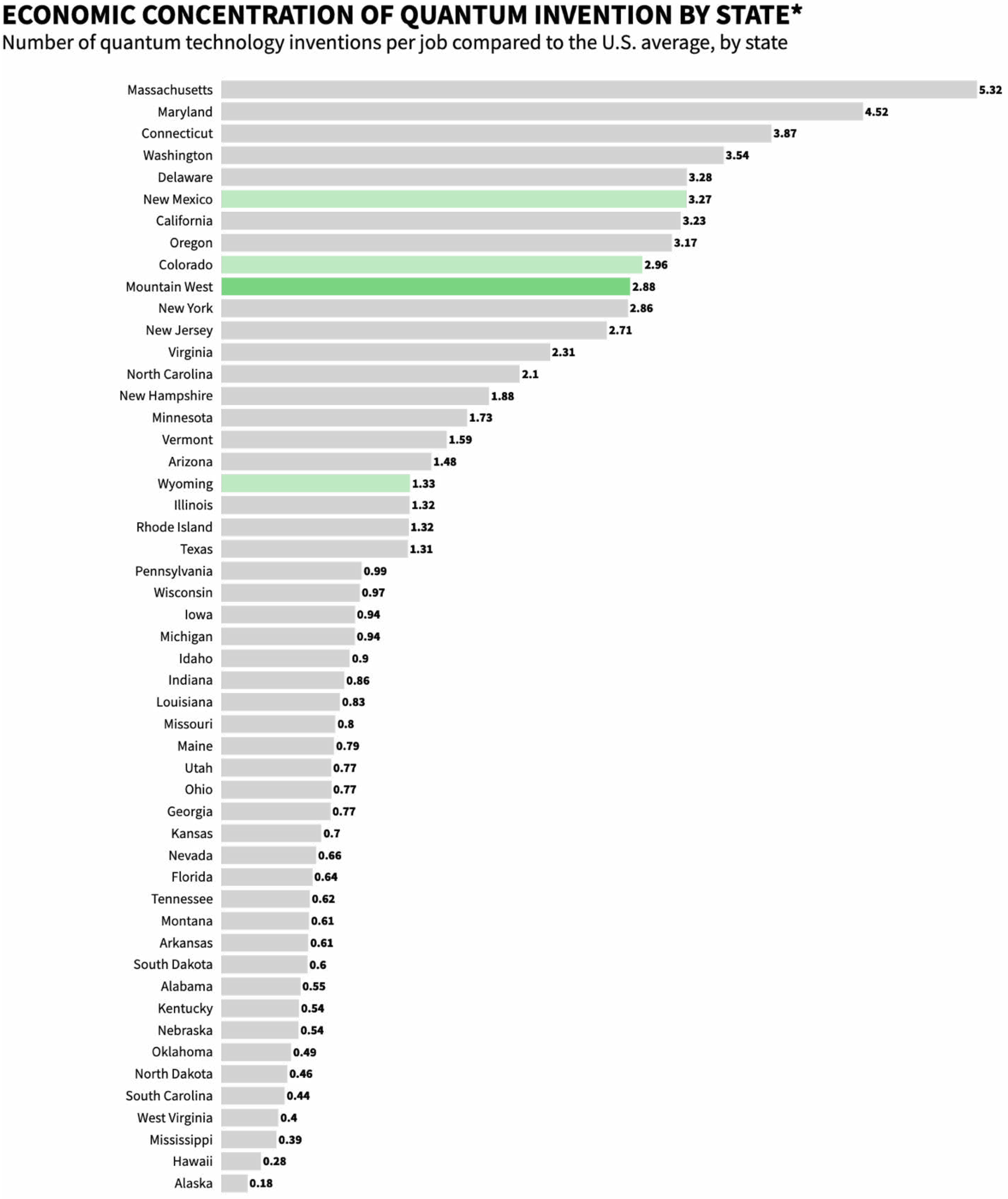
The photonics stack is the strongest part of that profile. Photonics itself is more than four times the national average, and both lasers and gyroscopes stand out as major specializations. The gyroscope result is the most distinctive single signal in the section. At 8.86x the U.S. average, it points to a concentrated family of inventions tied directly to navigation, inertial sensing, and precision measurement. Those are technology areas where operational thresholds matter because the system's value depends on stable performance outside the lab.[132]

The regional specialization extends well beyond photonics into the rest of the measurement layer. Optics and magnetometry both sit above 3.0x, and single-photon detectors are also strongly above average. These are enabling technologies. They determine whether fragile quantum effects can be stabilized, read out, and trusted in real-world environments. Their prominence is the strongest quantitative basis in the chapter for arguing that the Mountain West’s advantage lies close to the bottlenecks that govern system performance, rather than solely in downstream application claims.

The region’s hardware profile also matters because it is broader than a narrow device niche. Hardware and architectures overall are well above average, and specific hardware applications are even more concentrated at 3.67x. That combination is consistent with a region that not only produces device concepts but also exhibits higher invention intensity in hardware categories closer to system-use and integration targets. In other words, the region’s comparative advantage is not confined to foundational science. It reaches into the parts of the hardware layer where system-assembly pressure tends to surface.

Colorado and New Mexico again appear as complementary expressions of the same regional story. Colorado is especially concentrated in quantum gyroscopes and remains strongly concentrated in photonics and software-adjacent categories. New Mexico is strongly concentrated in lasers, optics, magnetometry, and sensing overall. Read together, the region’s specialization is not a single-point bet. It is a measurement-stack-weighted portfolio spanning two distinct institutional settings: Boulder’s metrology and research complex and New Mexico’s mission-oriented laboratory infrastructure. That pattern has also attracted targeted federal reinforcement, including the NSF Quantum Leap Challenge Institute on sensing led by the University of Colorado Boulder in partnership with the University of New Mexico.[133]

Figure 43. Mountain West states rank highly for concentration of quantum invention



* Inventions can originate from more than one state. • This is a comparison of two ratios, similar to a location quotient (LQ) or "revealed comparative advantage" (RCA).

Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

6.2.4 What this concentration profile says about advantage

This section provides the chapter's first genuinely comparative test of stack position. It shows that the Mountain West is not only present in quantum invention. It is unusually concentrated, relative to the U.S. baseline, in a set of enabling technologies that sit close to the stack layers most often associated with performance bottlenecks. The most defensible conclusion is therefore narrow but important: the region's comparative advantage lies in measurement-, photonics-, and deployment-facing enabling layers. That is the clearest quantitative basis for treating the Mountain West as more than a participant in the quantum system.

The limits of the evidence matter just as much. Concentration in these layers does not yet prove integration capacity, commercialization maturity, or deployment readiness. It does show that the region is unusually dense in the parts of the stack where readout, control, calibration, and validation burdens tend to bind earliest. Those are exactly the conditions under which regional position can begin to matter for system assembly. The next section turns to a different question: whether the Mountain West's concentrated strengths are also where recent momentum is accumulating.

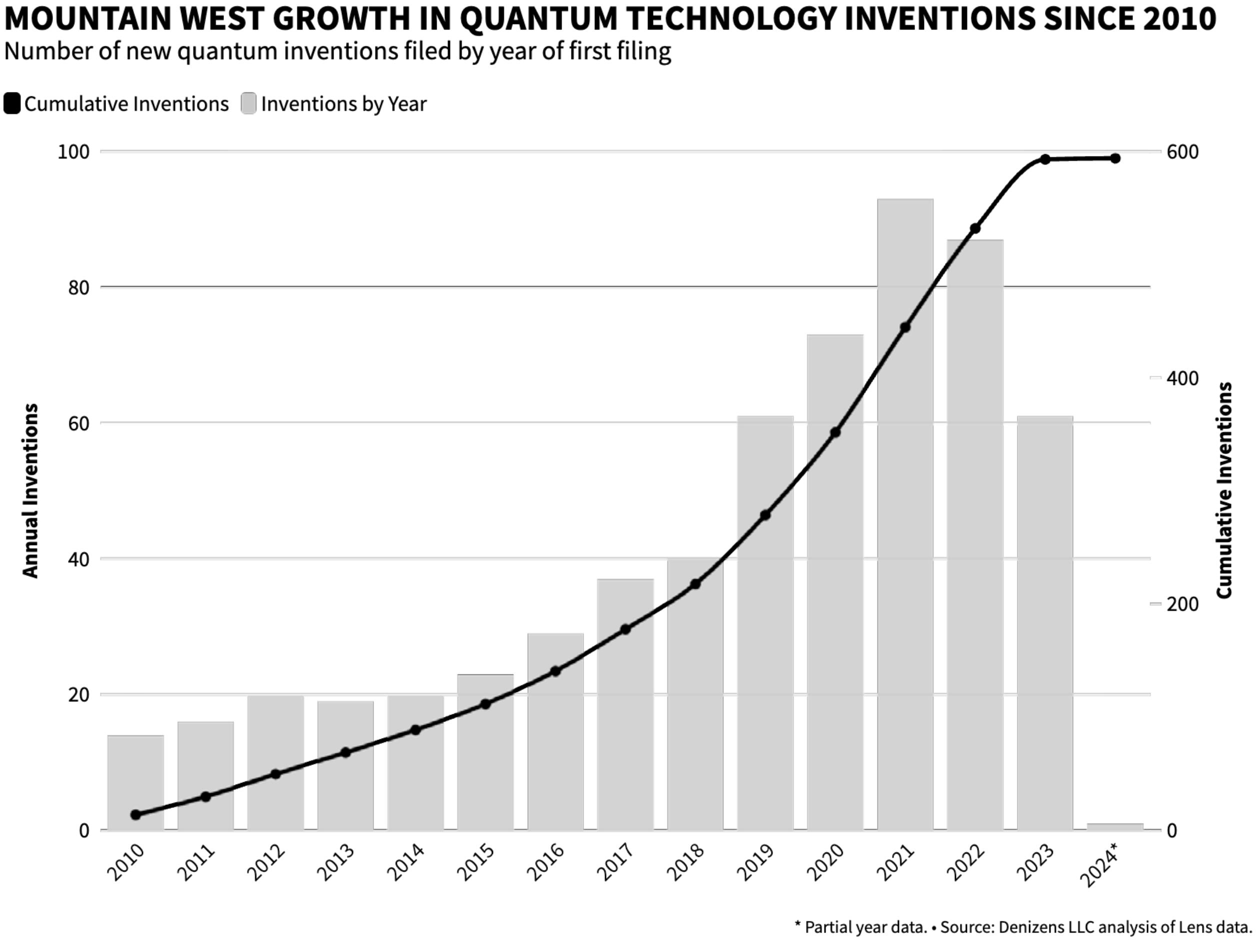
6.3 The Mountain West's accelerating progress—and leverage

Sections 6.1 and 6.2 established two baseline facts. The Mountain West has a material quantum invention footprint, and that footprint is unusually concentrated relative to the size of the regional economy—especially in sensing and photonics-enabled measurement technologies. The next question is whether those strengths are static or whether the region is gaining ground over time in the parts of the stack most likely to shape system assembly.

Growth is not an outcome by itself, but it is a meaningful signal. Regions that influence system assembly tend to show accelerating activity in the enabling layers that increase recombination, integration, and downstream optionality. We cannot reproduce the generativity and emergence measures from Chapter 2 at the regional level with the same analytic machinery. We can, however, read Mountain West momentum against that broader system diagnosis—especially the finding that leverage in quantum often concentrates in software, control, photonics, instrumentation, and other platforms that make fragile capabilities more usable and composable.

This recent acceleration has also coincided with a more deliberate regional effort to organize across state lines around shared facilities, workforce pipelines, and commercialization support. That does not explain the growth rates reported here, and it should not be treated as proof of durable assembly capacity. It does mean, however, that the region's momentum is being actively reinforced rather than passively observed. Figure 44 shows this recent acceleration clearly.

Figure 44. The region's growth in quantum invention has accelerated



MOUNTAIN WEST GROWTH IN QUANTUM TECHNOLOGY INVENTIONS SINCE 2010

Number of new quantum inventions filed by year of first filing

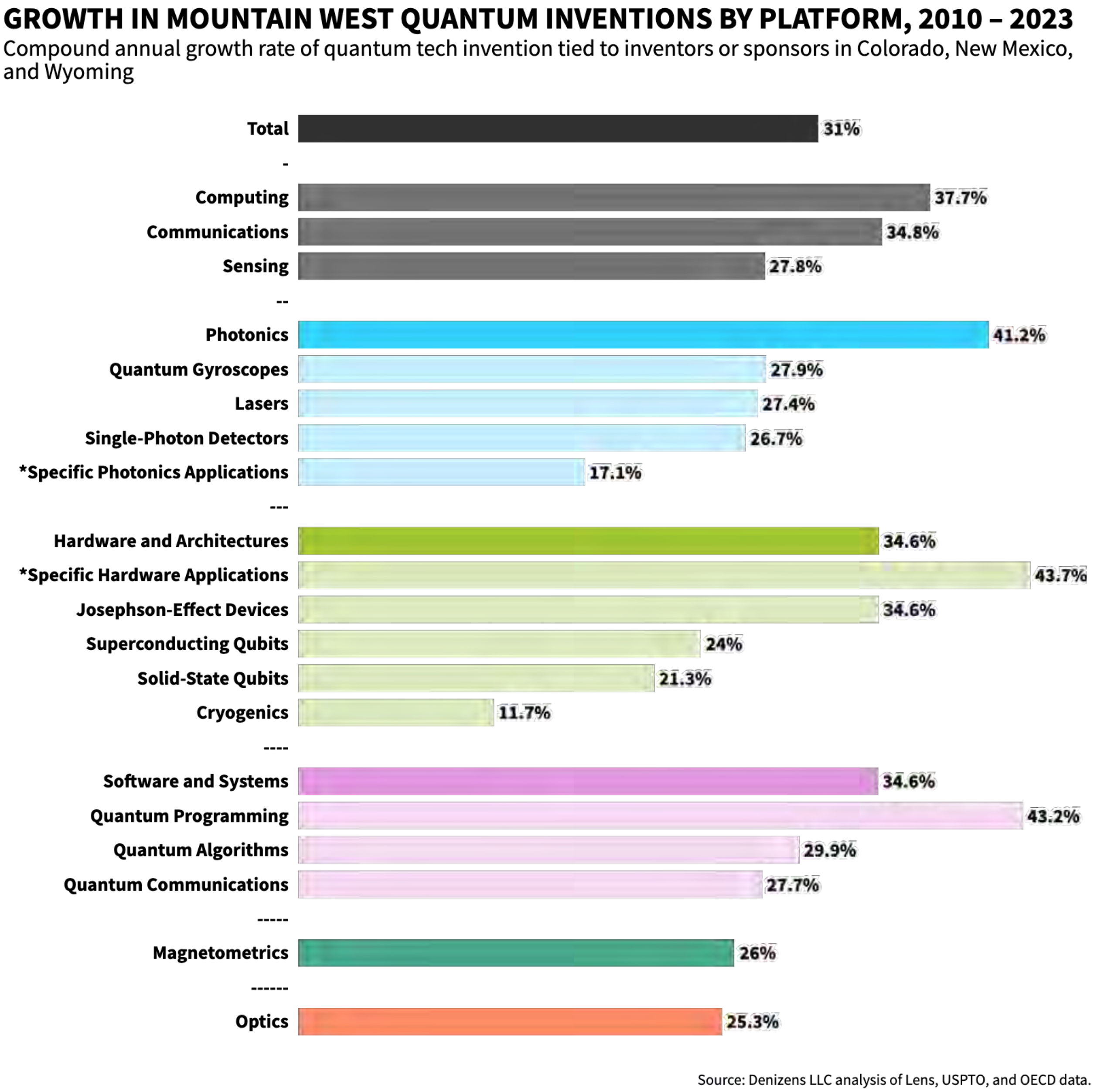
* Partial year data. • Source: Denizens LLC analysis of Lens data.

6.3.1 The Mountain West’s quantum invention volumes are growing quickly

At the aggregate level, Mountain West quantum invention activity grew at a roughly 31 percent compound annual growth rate from 2010 to 2023. By any conventional technology benchmark, that is rapid growth. It places the region among the faster-growing U.S. quantum geographies in the dataset and confirms that the Mountain West is not merely preserving an existing foothold. It is expanding it.

Colorado is the primary engine of that growth. Colorado’s quantum inventions grew at roughly 36 percent annually over the period, one of the strongest state-level growth rates in the dataset. New Mexico also expanded meaningfully, at roughly 23.5 percent annually. Wyoming’s growth rate was of a similar order, at roughly 22.9 percent, but its much smaller base makes that figure inherently fragile and less analytically important. The regional pattern is therefore clear even without over-reading the smaller state signals: recent Mountain West momentum is real, and it is driven above all by Colorado.

Figure 45. The region's growth in inventions is uneven across the quantum stack



GROWTH IN MOUNTAIN WEST QUANTUM INVENTIONS BY PLATFORM, 2010 – 2023

Compound annual growth rate of quantum tech invention tied to inventors or sponsors in Colorado, New Mexico, and Wyoming

Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

That does not mean momentum guarantees durable advantage. It does mean the region’s specialized position in sensing and measurement-adjacent platforms is unfolding in a context of rapid expansion rather than stagnation or plateau. The next question is whether that expansion is broad-based across the quantum application areas and, more importantly, whether it is strongest in the platforms most likely to shape system assembly.

6.3.2 Momentum by quantum application area

Momentum is broad-based across the three quantum application areas. From 2010 to 2023, Mountain West quantum invention grew at roughly 37.7% CAGR in computing, 34.8% in communications, and 27.8% in sensing. That spread matters because it shows the region is not riding a single narrow specialty. Its inventive activity is accelerating across the field's main application areas, even if not at identical rates.

The ordering of those growth rates is also interpretable. The fastest growth appears in computing and communications, the two application areas where iteration can often proceed through systems engineering, software abstractions, and architecture-level work. Earlier chapters showed why those parts of the stack can expand faster than measurement- and hardware-heavy layers: they are less tightly bound to fabrication, calibration, and other physical constraints that slow progress closer to deployment. Seen in that context, the region's stronger growth in computing and communications is not surprising. It is consistent with the broader system logic of quantum progress.

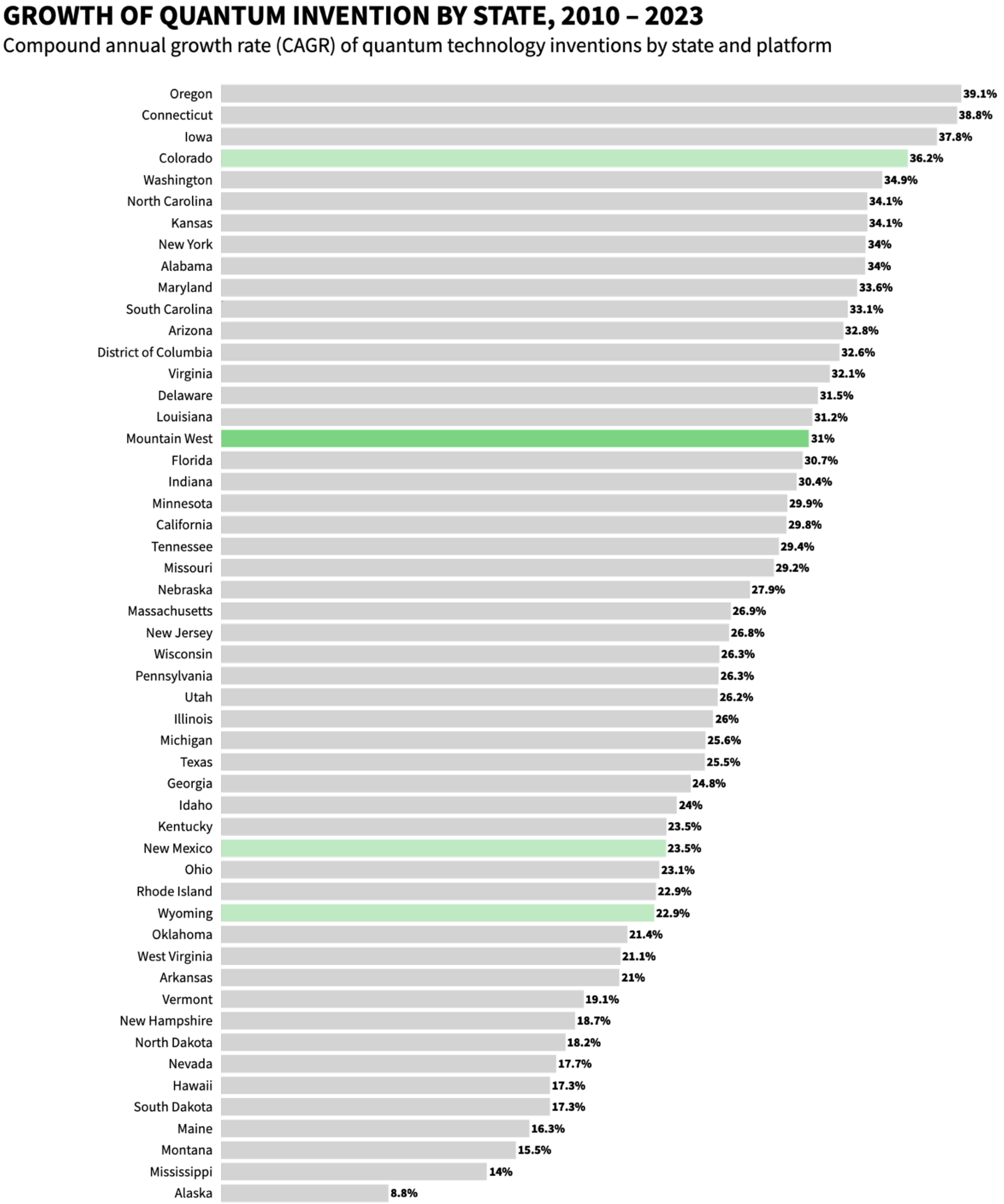
Sensing, however, is the more consequential result. Its growth rate is lower than computing's and communications', but at 27.8% CAGR, it is still rapid in absolute terms. That rate of growth is also roughly three times the global rate for sensing. And, consequentially, sensing is the Mountain West's strongest concentration signal, as shown in Section 6.2. The combination matters. It means the region's most distinctive application-area position is not fading as the overall field expands. The Mountain West is not shifting away from sensing as quantum activity broadens; it is deepening a sensing-weighted regional profile while also adding momentum in the adjacent application areas that help make sensing systems usable, integrated, and scalable.

Recent capability-building efforts reinforce that reading, especially in communications. New Mexico is moving to build enabling infrastructure through plans for a multi-node quantum network testbed in downtown Albuquerque and through venture-studio efforts to attract quantum networking and computing company presences. Colorado, in parallel, brings aerospace capabilities in free-space optics and satellite communications that can support communications-oriented quantum pathways. These initiatives do not prove outcomes, but they do make the pattern easier to interpret as part of a deliberate regional systems trajectory rather than as a purely statistical rise in filings.[134]

6.3.3 Momentum by platform: acceleration in application-facing hardware

The platform view makes the Mountain West's progress more interpretable in system–platform–stack terms. Several categories stand out as both fast-growing and plausibly leverage-bearing: photonics at roughly 41% CAGR, quantum programming at roughly 43%, specific hardware applications at roughly 44%, software and systems overall at roughly 35%, and hardware and architectures overall at roughly 35%. This is a consequential pattern because it shows acceleration not in a single narrow technical line, but across multiple platforms that sit close to the interface between quantum effects and usable systems.

Figure 46. Colorado has achieved notable acceleration in quantum invention



* Inventions can originate from more than one state. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

That mix matters for how regional advantage should be read. Photonics is a core enabling layer for sensing and communications, and increasingly for readout and control pathways across the stack. Quantum programming and the broader software-and-systems layer are where capabilities become repeatable, testable, and recombinable, often allowing progress to scale even while hardware remains fragile. And the rise of application-facing hardware suggests movement toward system-relevant embodiments rather than purely device-physics exploration. Read together, these are the kinds of platforms through which leverage tends to propagate in an assembly-constrained field.

Not all subclusters are moving at the same rate, and that asymmetry should not be misread. Slower growth in some foundational categories is consistent with the broader field-wide reality that certain layers remain manufacturing- and physics-constrained. The key point is not that slower-moving categories are unimportant, but that the Mountain West's strongest acceleration is occurring in enabling and system-facing layers rather than in the slowest foundational categories. That is a meaningful distinction in a technology system where control over interfaces, readout, orchestration, and validation often matters more than raw novelty alone.

Several institutional investments point in the same direction. The region has attracted federal support tied explicitly to sensing and measurement frontiers, including a major NSF institute focused on entanglement-enhanced sensors led by CU Boulder in partnership with UNM, while shared physical infrastructure is being built to compress iteration cycles for hardware and photonics through cleanroom and nanofabrication access, cryogenic test bays, and packaging and test capabilities. That does not establish causality. It does show alignment: the platforms accelerating in the invention record are the same ones the region is actively building enabling capacity for.[135]

6.3.4 Progress is recent and wave-like

Year-by-year patterns reinforce the momentum signal. The Mountain West's inventive activity is heavily back-loaded into the last several years: roughly 70% of the region's quantum inventions filed between 2010 and 2023 were filed since 2018, and roughly 53% since 2020. In other words, the regional footprint is not only large; it has intensified recently. That recency matters because it suggests that the Mountain West's current position is not simply the residual effect of older institutional strengths. It is being actively extended.

The wave structure is even more pronounced in several leverage-relevant categories, especially quantum programming, specific hardware applications, and quantum gyroscopes. These are the kinds of back-loaded patterns that, at the global level, often accompany a shift from isolated demonstrations toward more systematic system-building: activity becomes denser, more recent, and more concentrated around platforms that enable repeatability and integration. That still falls short of proof that durable advantage has been secured. It does, however, suggest that some of the region's most important capabilities are moving from longstanding scientific presence toward a more active period of technical consolidation.

This recent acceleration also coincides with a more deliberate scaling of the regional translation layer, especially in workforce and institutional coordination. Colorado School of Mines launched one of the nation’s first quantum engineering master’s programs in 2020, and New Mexico formalized a deeper university–lab partnership through the Quantum New Mexico Institute, a joint UNM–Sandia initiative designed to coordinate research and workforce training. These developments do not replace the invention record as evidence. They do make the post-2020 wave easier to interpret as something more than statistical back-loading: a period in which the region’s engineering, technician, and coordination capacity is beginning to catch up to its scientific and inventive strengths.[136]

6.3.5 Interpreting momentum through the generativity and emergence lens

The growth pattern described above does not, by itself, prove that the Mountain West has achieved durable system influence. It supports a narrower, more defensible conclusion. The region’s momentum is strongest in the kinds of platforms that often matter most when a technology system begins to consolidate: layers that enable recombination, improve control, and help translate fragile technical performance into more usable configurations. In that sense, the regional pattern aligns with the broader logic established in Chapter 2, where progress becomes strategically meaningful not only when activity expands, but when it reorganizes around platforms that other parts of the system increasingly depend on.

That is the most useful way to read the Mountain West’s recent momentum through the lenses of generativity and emergence. Generativity captures a platform’s enabling role within the system: whether other parts of the field repeatedly draw on it, recombine through it, or depend on it to advance. Emergence captures change in that role over time: whether a platform is becoming more consequential to how progress is organized, even if its absolute scale remains modest. We cannot calculate those measures regionally with the same machinery used in Chapter 2. We can still use their logic to interpret what matters in the Mountain West record. Growth is clustering in platforms that look more like enablers and organizers than isolated end uses. That makes the regional signal more significant than raw counts alone would suggest.

The strongest evidence lies in the combination rather than in any single metric. Section 6.2 showed that the region is unusually concentrated in sensing, photonics, optics, magnetometry, and related measurement-facing layers. The preceding subsections showed that recent momentum is also accumulating in photonics, software and systems, quantum programming, and application-facing hardware, with a heavy post-2018 and post-2020 back-loading. Read together, those patterns are consistent with a region whose strengths are not only present, but intensifying in the parts of the stack where coordination, readout, validation, and integration pressures tend to surface first. That does not establish that the region has solved those pressures. It does suggest that the Mountain West is becoming more consequential in the technical layers through which such pressures are worked out.

This is also where the Colorado–New Mexico pairing matters most. Colorado provides much of the visible acceleration, especially in platforms associated with software, photonics, and application-facing hardware. New Mexico contributes a different kind of weight: mission-oriented depth, laboratory infrastructure, and settings in which measurement and hardware capabilities can be hardened, tested, and connected to operational use. The regional pattern is therefore not just one of rapid growth. It is one of increasingly differentiated growth across two anchors whose capabilities are plausibly complementary in a system-assembly frame.

6.4 Quantum commercialization in the Mountain West

Chapter 5 argued that quantum commercialization is best understood as systems assembly. The relevant question is therefore not simply how many startups a region has or how much money is flowing. It is whether a region shows organizations and conditions capable of absorbing integration risk: mission-driven institutions that can tolerate long qualification cycles, platform firms that can productize enabling technologies, and companies working across enough of the stack to move from invention toward repeatable deployment.

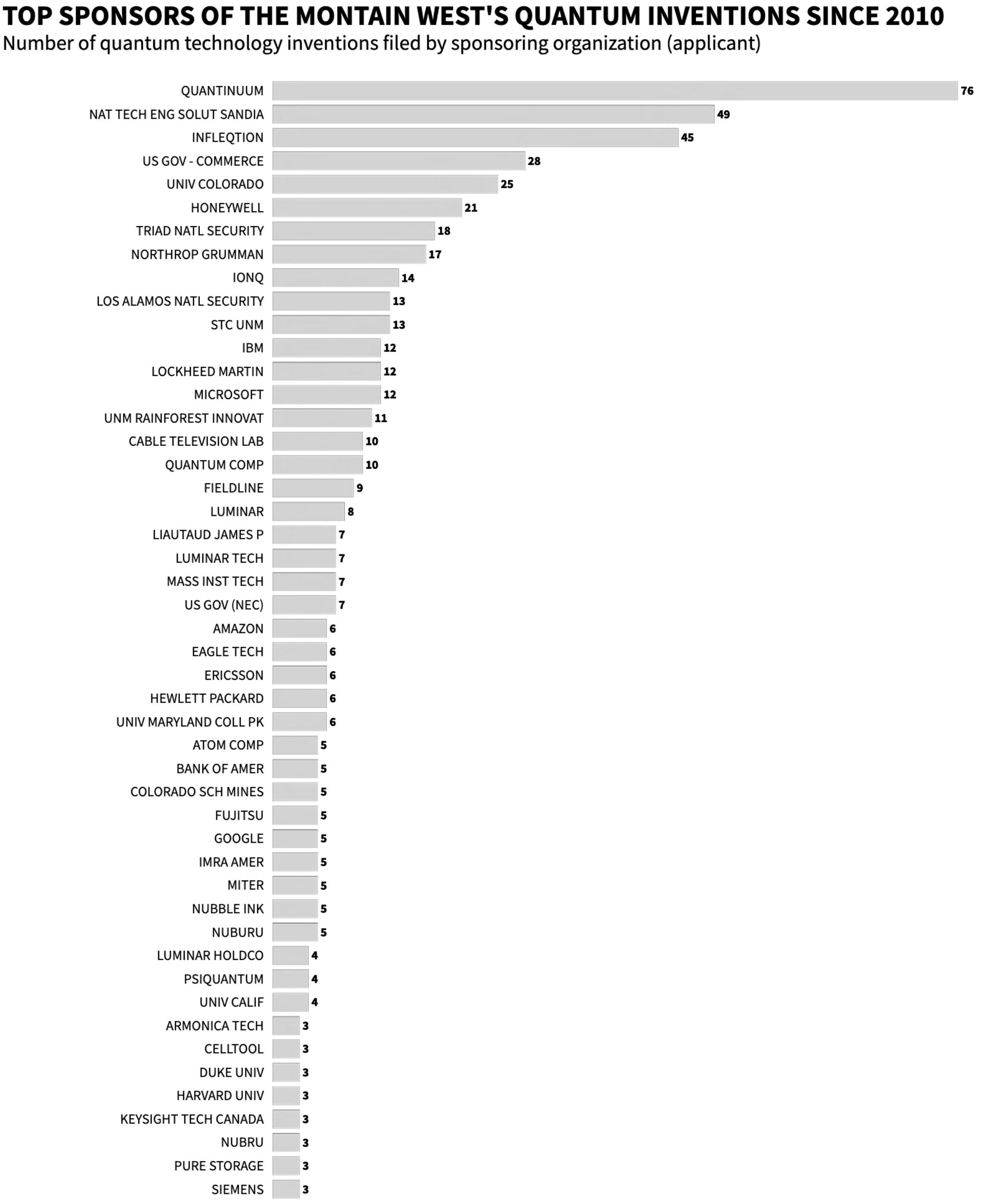
The Mountain West shows early but meaningful signals of that kind of commercialization. Two indicators are especially useful. The first is the sponsor structure of the region's invention record: who is producing quantum inventions, and in what institutional settings. The second is the pattern of growth-capital flows to quantum-related startups. Taken together, these indicators show what kind of commercialization is beginning to form around the region's technical strengths.

6.4.1 A dual anchoring in government and startups

One of the Mountain West's clearest commercialization signals is visible directly in the patent sponsor record. Compared with the United States overall, the region's invention sponsorship is more government-anchored and shows higher participation by growth-capital-backed companies. Across quantum inventions since 2010, Mountain West sponsors break down as follows: 60.3% company sponsors, compared with 69.9% nationally; 16.4% academic sponsors, compared with 17.8% nationally; 18.5% government sponsors, compared with 6.1% nationally; and 14.0% growth-capital-backed companies, compared with 9.6% nationally. This is not a marginal variation on the national pattern. It is a different commercialization profile.

The unusually large government share matters because quantum systems often move toward use in mission environments before entering broader commercial markets. In a field characterized by long qualification cycles, high failure costs, and difficult integration, mission-driven institutions can serve as early customers, validators, and risk absorbers. The Mountain West is unusually well positioned on that front. Sandia National Laboratories and Los Alamos National Laboratory are central federal assets in quantum research and engineering. NIST Boulder is one of the country's core institutions for quantum measurement, standards, and metrology. Those are not incidental regional assets. They are exactly the kinds of institutions that can sustain long development cycles and help move fragile technical capabilities toward operationally meaningful performance.[137]

Figure 47. Government and startups drive the Mountain West’s quantum invention

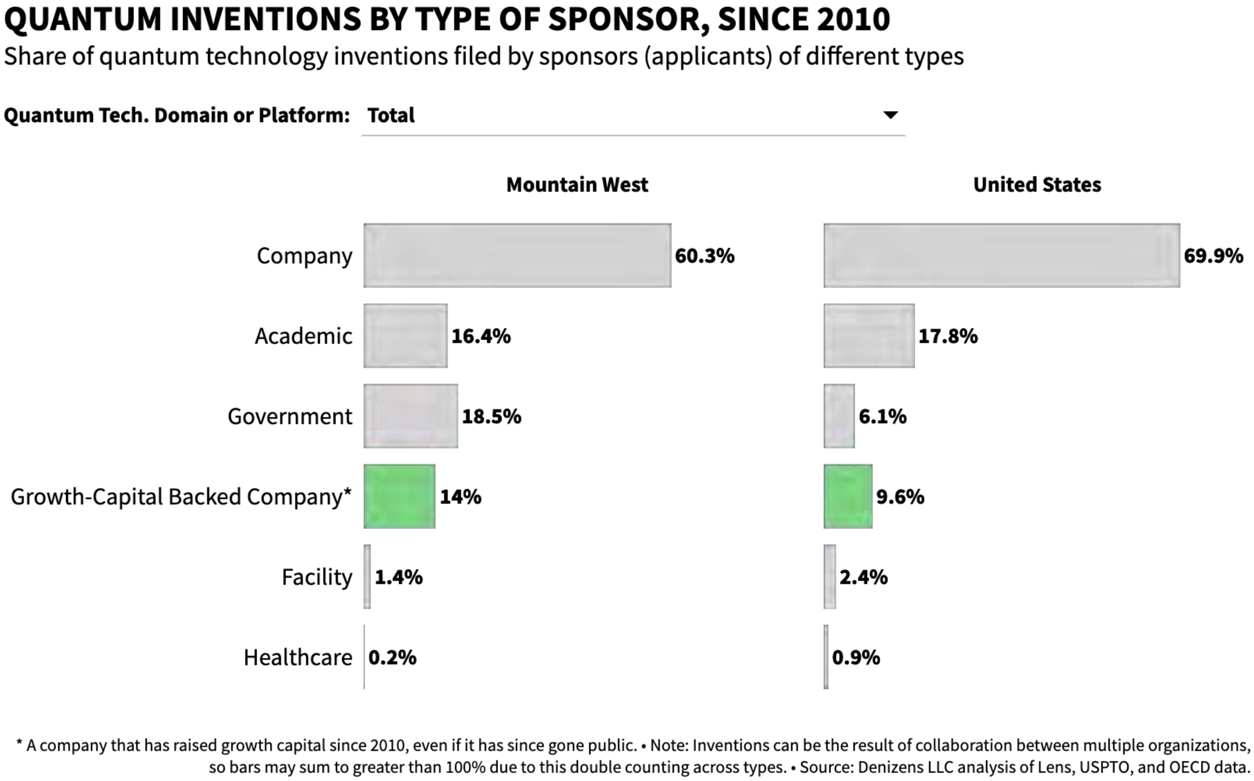


TOP SPONSORS OF THE MONTAIN WEST'S QUANTUM INVENTIONS SINCE 2010

Number of quantum technology inventions filed by sponsoring organization (applicant)

Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

Figure 48. Government and startups play an outsized role in the region's quantum invention compared to the United States as a whole



QUANTUM INVENTIONS BY TYPE OF SPONSOR, SINCE 2010

Share of quantum technology inventions filed by sponsors (applicants) of different types

* A company that has raised growth capital since 2010, even if it has since gone public. • Note: Inventions can be the result of collaboration between multiple organizations, so bars may sum to greater than 100% due to this double counting across types. • Source: Denizens LLC analysis of Lens, USPTO, and OECD data.

The region’s corporate sponsor profile matters just as much because commercialization is not confined to those mission institutions. Growth-capital-backed sponsors account for 14.0% of the Mountain West’s quantum inventions, well above the 9.6% national figure. That suggests a meaningful share of regional invention is occurring in firms that have already attracted substantial private capital and are trying to move beyond research alone toward productization, repeatability, and scale. In Chapter 5 terms, that combination is one of the more credible early patterns for systems assembly: public-sector settings absorb risk and define performance constraints, while venture-backed firms push toward more standardized and commercially legible system pathways.

The sponsor roster reinforces that mixed structure. The leading sponsors in the region include Quantinuum, Sandia, Infleqtion, the U.S. Department of Commerce through NIST-linked activity, the University of Colorado, Honeywell, Triad National Security, Northrop Grumman, Los Alamos National Security, STC UNM, IBM, and Lockheed Martin. The significance lies less in the names themselves than in what the mix reveals. Mountain West inventive activity is distributed across organizational forms that matter for systems assembly: major quantum firms, national-lab-linked entities, research universities, and defense-adjacent corporates. That is a stronger commercialization signal than a region dominated only by university labs or only by isolated startups.

This sponsor pattern does not yet demonstrate sufficient depth for broad commercialization. It shows that the Mountain West's invention base is anchored in institutions capable of advancing quantum technologies through longer qualification and integration pathways than a startup-only system usually can. That is an important early condition for translation, and it is one reason the region's commercialization signals deserve to be taken seriously before turning to the capital data itself.

6.4.2 The Mountain West has seen a surge in growth capital

Capital flows to Mountain West quantum startups are substantial. In the curated time series, companies headquartered in the region raised $1.943 billion in growth capital between 2010 and 2025. The timing is more revealing than the total. Roughly 74 percent of that capital arrived in 2024–2025, and 2025 alone accounts for about $1.037 billion—more than half of the entire 2010–2025 total. As Figures 49 and 50 show, this is not the profile of a mature, steady commercialization engine. It is the profile of a recent step-change in investor attention.

That shift can be read in two ways, and both are relevant. Optimistically, it suggests that at least a small number of Mountain West firms have crossed technical or market thresholds, making their paths legible to investors. More cautiously, it suggests that the capital signal is being driven by a limited number of large financings rather than by a broad, deep bench of commercialized companies. Both interpretations are consistent with the Chapter 5 argument that commercialization in quantum appears first in selective pathways, where integration pressures can no longer be deferred, rather than across the field all at once. The capital is real. The breadth of the underlying engine remains much less certain.

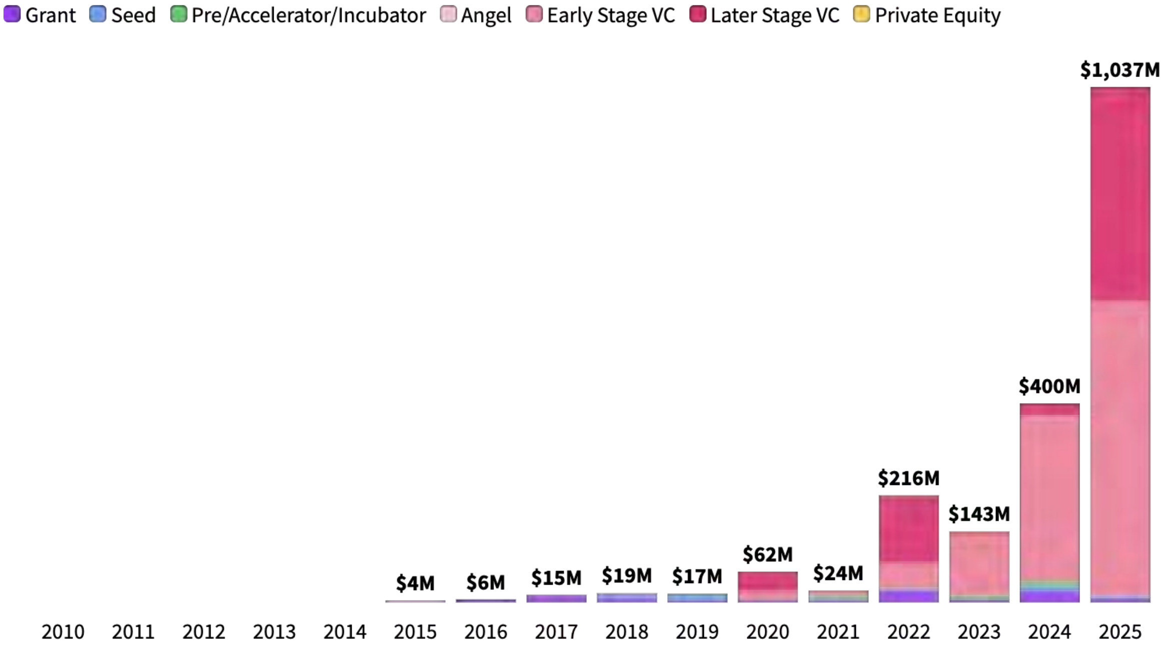
The stage mix sharpens that interpretation. Across 2010–2025, the Mountain West's quantum capital is overwhelmingly venture-stage: early-stage VC accounts for $1.129 billion (58 percent), later-stage VC for $632 million (33 percent), and grants for $106.5 million (5.5 percent). The seed, pre-accelerator, angel, and private equity categories are comparatively small. This distribution matters because it shows that the regional capital signal is not being driven primarily by basic research support or very early experimentation. It is being driven by financings aimed at firms trying to move from promising technical capabilities toward productization, repeatability, and more system-facing development.

That stage profile should still be read with caution. Venture-stage funding can accelerate integration, packaging, and go-to-market work, but it can also create pressure to tell coherent product stories before qualification, validation, and standards are fully in place. In a field as assembly-constrained as quantum, those frictions matter. The Mountain West's financing profile therefore points less to broad readiness than to a smaller number of firms being capitalized to push selected pathways through the expensive middle zone between research and dependable deployment.

Figure 49. Regional quantum startups raised large rounds of investment in recently

GROWTH CAPITAL INVESTED IN MOUNTAIN WEST QUANTUM COMPANIES, BY YEAR AND SOURCE

Capital raised by startup companies to finance growth, in current U.S. dollars

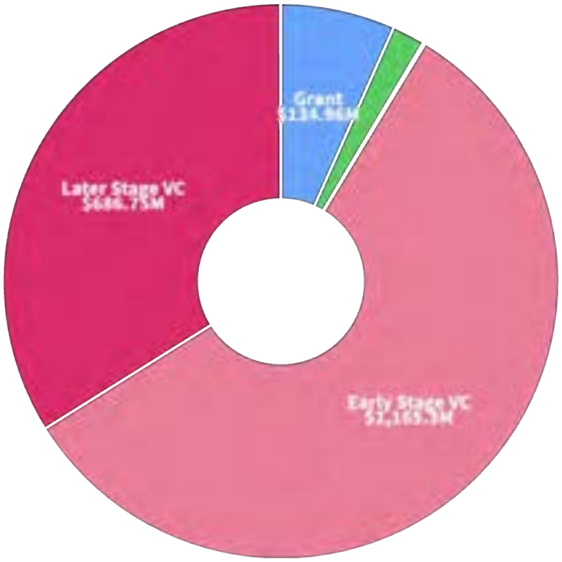


* Partial year data. • Note: Deals missing a value were assigned an investment value of $1 Million. • Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data

Figure 50. Early-stage VC is the Mountain West's largest capital source

SOURCES OF GROWTH CAPITAL INVESTED IN MOUNTAIN WEST QUANTUM COMPANIES, 2010 – 2025

Capital raised by startup companies to finance growth, in current U.S. dollars



Source: PitchBook Data, Inc.

6.4.3 Shared infrastructure and the bespoke prototyping problem

These capital signals are emerging alongside a more deliberate build-out of what might be called assembly-support infrastructure. Elevate Quantum's Tech Hub designation and Phase 2 federal award, matched by substantial state commitments, have been used explicitly to accelerate lab-to-market transitions and strengthen the regional translation layer.[138] Colorado and New Mexico have paired that federal recognition with more targeted state tools, including quantum tax credits in Colorado and a state-backed Quantum Venture Studio in New Mexico. That institutional build-out does not prove commercialization success, but it does indicate that the region is trying to address one of quantum's most stubborn practical problems: the bespoke nature of prototyping and early system integration.

That problem is structural. Quantum prototypes often require custom lab environments, specialized photonics and packaging capacity, cryogenic infrastructure, calibration support, and repeated interface engineering across hardware, software, and measurement subsystems. Those requirements drive up fixed costs and make early company formation unusually expensive. Shared infrastructure can partially reduce that burden. It does not eliminate the bespoke nature of quantum development, but it can lower the cost of entering it and shorten the path from prototype to iteration.

New Mexico's approach is unusually explicit on this front. Its venture-studio model is designed to provide shared facilities, including a dilution refrigerator lab, photonics packaging, and a multi-node quantum network testbed, while co-locating an Elevate Quantum packaging facility so that Albuquerque can function as a fabrication and assembly complement to Boulder's research strengths. The practical significance is straightforward: these are not generic startup amenities. They are attempts to supply pieces of the physical and validation environment that young quantum firms would otherwise have to build or access one by one at very high cost.

Colorado is building a complementary version of the same support layer. Techstars has committed to quantum-focused accelerator rounds, and Quantum Commons in Boulder provides turnkey lab space with optical tables, laser-safety infrastructure, and shared equipment. Those assets matter because they may let new teams prototype and test without taking on the full capital burden of building a custom lab from scratch. In a field where many interface problems still have to be solved manually, shared facilities can also create a more cumulative environment: firms encounter similar packaging, calibration, and integration challenges in the same places rather than rediscovering them in isolation.

The strongest reading of this infrastructure is therefore specific and bounded. It does not show that the Mountain West has already solved the problems of validation, interoperability, ruggedization, or repeatable assembly. It does show that the region is beginning to build institutions aligned with those problems. In commercialization terms, that matters because one of the surest signs of an emerging translation environment is not just capital arriving, but infrastructure appearing that reduces the per-firm cost of bespoke prototyping and makes stack-level problems more tractable to solve.

6.4.4 Growth capital flows to startups that integrate across the stack

A technology lens clarifies the kind of commercialization this capital supports. If the Mountain West’s largest growth-capital-backed, patent-linked startup investments are mapped onto the technology platforms represented in those firms’ patent portfolios, the same dollars appear across multiple platforms. That overlap is not a reporting artifact. It reflects that the best-capitalized firms in this subset are not narrow component plays. Their patenting spans multiple quantum application areas and multiple layers of the stack, including computing, communications, and sensing, alongside software and systems and hardware and architectures. That pattern is consistent with the argument developed in Chapter 5: commercialization in quantum often depends on stack-spanning strategies that can absorb integration risk and control key interfaces.

The platform mapping also sharpens the region’s earlier convergence signal. Section 6.1 showed substantial overlap across the Mountain West’s invention base, especially between computing and communications. The commercialized subset shows a parallel pattern. Most of the capital is associated with firms whose invention portfolios span software and systems, quantum communications, algorithms, and hardware and architectures, with two to three companies accounting for the bulk of this stack-spanning footprint. In other words, the region’s cross-area coupling is not just a research classification phenomenon. It is also visible in the inventive behavior of the firms attracting the largest checks.

At the same time, the technology lens makes concentration easier to read. Photonics and optics do appear materially in the venture-backed patent subset, with two companies, 59 inventions, and roughly $371 million of associated capital. Several measurement-adjacent categories also appear as what is effectively a one-company profile, with 57 inventions and roughly $344 million associated with magnetometry-, gyroscope-, and detector-related activity. But the largest capital signal remains tied to the stack-spanning software and hardware categories. Read against Section 6.2, where the Mountain West’s structural specialization is strongest in photonics and sensing-enabling layers, the implication is nuanced. The region’s enabling-layer advantage is evident in venture-backed commercialization, but it is carried by a narrow set of firms, while headline capital numbers are dominated by a small number of more broadly positioned platform companies.

This stack-spanning commercialization pattern also fits how the Colorado cluster is often described by practitioners: less as a single-technology enclave than as a fuller-stack environment in which firms span components, enabling tools, and software, making it easier for startups to find local suppliers and iterate across interfaces such as optics, cryogenics, packaging, and control systems. That does not prove regional self-sufficiency. It helps explain why some of the region’s strongest commercialization signals attach to firms whose technical position spans multiple parts of the stack rather than to firms confined to a single niche.

6.4.5 The Mountain West's growth capital is highly concentrated

The strongest commercialization signals in the Mountain West are also the most unevenly distributed. Capital concentration is visible in two ways. First, dollars concentrate by primary industry. In the curated dataset, Computers, Parts & Peripherals account for roughly $1.276 billion, or about 66 percent of total capital, while Aerospace & Defense accounts for roughly $486 million, or about 25 percent. All other categories combined account for only about 9 percent. This split is revealing. It suggests two distinct commercialization orientations: one centered on computing- and platform-oriented narratives, the other on aerospace- and defense-adjacent pathways. Both can be compatible with systems assembly, but they tend to involve different development tempos, customer structures, and qualification pathways.

Second, capital concentration is extreme among patent-linked startups. In the matched subset of growth-capital-backed companies that also sponsor quantum inventions, the dataset identifies four companies with patented quantum inventions and a total investment of roughly $1.3 billion. That total, however, is overwhelmingly driven by one company, which accounts for roughly 97 percent of the subset's capital, while the remaining firms account for only a small fraction. This is the key interpretive point. The Mountain West's capital formation is real and notable, but it is also lumpy. The region appears to be producing breakout commercialization events rather than a uniformly deep bench of capitalized quantum firms.

That does not diminish the significance of the signal. It clarifies what kind of signal it is. A few very large deals can reflect genuine technical and market traction. They do not, on their own, demonstrate broad ecosystem completeness.

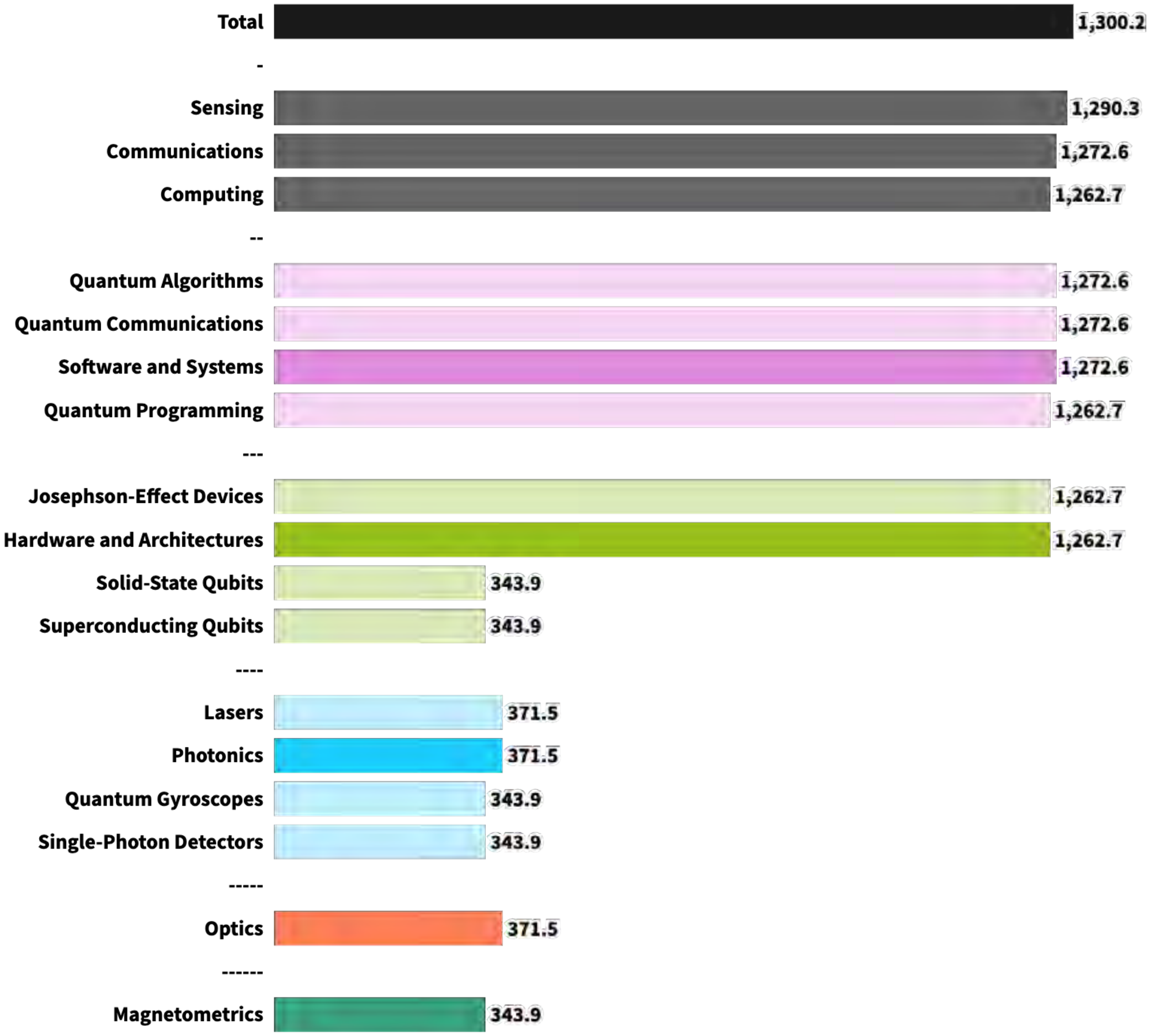
6.4.6 Interpreting commercialization through the systems-assembly lens

Read through the Chapter 5 lens, the Mountain West's commercialization profile has a distinctive shape. It combines mission anchoring, evident in the region's unusually high government-sponsor share, with venture-backed innovation, evident in the above-average share of growth-capital-backed invention sponsors and the recent surge in large financings. It also remains highly concentrated, suggesting that commercialization advantage is present, but disproportionately held by a limited set of firms and platform positions.

Three bounded assessments follow. First, institutional anchoring is a real regional strength. The Mountain West's government-linked invention sponsorship is materially above the national pattern and is consistent with the presence of mission-driven partners capable of absorbing deployment uncertainty and supporting long qualification cycles. Second, commercialization signals are real but selective. Capital has arrived at meaningful scale, and some firms are clearly being financed to pursue system-facing development rather than research alone. But the signal remains narrow and uneven. Third, the decisive test is still systems assembly. The real question is whether the region can convert these early commercialization signals into repeatable integration, validation, and qualification capacity rather than a small number of isolated success stories.

Figure 51. Growth capital has flowed to quantum invention in "lumps"

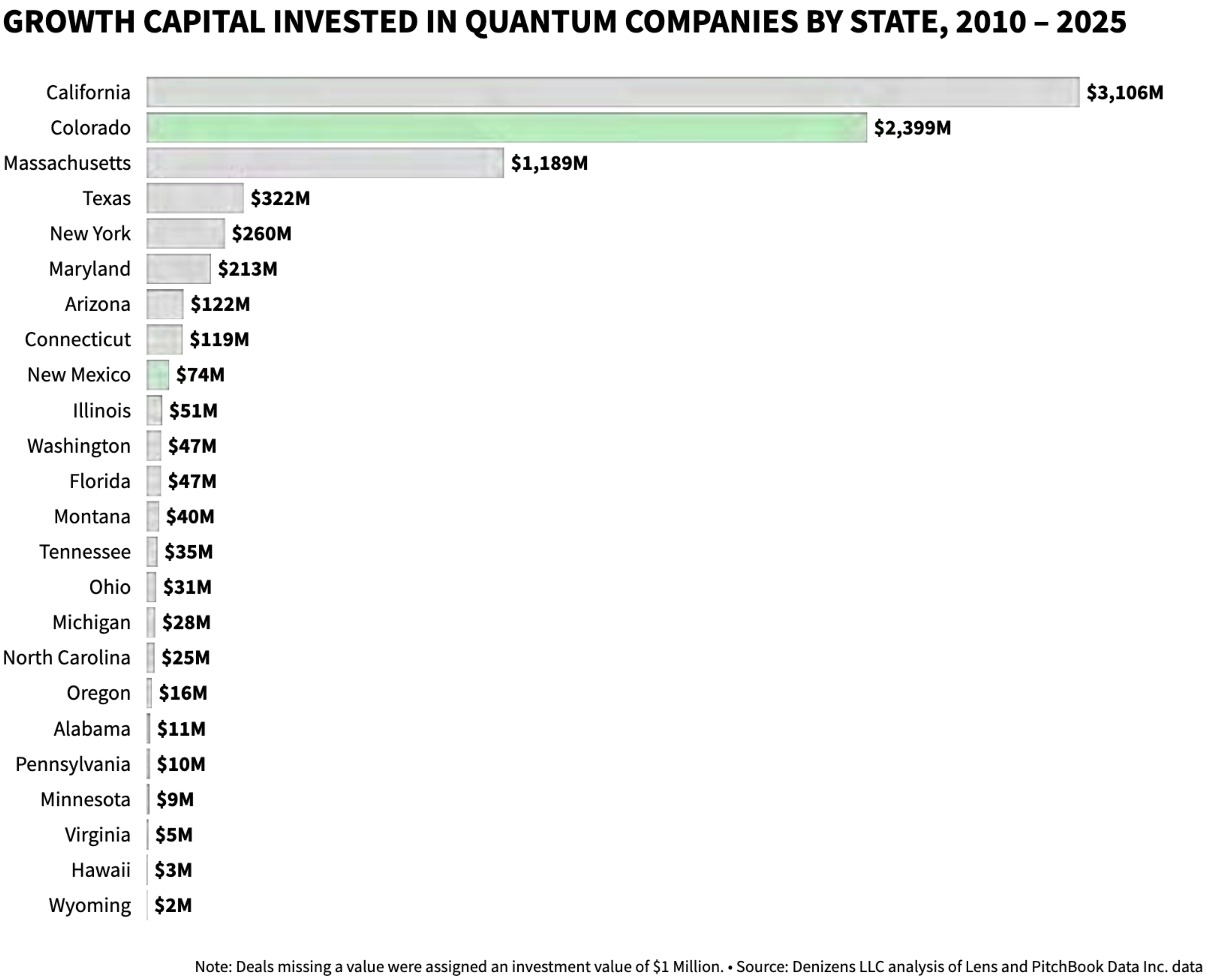
GROWTH CAPITAL INVESTMENT DYNAMICS FOR MOUNTAIN WEST QUANTUM COMPANIES, BY PLATFORM



Note: Deals missing a value were assigned an investment value of $1 Million. • Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data

That is the proper conclusion of this section. The Mountain West is producing credible commercialization signals around its strongest technical positions, but not yet a broad or uniformly deep commercialization engine. The next section asks whether the combined evidence on stack position, momentum, institutional anchoring, and selective commercialization is strong enough to read the region as a genuine system-assembly node rather than a promising but still fragmented set of strengths.

Figure 52. Colorado leads in quantum growth capital investment



GROWTH CAPITAL INVESTED IN QUANTUM COMPANIES BY STATE, 2010 – 2025

Note: Deals missing a value were assigned an investment value of $1 Million. • Source: Denizens LLC analysis of Lens and PitchBook Data Inc. data

6.5 The Mountain West as a system-assembly node

Sections 6.1 through 6.4 established that the Mountain West has a material quantum invention base, unusually strong concentration in measurement- and photonics-adjacent enabling layers, recent momentum in several stack-relevant platforms, and selective but credible commercialization signals. The question now is what kind of regional role the evidence supports. The relevant test is not whether the Mountain West can match the largest coastal hubs on raw scale. It is whether the region is strong in the parts of the stack that must stabilize, measure, calibrate, validate, and connect quantum systems to real operating environments. On that national map, the region is not peripheral. Federal quantum investment has produced a distributed set of regional hubs, and the Mountain West contains seven major federal quantum investments, four in Colorado and three in New Mexico. The issue is not presence. It is what kind of node that presence makes possible.[139]

6.5.1 A defensible source of advantage: bottleneck-layer positioning

The Mountain West's clearest advantage signal is not volume. It is concentration in the enabling layers closest to the system's hardest constraints. Section 6.2 showed overall regional concentration at 2.88x the U.S. average, with sensing at 3.31x, photonics at 4.53x, lasers at 4.51x, quantum gyroscopes at 8.86x, single-photon detectors at 3.42x, magnetometry at 3.21x, and optics at 3.05x. These are not abstract upstream specialties. They are the parts of the stack that systems must be read out, stabilized, calibrated, and trusted outside controlled settings. In practical terms, they sit close to the bottlenecks that still determine whether quantum performance can survive contact with the world.

That concentration profile is consistent with the region's institutional anchors. Colorado's strength is rooted in precision measurement and timekeeping, anchored by the NIST/JILA complex, which provides metrology infrastructure and an enduring talent base in quantum measurement science. New Mexico adds weight through Sandia and Los Alamos, where mission-oriented engineering, applied physics, hardening, and qualification have long been central rather than optional. Read through the Chapter 5 rubric, this is the Mountain West's most defensible source of advantage: it is positioned close to the point where quantum systems stop being scientific demonstrations and start becoming operational claims.

6.5.2 System integration capacity: increasingly formalized but uneven

Stack position alone does not make a system-assembly node. A region also needs actors capable of assembling multi-layer systems and managing interfaces across hardware, control, photonics, software, and validation workflows. The evidence assembled earlier in the chapter offers indirect but meaningful support on that front. Section 6.1 showed substantial overlap across the three quantum application areas, including 186 inventions shared between computing and communications, 124 between computing and sensing, and 59 between sensing and communications. Section 6.4 then showed that the most heavily capitalized patent-linked firms in the region tend to span multiple layers of the stack rather than occupy only one narrow component niche. Taken together, those patterns are more consistent with integration work than with isolated device specialization.

That integration capacity is more plausible in Colorado than evenly across the region. Colorado's quantum industry is comparatively broad, spanning enabling components, fabrication-adjacent activity, software, and applications. That breadth reduces friction in iterative system building and supports specialized supplier relationships in areas such as cryostats and precision optics, which help firms move from lab prototypes to engineered systems. New Mexico's private-sector layer has historically been thinner relative to the scale of its research base, but recent efforts are explicitly designed to thicken that translation layer by importing firms and co-locating them with shared infrastructure. Wyoming's near-term role may center on education, workforce development, and multi-state coordination. The right interpretation is therefore not a uniform regional cluster. It is a two-anchor system: Colorado as the broader integration anchor, New Mexico as the mission and hardening complement, and Wyoming as an enabling support node.

6.5.3 Validation and testbeds: a credible assembly-signaling move

The Chapter 5 rubric treats validation and testbed capacity as a core test of systems assembly because invention alone does not qualify a quantum system for use. Systems have to be calibrated, packaged, tested under noise, and assessed against operational requirements. On that dimension, the Mountain West shows one of its clearest recent institutional signals. The region is beginning to build shared environments aimed directly at those functions, rather than relying only on the strength of its research base.

New Mexico's strategy is the most explicit example. Its state-backed venture-studio model is paired with shared facilities, including a dilution refrigerator lab, photonics packaging, and a multi-node quantum network testbed. Those assets are intended to lower fixed costs for deep-tech firms and position Albuquerque as a fabrication and assembly complement to Boulder rather than as a standalone rival. Colorado is building the complementary side of the same support layer through Quantum Commons and accelerator-backed shared lab space designed to shorten the path from prototype to engineered iteration.

These developments matter because markets routinely underprovide exactly these functions. Calibration infrastructure, packaging, iteration space, and early trial environments rarely generate immediate firm-level returns, even though they determine whether measurement-heavy technologies can be qualified and trusted. A region that builds them is not proving that it already has decisive validation throughput. It is showing that its institutions are aligning with the real points of friction in quantum systems assembly.

The limitation should be stated plainly. Many of these facilities are still prospective through 2026, and the current evidence does not yet show mature, repeatable validation throughput at regional scale. The stronger reading is narrower: the Mountain West is moving from implicit measurement strength toward explicit institutional capacity to reduce integration risk.

6.5.4 Institutional anchoring and network position: a clear strength

The Mountain West's clearest differentiator relative to many mid-scale regions is the combination of mission anchoring and organized coordination. Section 6.4 showed that government sponsors account for 18.5% of the region's quantum inventions, compared with 6.1% nationally. That pattern is credible because the region's technical base is anchored by Sandia, Los Alamos, and NIST Boulder—institutions tied directly to national quantum programs, metrology, validation, and mission-driven engineering.

Coordination capacity is also more explicit than in many peer regions. A consortium of dozens of organizations across Colorado, New Mexico, and Wyoming secured an EDA Tech Hub designation, then a $40.5 million Phase 2 federal award, matched by more than $80 million in state support. Colorado added a quantum tax credit program. New Mexico added venture-studio and workforce funding. Those numbers do not prove assembly capacity on their own. They do show that the region has moved beyond passive asset accumulation toward deliberate cross-institutional organization.

The node claim, however, is only credible if that coordination operates outward. Quantum systems do not become consequential inside a closed regional loop. They become consequential when prototypes, validation protocols, components, and trusted performance claims circulate through broader national and allied pathways: co-production with other U.S. hubs, participation in standards-setting, qualification with mission users, and deployment into markets and procurement channels outside the region. On that test, the Mountain West's two-anchor structure is potentially an advantage. Colorado's measurement depth and supplier base and New Mexico's mission-validation capacity are most valuable when they connect to a wider distributed system rather than trying to substitute for one.

That outward network posture is one of the region's central conditions of durability. A self-contained three-state cluster would remain too thin to shape the field on its own. A two-anchor Mountain West node that helps other U.S. and allied partners move systems across validation, procurement, and deployment thresholds is a different proposition. That is the stronger reading of the evidence assembled in this chapter.

6.5.5 Structural vulnerabilities and competitive pressures remain real

The Mountain West has a meaningful quantum technology invention base, but it remains geographically and organizationally concentrated. Of the region's 594 quantum inventions since 2010, 439 are tied to Colorado and 144 to New Mexico. On the commercialization side, the patent-linked startup subset is thinner still: roughly $1.3 billion in growth capital is tied to just four firms, and one company accounts for about 97% of that total. That is not a trivial achievement. It does mean the region's visible commercial momentum is being carried by a narrow bench. A node can matter without being broad, but thinness increases the risk of firm failure, project delays, or a shift in investor sentiment.

The same caution applies to the region's institutional structure. Government sponsors account for 18.5% of Mountain West quantum inventions, compared with 6.1% nationally, which is a real advantage when qualification cycles are long and mission environments matter. It also creates dependence on a limited set of federal institutions, priorities, and procurement pathways. A regional system anchored heavily by national labs, NIST-related measurement infrastructure, and defense-adjacent demand can be powerful, but it is not fully self-propelling. If external mission priorities shift, or if federal support for shared facilities and translation programs weakens, the region's throughput could slow quickly.

Commercialization signals are also newer and more fragile than the headline dollar totals suggest. The region's startups raised $1.943 billion in growth capital between 2010 and 2025, but about 74% of that arrived in 2024–2025 alone. Early-stage and later-stage venture capital account for almost all of it. That pattern is consistent with a field that has recently become more legible to investors. It is not yet evidence of a mature capital market matched to quantum's long engineering, validation, and procurement cycles. Quantum firms often need patient capital, specialized infrastructure, and buyers willing to tolerate extended qualification periods. Venture attention can help, but it does not eliminate those structural frictions.

The region also faces competitive pressure from larger and deeper ecosystems. Bigger coastal hubs and a few leading Mid-Atlantic and Midwest nodes combine greater raw scale with thicker supplier networks, larger pools of specialized labor, and more diversified capital sources. The Mountain West’s response cannot be to match that scale directly. The evidence in this chapter does not support such a reading. Its more credible path is narrower: maintaining strength where measurement, photonics, mission validation, and system integration pressures intersect. That is a defensible competitive position, but it is also a bounded one.

6.5.6 Positioned to influence system assembly, conditionally

Taken together, the evidence in this chapter supports a clear but disciplined conclusion. The Mountain West is plausibly becoming a system-assembly node within the broader U.S. and allied quantum landscape. That judgment rests on four cumulative findings: a material invention base of 594 inventions; unusually high economic concentration in sensing and measurement-adjacent enabling layers, including 3.31x concentration in sensing and 4.53x in photonics; rapid recent momentum in several leverage-bearing platforms; and an institutional structure that combines national-lab and metrology anchoring with early, if uneven, commercialization signals.

The strongest version of the claim is not that the region is a self-contained quantum powerhouse, or that it is already demonstrating large-scale validation throughput across the stack. The stronger reading is more specific. The Mountain West appears increasingly well positioned to help move certain quantum capabilities—especially those tied to measurement, readout, photonics, navigation, and mission-relevant sensing—across the difficult boundary between laboratory performance and trusted operational use. Colorado and New Mexico contribute differently to that role. Colorado supplies more visible scale, firm formation, and platform breadth. New Mexico supplies mission depth, engineering environments, and qualification-relevant infrastructure. The regional proposition is strongest when those roles are treated as complementary parts of a distributed system.

This role remains conditional. To endure, the region will need more than concentration and recent momentum. It will need repeatable validation throughput, a somewhat deeper commercial bench, and sustained outward linkage to other U.S. and allied nodes where standards, procurement, and deployment pathways are being shaped. The chapter’s evidence does not yet prove those conditions have been fully met. It does show that the Mountain West has moved beyond generic participation. It has developed a distinctive position in parts of the quantum stack that matter disproportionately for system assembly, and that makes it more consequential than raw scale alone would suggest.

* * *

The evidence in this chapter supports a clear but bounded conclusion. The Mountain West has a material quantum-invention base, an unusually strong concentration in measurement- and photonics-adjacent enabling layers, rapid recent momentum across several system-relevant platforms, and selective but credible commercialization signals. Those findings do not show a region prepared to dominate the quantum field on raw scale alone. They do show a region whose strongest capabilities lie near the point at which quantum performance must be stabilized, validated, and translated into trusted use.

That position is most plausibly understood as a regional system-assembly role inside a broader U.S. and allied quantum architecture. Colorado and New Mexico contribute differently to that role. Colorado supplies more visible scale, platform breadth, and private-sector momentum. New Mexico contributes mission depth, engineering environments, and validation-relevant infrastructure. The region’s strength is therefore not its uniformity. It is the combination of complementary capabilities, concentrated in parts of the stack that matter disproportionately, when fragile technical advances must become operationally meaningful.

That role remains conditional. The Mountain West’s advantages will matter most if they are converted into repeatable throughput in integration, validation, packaging, qualification, and deployment-facing collaboration with other U.S. hubs and allied partners. The chapter’s evidence does not yet prove that those conditions have been fully met. It does show that the region has moved beyond generic participation and now occupies a more consequential position in the quantum system than raw scale alone would suggest.

For ASCEND technology development, that conclusion is especially relevant in one respect. The region’s strongest evidence sits in the layers that make trusted measurement possible in practice: photonics, precision instrumentation, readout, validation, and related system-facing capabilities. Those are also the layers most likely to shape whether environmental, infrastructure, and decision-relevant quantum pathways become usable outside the lab.

7. Strategic implications for the Mountain West

Chapter 6 established that the Mountain West possesses real, unusually concentrated quantum strength. Since 2010, inventors and patent sponsors in Colorado, New Mexico, and Wyoming have produced 594 quantum inventions. On an employment-normalized basis, the region's overall quantum concentration is 2.88 times the U.S. average, with its strongest quantum application-area signal in sensing at 3.31 times. Commercialization signals are also promising but as yet uneven.

Those facts suggest that quantum progress now turns less on isolated demonstrations than on system assembly: the work of stabilizing performance, integrating subsystems, qualifying results, and making claims credible outside controlled environments. Chapter 7, therefore, does not offer a generic regional strategy memo. It draws out the implications of the diagnosis for leaders deciding where subnational action can actually change outcomes—where regional institutions can reduce integration risk, shorten qualification cycles, and strengthen the conditions for repeatable deployment.

The report's broader argument points to a specific conclusion. The Mountain West's most plausible long-run role is as a national system-assembly node inside a distributed U.S.-allied quantum system. That role is broader than advanced sensing and computing for environmental decision-making (or "ASCEND") technologies, though ASCEND-adjacent pathways remain one of its clearest applied tests because environmental intelligence, infrastructure monitoring, and resilient decision systems all depend on the same measurement, photonics, control, and validation layers that shape the wider field.

7.1 The Mountain West as a national system-assembly node

Subnational regions do not matter in quantum by reproducing the full stack locally. They matter because they own functions that the wider system needs. Federal quantum investment in the United States has already been organized as a distributed network of regional hubs rather than a single centralized program, and the Mountain West contains seven major federal quantum investments—four in Colorado and three in New Mexico. The relevant question is not whether the region can outscale California, Massachusetts, or Maryland. It is whether it can become hard to substitute in the layers where quantum systems are stabilized, measured, qualified, and connected to use.

The Mountain West's first claim to that role is bottleneck-layer position. Section 6.2 showed concentration where quantum systems usually fail first outside the lab: photonics at 4.53 times the U.S. average, lasers at 4.51, quantum gyroscopes at 8.86, single-photon detectors at 3.42, magnetometry at 3.21, and optics at 3.05. These are bottleneck layers because they govern readout fidelity, timing stability, calibration, noise management, and signal trust. A quantum device can be scientifically impressive and still fail operationally if those layers remain fragile. The Mountain West is stronger in exactly those layers than in a broad, fully balanced regional stack.

The second claim is qualification and validation. Boulder's NIST/JILA complex gives the region metrology, precision-measurement, and timekeeping depth that few places can match. New Mexico adds Sandia and Los Alamos, where mission-oriented engineering, hardening, and qualification have long been central rather than optional. More recent institutional build-out points in the same direction. Elevate Quantum's Tech Hub designation and Phase 2 award, Colorado's quantum tax credits, the New Mexico Quantum Venture Studio, Quantum Commons in Boulder, and new shared facilities in Albuquerque are all attempts to lower the fixed costs of packaging, testing, and early system integration. None of that proves mature deployment capacity. It does show a region building around the right constraint.

The third claim is mission anchoring and demand pull. Quantum systems often move toward use in mission settings before they enter broad commercial markets because qualification cycles are long and failure costs are high. The Mountain West's invention record fits that pattern. Government sponsors account for 18.5 percent of regional quantum inventions, versus 6.1 percent nationally. The sponsor roster also shows that the region is not driven by public institutions alone. It includes a mixed bench of national-lab-linked entities, research universities, and companies trying to productize quantum capabilities, including Quantinuum, Infleqtion, Honeywell, Northrop Grumman, Lockheed Martin, and University of Colorado-linked activity. That mix matters because mission institutions can absorb risk and define performance requirements, while firms push toward repeatability, product form, and scale.

The regional structure supporting those functions is asymmetric, and that asymmetry is an advantage if it is managed deliberately. Colorado carries most of the region's scale, momentum, and private-sector breadth. New Mexico supplies the mission, hardening, and validation complement. Wyoming remains a supporting node whose near-term contribution is workforce, education, and multi-state coordination rather than concentrated industrial depth. The Mountain West is therefore not a uniform cluster. It is a two-anchor system whose practical influence depends on complementarity across state lines.

Node status will depend on network posture as much as on local assets. The Mountain West will matter most if Colorado's platform-building strength and New Mexico's mission-validation capacity are used outward—into allied markets, shared standards, procurement pathways, and collaborative test environments—rather than treated as the basis for a self-contained regional sector. That is the durable path because quantum remains interdependent. Fabrication, software, calibration standards, and deployment partners still sit in multiple places at once. A region in this field gains influence when it repeatedly helps the wider system close the stack.

The strategic test is therefore specific. Can the Mountain West turn strong position in measurement-facing bottlenecks, real validation assets, and mission-linked demand into repeatable assembly capacity? Capital interest suggests the possibility is real—regional quantum firms have raised $1.943 billion since 2010, with roughly 74 percent arriving in 2024–2025—but that capital is still concentrated and does not by itself prove maturity. The node thesis is plausible. It is not automatic.

7.2 Priority pathways as “signature assembly arenas”

Chapter 5 showed that quantum commercialization pressure does not emerge where novelty is highest or where forecasts point to the largest eventual markets. It emerges where systems must operate outside the lab, where failure is costly, and where integration cannot be deferred. The relevant test in those settings is straightforward: can a quantum-enabled system be deployed, calibrated, maintained, and trusted under operational constraints? Read through that lens, three operational contexts surface early and consistently: resilient navigation and timing, secure communications and cryptographic transition, and infrastructure-adjacent sensing. These arenas differ technically, but they share the same commercial logic. The value proposition is immediate, the operating environment is unforgiving, and adoption depends more on validation than on novelty.

The term “signature assembly arenas” is deliberate. The point is not to nominate a short list of markets for the region to chase. It is to identify the contexts most likely to force stack closure, reward validation throughput, and reveal whether the Mountain West can repeatedly reduce integration risk for the wider U.S.-allied system. That framing fits the region’s strongest empirical signal from Chapter 6. The Mountain West’s most distinctive quantum application-area concentration is in sensing at 3.31 times the U.S. average, and its platform profile is unusually dense in measurement-facing layers: photonics at 4.53 times, lasers at 4.51, quantum gyroscopes at 8.86, single-photon detectors at 3.42, magnetometry at 3.21, and optics at 3.05. Those are the layers that often determine whether quantum performance becomes trusted capability.

These arenas matter because they are where regional influence is most plausibly durable. Qualification regimes, calibration standards, workflow integration, and mission partners determine whether capability becomes operational. In other words, these are the places where comparative advantage is most likely to show up as system assembly capacity rather than as isolated invention. For the Mountain West, that is the right test. A distributed region will matter in quantum if it can make specific pathways easier to trust, easier to qualify, and harder to substitute inside a broader national and allied network.

7.2.1 Resilient navigation and timing

Resilient positioning, navigation, and timing is one of the clearest early tests of system assembly because PNT sits underneath modern economic and security infrastructure. GPS-enabled timing supports financial transactions, communications networks, and grid synchronization. GPS-enabled positioning supports aviation, maritime logistics, precision operations, and defense. That dependence now carries visible risk because jamming and spoofing have moved from a niche concern to an operational one. In this context, quantum sensing should be understood as a resilience layer, not as a wholesale replacement for GPS. The practical question is whether alternative timing and inertial systems can preserve trusted operation when satellite signals are degraded, denied, or manipulated.

This arena forces assembly early because the cost of error is high and certification burdens are unforgiving. A PNT system is valuable only if it can survive noise, maintain calibration, integrate with existing avionics and control systems, and produce outputs users are willing to trust in motion. That is why ruggedization, packaging, SWaP reduction, and interface engineering matter as much as the sensing physics itself. In resilient PNT, those elements are not secondary. They are the product. A more precise clock or a better inertial sensor means little unless it can be stabilized, fused with other data, and qualified.

The Mountain West fits this arena unusually well because its strongest regional signals sit close to the measurement primitives PNT depends on. The region's sensing concentration is 3.31 times the U.S. average, but the more telling numbers are lower in the stack: photonics at 4.53 times, lasers at 4.51, and quantum gyroscopes at 8.86. Colorado and New Mexico express those strengths differently. Boulder's NIST/JILA complex anchors precision measurement, timekeeping, and metrology. Sandia and Los Alamos add mission-oriented engineering, hardening, and qualification depth. Together they place the region near the layers that determine whether clocks, inertial systems, and related modalities can be stabilized and trusted under operational conditions.

That combination also gives PNT an applied relevance to ASCEND technologies. Environmental intelligence and infrastructure monitoring both depend on continuity of measurement under degraded conditions. But the regional opportunity is broader than any one application family. If the Mountain West can help qualify jam-resistant timing and inertial stacks for federal users, aerospace platforms, and allied resilience architectures, it becomes valuable here as a deployment and validation partner, not just as a research site.

7.2.2 Secure communications and cryptographic transition

Secure communications is a second assembly arena, but its near-term logic differs from PNT. The most immediate pressure point is not the widespread deployment of quantum networks. It is the transition in cryptographic and communications infrastructure triggered by the expectation that future quantum computers will threaten today's widely used encryption standards. That shows how commercialization can advance through standards, verification, migration, and interface hardening even while frontier hardware remains unsettled. The operative challenge is not simply to invent a better communications component. It is to move large installed systems across a trust transition without breaking interoperability.

This is still an assembly arena because the core work is institutional and integrative. Protocols have to be updated. Implementations have to be validated. Interfaces have to be hardened across regulated sectors, supply chains, procurement systems, and legacy networks. In that sense, cryptographic transition is system assembly in the classical world. The binding constraints are coordination, verification, and interface stabilization rather than frontier sensing performance alone. That is also why this arena fits the report's broader argument that institutions matter disproportionately in quantum commercialization: standards bodies, regulated industries, and government buyers often define the adoption timetable long before mass-market demand does.

The Mountain West's role here is therefore narrower and more specific than in PNT. The region's communications concentration, at 2.64 times the U.S. average, is real but less distinctive than sensing. Its stronger claim lies in the enabling and institutional layers that secure systems depend on: photonics, detectors, metrology, verification environments, and network experimentation. That makes NIST especially important, because standards and measurement are central in this arena, and it makes New Mexico's emerging infrastructure relevant in a bounded way, including photonics packaging and a multi-node quantum network testbed. The region does not need to own the entire secure-communications stack to matter. It needs to help solve the interoperability and validation problems that determine whether trusted systems can actually travel.

That outward-facing requirement is decisive. Secure communications and cryptographic transition are only strategically meaningful when they align with national standards, regulated procurement, and allied migration pathways. The Mountain West will matter here to the extent that it contributes to those shared regimes—through metrology, verification, testbeds, and photonics-adjacent enabling capacity—rather than by trying to build a self-contained communications sector of its own.

7.2.3 Infrastructure-adjacent sensing

Infrastructure-adjacent sensing is the most regionally grounded of the three arenas and the one with the clearest bounded connection to ASCEND technologies. The category is intentionally broad. It includes subsurface mapping, underground imaging, environmental and geophysical monitoring, aviation-support sensing, and other high-value operational contexts in which small improvements in trusted measurement can yield meaningful gains. These are not consumer markets waiting for polished products. They are institutional settings where operators will fund pilots, testbeds, and validation-heavy deployments if a system can demonstrate reliable in situ operation.

This arena rewards the Mountain West's measurement-stack profile because the real challenge is not simply to sense more faintly. It is to integrate the sensing system into decisions and operations. A fielded instrument has to survive vibration, drift, temperature variation, and electromagnetic noise. It has to be calibrated against standards. It has to connect to data fusion, models, and existing workflows. It has to produce outputs that operators trust enough to act on. Commercial readiness in sensing is often misread. The frontier is rarely the invention itself. It is the ability to deploy, maintain, and trust the system.

The Mountain West is unusually well positioned in this arena because its strongest comparative signals sit precisely in the enabling layers infrastructure-adjacent sensing depends on. Sensing is the region's most distinctive quantum application-area signal at 3.31 times the U.S. average. The supporting platform profile is just as important: lasers at 4.51 times, magnetometry at 3.21, optics at 3.05, and single-photon detectors at 3.42. Those categories are closely tied to real-world measurement performance. Colorado's NIST/JILA complex and broader photonics base reinforce the precision-measurement side of that story. Sandia and Los Alamos reinforce the mission, hardening, and validation side. The result is not a generic regional science cluster. It is a two-anchor system unusually close to the places where ruggedization, calibration, and interface credibility determine adoption.

This opportunity also connects directly to the Mountain West's U.S. NSF ASCEND Engine program. Chapter 3 argued that climate- and environment-relevant pathways remain pre-invention rather than invention-dense. That caution still matters. Relevance to environmental applications should not be mistaken for proof of market maturity. Yet these pathways remain strategically important because they depend on the same measurement, photonics, control, and validation layers that matter across the broader quantum field. Infrastructure-adjacent sensing is therefore where ASCEND technology relevance is most real, but also where realism matters most. The opportunity is not a sudden wave of finished climate products. It is the chance to turn regional strength in trusted measurement into systems that can enter longer-run environmental, infrastructure, defense, and industrial workflows.

The Mountain West's geographic and operational environments strengthen that case by making frontier conditions legible. Difficult terrain, remote infrastructure, signal-denied settings, and mission-heavy operating contexts provide the region with places where ruggedization, calibration, and sustainment constraints can be tested under real-world conditions. That does not remove the need for outward-facing collaboration. It sharpens it. Infrastructure-adjacent sensing becomes a durable regional role only if systems proven in the Mountain West can extend into broader procurement channels, standards regimes, and allied operating environments. This arena is the clearest proving ground for the region's system-assembly thesis. It offers a credible path for converting measurement-adjacent strengths into deployable system influence.

Across all three arenas, the shared structural point is the same. Commercialization pressure arrives early, where systems have to function outside controlled environments, where reliability and calibration determine value, where integration with legacy infrastructure cannot be avoided, and where institutions can absorb uncertainty through pilots, testbeds, and qualification partnerships. Those are the arenas in which the Mountain West's core advantage can be tested most credibly. They are also the arenas in which the region will matter only if its strengths travel outward—into national and allied standards, procurement, and deployment pathways that make quantum systems usable beyond the region itself.

7.3 What the diagnosis implies for durable systems assembly

The central question is no longer whether the Mountain West has real quantum strengths. Chapter 6 established that it does. The harder question is whether those strengths can become durable system-assembly capacity rather than a short burst of invention, funding, and institutional attention. Read through the Chapter 5 rubric, durability means something specific: repeatable ability to move quantum systems across integration, qualification, and deployment thresholds. It does not mean generic momentum. It does not mean a few large financings. It does not mean one or two standout institutions. It means a region can repeatedly help fragile capabilities become trusted systems under real operating constraints.

The Mountain West starts that test from a strong position because its clearest comparative signal sits in the layers where quantum systems usually fail first outside the lab. The region's overall concentration is 2.88 times the U.S. average, with sensing at 3.31 times. Its platform profile is even stronger: photonics at 4.53, lasers at 4.51, quantum gyroscopes at 8.86, single-photon detectors at 3.42, magnetometry at 3.21, and optics at 3.05. Those are not downstream use cases. They are the enabling layers that govern readout fidelity, timing stability, calibration, and signal trust. Durable influence will begin there because that is where quantum performance becomes operationally legible.

That stack position matters, but it is not enough on its own. A region can be highly concentrated in bottleneck layers and remain substitutable if it does not shape the interfaces that govern how those layers are used. The next threshold is therefore validation and system integration. Quantum systems are still built to custom specifications for specific research or demonstration contexts. Shared benchmarks remain limited. Common interfaces remain thin. Calibration standards are still uneven. Every deployment, therefore, has to solve too much of its own integration problem by hand, which the NIST/JILA complex is unusually positioned to reduce.

The Mountain West's emerging advantage is institutional. The NIST/JILA complex anchors metrology and precision measurement in Boulder. Sandia and Los Alamos anchor mission-oriented engineering, hardening, and qualification in New Mexico. Quantum Commons in Boulder and New Mexico's emerging shared facilities—including photonics packaging, a dilution refrigerator lab, and a multi-node network testbed—matter because they lower the cost of solving the same interface problems repeatedly in shared environments. That is how a region begins to turn bespoke engineering into repeatable assembly routines.

Durability also depends on whether mission anchoring stabilizes the system without trapping it inside bespoke mission solutions. The Mountain West has a real advantage here. Government sponsors account for 18.5 percent of regional quantum invention, versus 6.1 percent nationally, and growth-capital-backed sponsors account for 14.0 percent, versus 9.6 percent nationally. That mix matters because mission institutions can absorb long qualification cycles and define demanding performance requirements, while private firms push toward productization and repeatability. Sandia, Los Alamos, and NIST Boulder are the clearest institutional anchors. The region's sponsor roster also includes firms and organizations such as Quantinuum, Infleqtion, Honeywell, IBM, Lockheed Martin, Northrop Grumman, Triad National Security, and University of Colorado- and UNM-linked entities. That is a stronger translation profile than a region driven only by university labs or only by venture-backed startups. But mission density is a stabilizer, not a substitute for a broader translation layer. The region still has to turn mission-linked qualification work into repeatable learning that travels beyond one customer, one lab, or one program. That is also the bounded ASCEND implication in this section: the same validation and trust infrastructure that will determine broader quantum durability will also determine whether ASCEND-relevant sensing pathways move from promising adjacency toward dependable deployment.

Commercial breadth is the next test. The region's capital signal is substantial: Mountain West quantum startups raised $1.943 billion between 2010 and 2025, with roughly 74 percent of that arriving in 2024–2025. That is real traction. It is also highly concentrated. The report's own commercialization analysis is explicit that these flows are best read as breakout events rather than proof of a broad, mature regional engine. Durable system assembly requires more than a handful of visible firms. It requires a wider bench of platform firms, integrators, specialized suppliers, packaging capacity, validation partners, and translation talent. Colorado is closer to that condition because its private-sector base is broader across enabling components, software, and applications. New Mexico is building toward it by thickening the translation layer around shared infrastructure and mission-linked engineering. Wyoming's role remains enabling rather than anchoring, centered more on workforce, education, and multi-state coordination than on industrial depth. The right reading is therefore a two-anchor system with real but still incomplete commercial breadth.

The last condition is outward network position. The Mountain West will not become durable by behaving like a self-contained cluster. Quantum remains too interdependent for that. Critical inputs, validation partners, deployment pathways, and standards-setting functions remain distributed across the wider U.S.-allied system. The region's advantage becomes durable only if Colorado's measurement and supplier strengths and New Mexico's mission-validation strengths are used outward—into co-production, qualification, procurement, and standards work with other U.S. hubs and allied partners. Elevate Quantum's consortium structure, the Tech Hub designation, the $40.5 million Phase 2 federal award, and more than $80 million in state support matter because they show the region has already begun to organize at scale. But network position becomes strategically meaningful only when collaboration turns into institutional routine rather than occasional cooperation. A region in this field gains durable influence when others repeatedly need it to move systems across the hardest thresholds.

The diagnosis is therefore conditional but strong. The Mountain West has the right kind of partial strengths for durable systems assembly because it is concentrated in bottleneck-layer platforms, anchored by metrology and mission institutions, and beginning to build the shared environments that reduce integration risk. The unresolved issue is whether those strengths harden into repeatable validation routines, a broader translation bench, and outward-facing institutional ties that make the region hard to replace. That is the real line between regional promise and durable assembly influence.

7.4 How different actors contribute to system assembly

Assembly-constrained technologies do not stall mainly because invention is weak. They stall because the work required to make systems deployable, maintainable, calibratable, and trusted does not sit neatly inside any one firm’s, lab’s, or agency’s incentives. Testbeds, standards, validation environments, and early deployment partners are not peripheral supports. They are part of commercialization itself. Chapter 5 made the same point at the system level: commercialization proceeds fastest where institutions provide shared infrastructure, early demand, and standards.

Role clarity in the Mountain West therefore matters in the same way. The region's institutional functions need to be as deliberately organized as the assembly work they're meant to support. If the region’s plausible advantage lies in measurement-, validation-, and deployment-facing layers, the question is not simply who participates. It is which institutions reduce integration risk, which institutions define qualification thresholds. The region already has several pieces of that system. The shared operating model that would ensure those pieces work together consistently is still taking shape.

7.4.1 Ecosystem builders and regional public partners

Innosphere, Elevate Quantum, and their state and regional partners matter because they can support the work markets do not fund consistently: shared facilities, access rules, coordination routines, and lab-to-market scaffolding. Elevate Quantum’s Tech Hub designation and Phase 2 federal award, Colorado’s quantum tax credits, and New Mexico’s state-backed Quantum Venture Studio all point in the same direction. They are efforts to reduce the fixed costs of translation in a field where most firms cannot build their own full testing, packaging, and validation stack.

That role is strongest when shared infrastructure is treated as working infrastructure rather than symbolic inventory. The Mountain West has enough institutional momentum to build that kind of shared capacity. The harder test is whether those assets remain usable across the tri-state network rather than nominally regional but practically local. Access rules, cross-node pilots, and common benchmarking routines will determine whether public investment creates real assembly capacity or a looser collection of assets that firms still have to navigate one by one.

7.4.2 Investors and strategic capital

Investors play a narrower role than regional strategy language often implies. They do not fund the full system. They fund selected firms once enough uncertainty has been reduced to make a pathway legible. The Mountain West’s capital signal is substantial—$1.943 billion in growth capital since 2010—but it remains concentrated. That pattern suggests investors are responding to a limited number of breakout companies and clearer product narratives. It does not mean private capital is underwriting the full shared base of validation, workforce, and integration capacity the field still requires.

That should be read as a normal feature of the field, not as a regional failure. In quantum, venture and strategic capital usually arrive after part of the technical and qualification risk has already been reduced. They can accelerate packaging, productization, and go-to-market work once a pathway looks real. They are much less reliable sources for open-access testbeds, metrology assets, or workforce systems whose returns spill across many firms. In the Mountain West, private capital is therefore best understood as a selective translation signal. It is evidence that some regional pathways are becoming investable. It is not yet evidence that the deeper assembly problem has been solved.

7.4.3 Labs and universities

Boulder's NIST/JILA complex, Sandia and Los Alamos in New Mexico, and research universities including the University of Colorado and UNM contribute far more than scientific prestige. They anchor the trust infrastructure on which adoption depends: metrology, calibration routines, traceability, benchmarking, frontier facilities, and the talent pipeline needed to operate them. In a field where systems remain bespoke and interfaces remain unsettled, those functions are not background conditions. They are part of the path to a usable system.

The Mountain West is genuinely strong here. It has institutions that can sustain long development cycles and absorb technical uncertainty better than a startup-only network can. But those strengths become regionally decisive only when they are connected to repeatable pathways for packaging, testing, and qualification. The region does not lack scientific depth. It needs more of that depth to be translated into shared routines that smaller firms and newer entrants can use without recreating the full integration burden themselves. That is a capacity-building challenge, not a verdict against the region's research base.

7.4.4 Primes, operators, and mission users

Primes, operators, and mission users should be understood as qualification partners rather than passive customers at the end of the chain. In quantum sensing, navigation, communications resilience, and other failure-sensitive applications, the buyer often helps define the product by specifying tolerance for error, certification demands, maintenance burdens, and interface requirements. That is why institutional demand matters so much in this field. It creates environments in which systems are tested against working thresholds rather than compared only on abstract performance.

The Mountain West has a real advantage here because its invention base is more government-anchored than the national pattern and because its sponsor mix is unusually mixed. Government sponsors account for 18.5 percent of regional quantum invention, versus 6.1 percent nationally. Growth-capital-backed companies account for 14.0 percent, versus 9.6 percent nationally. The leading regional sponsors include Quantinuum, Sandia, Infleqtion, NIST-linked Department of Commerce activity, the University of Colorado, Honeywell, Triad National Security, Northrop Grumman, Los Alamos National Security, STC UNM, IBM, and Lockheed Martin. That combination shows that the region is better placed than many peers to move technologies through longer qualification cycles and into mission-linked use.

Seen through a system-assembly lens, mission users do more than create demand. They define credible benchmarks for use. When their participation is early and sustained, the region gains more than a pilot customer. It gains a route through certification, interoperability, and institutional trust. That is one reason the Mountain West's mission-heavy profile matters, even as broader commercial diffusion is still taking shape.

7.4.5 Misalignment is predictable—and avoidable

The main risk is not institutional absence. It is institutional misalignment. A region can have shared facilities, strong labs, interested investors, and mission users on paper and still fail to convert those assets into repeatable deployment. That failure is common in assembly-constrained fields because each institution is responding to a different time horizon, a different return logic, and a different definition of readiness.

Three misalignments are especially predictable. Shared infrastructure can exist without a workable access model, leaving assets nominally regional yet difficult for firms outside a single node to use. Investors may seek traction before validation environments are mature enough to deliver it. Mission users can be treated as late-stage customers when their real value lies earlier, in defining qualification pathways and operating benchmarks. None of these problems is unique to the Mountain West. All of them are plausible there because the region is still building the routines that connect shared assets, mission institutions, and private firms across state lines.

That is where the Colorado–New Mexico pairing matters most. Colorado brings the broader private-sector and platform-building base. New Mexico brings mission depth, laboratory infrastructure, and hardening environments. Those strengths are complementary. They become consequential only if the region sustains cross-node routines that link them. The evidence points to real movement in that direction, but not to completion. The Mountain West's practical test is whether it can keep shared assets genuinely shared, keep qualification work outward-facing, and keep institutional roles clear enough that firms know where to go to solve the next integration problem.

Much of the work described in this section is expensive, cross-institutional, and only partly captured by any single firm's return. That is why financing is not a separate implementation concern. It is part of system assembly itself. The next section takes up that problem directly.

7.5 Financing assembly capacity

Financing is part of system assembly. The agenda implied by Chapters 5 through 7 is not light coordination among existing firms. It is the construction and sustained use of shared validation capacity, translation infrastructure, and workforce pipelines that lower the cost of moving quantum systems from bespoke demonstrations toward repeatable deployment. Those assets behave like regional public goods because no single company can capture their full return, even when many firms depend on them. The Mountain West has already shown that this kind of funding logic is legible to public and place-based funders. Elevate Quantum's Tech Hub designation and Phase 2 federal award, matched by state commitments, were secured on exactly that premise: shared assets, lab-to-market transition, and workforce growth. Colorado's quantum tax credits and New Mexico's Quantum Venture Studio extend the same logic at the state level.

Private capital matters, but it cannot carry that system on its own. The region's capital signal is meaningful: Mountain West quantum startups raised $1.943 billion between 2010 and 2025, and roughly 74 percent of that total arrived in 2024 and 2025. The timing, however, is as important as the headline number. This is the profile of a recent step-change in investor attention, not of a mature and broadly distributed financing base. The stage mix reinforces that conclusion. Across the period, early-stage venture capital accounts for $1.129 billion, or 58 percent of total dollars; later-stage venture accounts for $632 million, or 33 percent; grants account for $106.5 million, or 5.5 percent; and other categories remain comparatively small. That pattern suggests that some regional pathways have become legible to investors, but it does not show that the deeper work of validation, standards, and integration has been financed at the same scale.

The practical issue, then, is not whether the Mountain West can attract capital in the abstract. It is whether the region can assemble the right capital stack for the kinds of assets its advantage thesis actually requires. Different funders are buying different forms of uncertainty reduction. Place-based competitiveness funders back shared assets, workforce systems, and coalition capacity because markets underprovide them. Mission agencies and mission-aligned public buyers tolerate long qualification cycles when the payoff is operational capability, which is why they can fund prototypes, pilots, test environments, and early procurement in ways private investors usually will not. Standards and measurement institutions matter because commercialization stalls when performance claims are not comparable and interfaces do not stabilize; in the Mountain West, NIST Boulder is especially important on that front. Private investors and strategic corporates play a different role. They tend to fund scale once qualification uncertainty has been bounded enough that market risk becomes the dominant uncertainty.

That distinction also clarifies which financing mechanisms are most relevant. Shared-capacity funding matters because it can underwrite assets that many firms use but few can build alone. Non-dilutive and flexible federal mechanisms matter because they help early firms cross qualification thresholds without forcing premature private financing. The current draft points to SBIR/STTR, OTAs, and CRADAs for exactly that reason: they turn agency interest into funded validation, accelerate prototyping, and open access to expensive national-lab capabilities and test equipment. Procurement pathways matter for a related reason. In this field, patient customers often function less as end-stage buyers than as qualification partners. Public or mission-aligned purchase can validate a system, generate revenue, and support scale where long development cycles would otherwise stall.

The Mountain West's emerging shared facilities show why this financing logic is consequential. In Albuquerque, the venture studio model is being built around common infrastructure, including a dilution refrigerator lab, photonics packaging, and a multi-node quantum network testbed, alongside an Elevate Quantum packaging facility intended to complement Boulder's research strengths. In Boulder, Quantum Commons reduces early laboratory capital expenditure by providing turnkey space and shared equipment, and Techstars has committed to quantum-focused accelerator rounds. These are still early moves, not evidence of a finished regional financing model. But they do address one of quantum's structural problems directly: too much prototype work remains bespoke, too expensive, and too difficult for individual teams to carry alone. Shared facilities and staged public finance reduce that burden because they let more firms solve qualification and integration problems in common environments rather than from scratch.

For ASCEND-relevant pathways, the implication is straightforward. Financing the region's quantum opportunity does not mainly mean backing a larger number of startups and waiting for a market to sort itself out. It means paying for the conditions under which trusted measurement can become usable in practice: calibration support, validation regimes, shared facilities, integration capacity, and partnerships with mission and infrastructure operators. Those are the elements most likely to matter in climate-, environment-, and infrastructure-adjacent sensing because those pathways depend on trust, workflow embedding, and sustained performance more than on sensitivity claims alone.

The broader conclusion is simple. Financing is one of the clearest practical tests of whether the Mountain West is becoming a real system-assembly node or only a promising one. A region that can align place-based funding, mission demand, standards and metrology support, non-dilutive prototype finance, and selective private capital is building the conditions for durable influence. A region that depends mainly on what venture markets will fund in the current cycle will tend to produce a few visible firms while leaving the shared trust infrastructure underbuilt. The Mountain West is not there yet. But it has already shown enough institutional traction, enough public support, and enough selective private capital to suggest that a more durable capital stack is plausible if it is built deliberately.

* * *

The implications of this chapter are specific. The Mountain West's strongest path is not to build a self-sufficient quantum sector or to compete on scale with larger hubs. It is to become a harder-to-substitute system-assembly node within a distributed U.S.-allied quantum system: a region that helps move fragile capabilities across the thresholds that matter most for use—calibration, validation, integration, qualification, and trusted deployment. That role is most plausibly tested in the operational arenas where those pressures arrive early, including resilient navigation and timing, secure communications and cryptographic transition, and infrastructure-adjacent sensing.

Whether that role becomes durable will depend on more than technical strength alone. It will depend on whether the region's advantages in measurement-, photonics-, and validation-facing layers are reinforced by shared test and integration capacity, mission-linked qualification pathways, clear institutional roles, and a capital stack that funds not only firms but also the regional public goods on which repeatable system assembly depends. The Mountain West has enough evidence of capability, institutional traction, and emerging coordination to make that outcome plausible. It is not there yet. The practical task is to turn partial strengths into repeatable, outward-facing system-building capacity that others in the wider quantum system increasingly need.

Conclusion

A frontier is a boundary—between what is known and what is not, between aspiration and capability, between a laboratory demonstration and a technology that can be trusted in the world. In that sense, the quantum frontier is not simply the bleeding edge of science. It is the point at which quantum effects are converted into reliable systems: calibrated, ruggedized, validated, integrated, and maintained—credible enough to become part of how economies measure, decide, and operate. If the Mountain West is to be a quantum frontier in more than a rhetorical sense, it will not be because the region can claim the largest share of quantum activity or the most dramatic breakthroughs. It will be because it occupies a more exacting and, in the long run, more consequential position: close to the layers where fragile performance must become trusted capability.

That is the central diagnosis of this report. Quantum progress is best understood as system formation, not a linear race for scale. The field is reorganizing around platforms and layers that make quantum effects usable: photonics and precision components, control and readout, software abstractions, calibration regimes, and the integration work that binds delicate phenomena into repeatable performance. This is why the language of races obscures more than it reveals. Races suggest a single track and a finish line. System formation produces multiple pathways, uneven maturation, shifting leverage, and strategic advantage that often accumulates far from the most visible milestone. In that environment, influence accrues disproportionately to the actors, institutions, and places that solve the hard, unglamorous problems of deployment—because those solutions become the shared scaffolding on which many downstream applications depend.

Quantum sensing brings this logic into sharpest focus because it is the application area where operational reality arrives early and unavoidably. Sensing systems do not remain pristine. They face vibration, drift, temperature variation, electromagnetic noise, size-weight-power constraints, calibration burdens, qualification requirements, and the simple fact that users must trust what a system says before they will rely on it. That confrontation is not a detour from progress. It is progress in a field that must ultimately function outside the laboratory. The implication is straightforward but often missed: the binding constraint on quantum impact is not whether a phenomenon can be demonstrated, but whether a capability can be trusted—reliably measured, repeatedly validated, integrated into workflows, and sustained over time. This is commercialization as system assembly, and it is where much of the real strategic competition is now being waged.

That is also why the Mountain West matters. The region does not need to lead every part of quantum technology to play a nationally significant role in it. The more relevant question is whether it can become indispensable in the parts of the system where credible progress is forged into deployable capability: where measurement is stabilized, platforms are integrated, systems are qualified, and operational trust is built. On the evidence presented here, that is not a speculative claim. It is a plausible, evidence-backed regional role. The Mountain West's advantages are not generic, and they are not evenly distributed. They are concentrated in sensing and measurement-adjacent enabling layers, and they are expressed through an unusually complementary structure: Colorado's scale, private-sector momentum, and platform-building depth; New Mexico's mission-oriented laboratory infrastructure, engineering capability, and validation environments; and Wyoming's potential supporting role within a broader regional system. Few regions combine those assets at meaningful scale and with direct relevance to deployment-facing layers of the stack.

But an advantage of this kind is not self-executing. It does not compound simply because it exists. System-assembly advantage is inherently fragile when it remains dependent on heroic, one-off integration efforts, on a narrow band of institutions, or on a short burst of funding attention. It becomes durable only when it is converted into repeatable capacity: shared environments for iteration and validation, calibration and standards regimes that make performance comparable and trusted, interfaces that reduce integration friction, procurement and qualification pathways that give promising systems room to mature, and financing structures that support trust infrastructure as well as firms. In other words, the Mountain West's opportunity is not merely to participate in quantum's growth. It is to institutionalize what remains scarce across the field as a whole: the connective tissue between invention and deployment.

That connective tissue is precisely what other regions and other countries are now trying to build. The competition is no longer only about who can publish, patent, or prototype. It is also about who can stabilize the stack, lower the cost of qualification, shape shared standards, create the environments in which performance becomes comparable, and build the routines through which emerging systems become easier to trust and harder to substitute. Early positional advantages in a field like this do not remain open indefinitely. They either harden into durable system roles, or they dissipate as other places build the institutional and industrial architecture to do the same work more coherently.

This framing also clarifies the real failure mode. The Mountain West should not mistake visible activity for durable influence. Patent volume, headline demonstrations, national designations, and episodic investment surges all matter, but none of them is sufficient. A region can appear dynamic and still remain strategically thin if shared infrastructure is underbuilt, if calibration and validation capacity remain fragmented, if role clarity across public partners, labs, firms, and mission users does not take hold, or if the strongest firms advance while the broader system remains too brittle to reproduce their progress. In a system-assembly field, fragmentation is not a nuisance. It is one of the main ways promising positions fail to mature.

The opportunity identified in this report is therefore narrower than the rhetoric around quantum often suggests, but more consequential for that reason. The Mountain West is not being presented here as a place that can do everything. It is being presented as a place that could matter disproportionately if it builds around what the evidence says it already has: strength in the layers where quantum becomes testable, trusted, and usable in practice. For ASCEND-relevant pathways, that means something especially important. The environmental, infrastructure, and decision-system applications that motivated this work will not mature simply because better measurements are technically possible. They will mature when those measurements can move through calibrated, validated, integrated systems that users trust enough to embed in real workflows. The wider quantum diagnosis and the narrower ASCEND technology opportunity are therefore not separate stories. They meet in the same technical and institutional layers.

A serious call to action follows from that diagnosis, even if it need not be stated as one. The question is no longer whether the Mountain West is “in” quantum. It clearly is. The question is whether the region’s strongest institutions and partners will treat its current position as consequential enough to build around with discipline, patience, and coherence—whether they will treat measurement, validation, integration, and deployment pathways as first-order strategic assets rather than as secondary supports to invention. In a field as contested, interdependent, and hype-prone as quantum, seriousness is itself a differentiator. So is patience. So is the willingness to build shared capacity before all returns are legible.

The frontier, in short, is not where quantum is most advanced in principle. It is where quantum becomes reliably usable in practice. The Mountain West’s evidence-backed path to influence is to become a place where qualification becomes faster, interfaces become more stable, measurement becomes more trusted, and deployment becomes more plausible—not once, but repeatedly enough that others increasingly need what the region can supply. That is a narrower ambition than generic claims of leadership. It is also the one most likely to matter.

Technical Appendix

Overview

This appendix documents the analytic choices that underpin the report's empirical findings and interpretive claims. Quantum patent landscape analysis is method-sensitive; results depend materially on how the corpus is constructed, how inventions are deduplicated and time-assigned, how technologies are tagged and counted, and how geographies and organizations are attributed. The purpose of this appendix is therefore twofold: (i) to situate this study's design relative to prior art and known measurement challenges, and (ii) to provide a transparent audit trail of the data sources, construction steps, counting conventions, and structural measures used throughout the report.

The appendix is organized into three parts. Section A summarizes key methodological challenges and the norms established in prior quantum landscape work. Section B specifies how this study operationalizes those norms: data sources, family construction, the corpus definition, tagging rules, and attribution conventions. Section C introduces a complementary structural layer—Generativity and Emergence indices—designed to interpret technologies and platforms by role and trajectory rather than volume alone.

A. Methodological context and prior art

Patent data is an imperfect proxy for innovation, but it remains one of the few global, structured, time-resolved datasets that can support ecosystem-level mapping: technology adjacency (via classification and text), actor participation (via applicants and inventors), and strategic behavior (via where and how broadly inventions are protected).

In quantum technology, however, patent landscaping is unusually sensitive to methodological choices. The difficulty is not a single bias that can be "corrected," but the fact that quantum is simultaneously nascent, cross-disciplinary, and terminologically unstable, while patent classification systems and publication practices differ across jurisdictions.[140]

For these reasons, a quantum patent landscape is not passively "found" in data; it is constructed through explicit boundary and counting choices. This section reviews recent efforts to define and measure this technology space, the challenges analysts faced, and the solutions they developed. This context leads directly into the description of how this study approached the same challenges to achieve the specific objectives of this project.

A.1 Recurring challenges documented in the literature

Prior patent landscape work across quantum computing, communications, and sensing converges on a consistent set of measurement challenges:

- **Classification sparsity and lag:** Dedicated quantum subclasses exist in some areas, but coverage remains incomplete—especially for sensing modalities and enabling platforms. Classification updates also trail technical evolution, creating systematic blind spots for emerging architectures.[141]

- **Cross-disciplinarity and enabling-platform spillover:** Quantum-relevant inventive activity spans optics/photonics, semiconductors, measurement and control, cryogenics, materials, and instrumentation. This dispersion makes single-code retrieval structurally insufficient and complicates decisions about what should count as “quantum” versus “quantum-enabling.”[142]
- **Keyword ambiguity (false positives and false negatives):** Broad terms (e.g., “quantum”) can be noisy, while many relevant inventions rely on architecture-specific language (e.g., “NV center,” “optically detected magnetic resonance,” “transmon”) without consistently using “quantum” in prominent fields. This pushes credible studies toward curated vocabularies, synonym expansion, and contextual exclusions.
- **Family-definition sensitivity:** Even before “quantum” is defined, “one invention” must be defined. Patent families differ materially depending on the definition. The EPO distinguishes DOCDB simple families (applications covering the same technical content) from INPADOC extended families (applications covering similar, not necessarily identical, content linked through direct or indirect priority relationships). These definitions imply different deduplication behavior and can change measured volumes and collaboration rates.[143]
- **Geographic comparability and internationalization:** Filing behaviors differ by jurisdiction, with domestic-only propensity, translation availability, and the likelihood of pursuing multi-jurisdictional protection varying systematically. Cross-country comparisons, therefore, depend heavily on whether the analysis emphasizes all patent families or only those with broader international protection.[144]

Discrepancies across quantum patent landscapes are not automatically errors. They are often artifacts of different, defensible construction choices (field definition, family standard, counting rule, geography assignment, and internationalization filter).

A.2 Family construction and its analytic consequences

Because patent families are central to deduplication and comparability, family definitions must be treated as first-order methodological choices rather than as metadata. DOCDB simple families are intended to approximate “same invention, same technical content,” while INPADOC extended families are intentionally more inclusive, allowing linkages through broader priority-claim networks and capturing related filings whose technical content may be similar rather than identical.

In quantum, the tradeoff is consequential. More inclusive family definitions tend to:

- reduce jurisdictional double-counting and better represent “innovation programs” pursued across filings, but
- increase the likelihood that related-but-not-identical filings are treated as a single observation.

A rigorous methodology must therefore disclose and defend (i) which family definition is used for the unit of analysis, and (ii) how that choice interacts with the study's purpose (ecosystem structure vs. claim-level adjudication).

A.3 Internationalization as a comparability device

Recent OECD–EPO work has placed internationalization at the center of interpreting the quantum ecosystem through international patent families (IPFs). In "Mapping the global quantum ecosystem," the OECD distinguishes IPFs from non-IPFs and defines an IPF as "a set of published patent applications filed with at least two authorities, the EPO or under the Patent Co-operation Treaty (PCT) to protect the same invention," while non-IPFs are families filed with a single authority.[145]

Two methodological claims in the OECD–EPO framing are especially relevant for policy-facing comparisons:

- Grouping applications into families allows filings for the same invention to be treated as a single observation.
- Focusing on IPFs "neutralizes national biases," enables more meaningful international comparisons, and provides a selection of higher-value patents (inventions applicants judge worth protecting beyond a single jurisdiction).

The EPO has also used international patent families in its technology insight reporting, describing them as patent documents for the same or similar inventions "published by at least 2 patent authorities."[146]

The policy implication is straightforward: national leadership looks materially different when measured by all families versus internationalized families, and a credible ecosystem assessment should expose that difference rather than bury it.

A.4 Structural views of the quantum technology landscape

A growing subset of quantum landscape reports goes beyond corpus construction and national rankings to say something about the structure of the field—typically by decomposing activity into domains and subfields, and by describing actor portfolios across those segments. Early landscape work often treats structure as a taxonomy: quantum is divided into distinct technology areas (e.g., telecommunications, computation, sensing, timing), and each area is analyzed separately.[147] More recent work extends this framing by explicitly incorporating enabling technologies and adjacent contributors into the definition of the ecosystem, reflecting that quantum innovation is not confined to three domains.[148]

Sector-specific reports also introduce structural segmentation at a finer grain. For example, sensing-focused analyses often partition activity by application subfields (e.g., time, magnetic fields, imaging), acknowledging that "quantum sensing" is not a single coherent pathway but a family of device classes and measurement modalities.[149] Similarly, white papers summarize activity and actors by domain (computing/communications/sensing) and track trends and leading organizations within each segment.[150] A smaller set of studies attempts to capture structure through flows and linkages, rather than categories alone. The OECD–EPO report, for example, includes an analysis of “diffusion of quantum innovation” using citation flows, and presents volumes alongside concentration and specialization patterns, explicitly noting dependencies in parts of the ecosystem.[151] These approaches offer meaningful signals about where knowledge and portfolio activity concentrate.

However, even where reports discuss “enabling technologies,” “dependencies,” or diffusion, structure is often presented primarily as segmentation and aggregation—counts, shares, and leading actors within predefined buckets—rather than as a systematic account of system roles. Most studies are strong at answering who is active, where, and in which domain, but provide less guidance on questions such as: which technologies appear to function as cross-cutting enablers; which clusters behave as bottlenecks or integration interfaces; and which niches are sharpening rapidly without yet being broadly coupled to the rest of the system.

This gap matters most for subnational innovation policy. National-level rankings and domain shares can inform “where the field is headed,” but they are less actionable for decisions about what capabilities to build locally—such as testbeds, instrumentation and metrology infrastructure, supply-chain nodes, specialized workforce pipelines, or translational assets that connect fragile quantum effects to fieldable systems. Without analytic tools that clarify structural roles (not just scale), regions can over-weight visible volume and underinvest in the enabling foundations and integration functions that often determine whether quantum capabilities become operational and economically consequential.

* * *

Prior work on landscape studies of quantum technology implies two requirements for a quantum ecosystem assessment to be interpretable and policy-relevant. First, the analysis must be transparent and comparable: field boundaries should be treated as constructed and documented; family definitions and counting conventions should be explicit; and internationalization should be treated as a first-order lens. Second, the analysis must be structurally informative: beyond segmentation into domains and subfields, it should clarify how technologies and platforms function within the system—distinguishing enabling foundations, integration interfaces, and emerging niches in ways that are actionable for program design and place-based capability building.

The sections that follow operationalize these requirements. Section B documents the study’s specific construction choices—data sources, family construction, two-stage corpus definition, tagging rules, attribution conventions, and comparability lenses—so that the empirical basis of subsequent results is transparent. Section C then introduces a complementary structural layer: network-derived measures that characterize the role and trajectory of CPC-coded technologies within defined platforms and time horizons. Together, these elements translate an inherently method-sensitive landscape into an analytic framework that supports interpretation not only of scale and shares, but of system function and evolution within the quantum technology space.

B. Study design and analytic intent

This study builds on the methodological norms that have emerged from that literature—hybrid retrieval, family-level deduplication, segmentation by domain and platform, and explicit attention to internationalization—but implements them in a way that is transparent and scalable within the constraints of this project. The design is oriented toward directional, system-level inference about quantum ecosystem structure: how inventive activity is distributed across domains; how enabling platforms overlap across domains; how participation varies across geographies and organizations; and how specific technologies and platforms appear to generate leverage within the broader quantum system.

Methodological choices throughout the appendix are oriented toward four goals:

- Transparent construction of a quantum patent corpus that is explicitly bounded;
- Reproducible tagging and attribution rules that preserve overlap;
- Interpretability of cross-country and cross-actor comparisons; and
- Structural analysis of the quantum invention record, enabling the identification of enabling platforms and emerging niches beyond what raw counts alone can show.

The study is not intended to adjudicate the technical validity of individual patent claims, nor to assert a definitive boundary for “quantum” inventions at the margin. Results should be interpreted as comparative signals about system structure, participation, and trajectories within the defined corpus and counting conventions.

B.1. Data sources and tools

Patent records were retrieved from The Lens (Cambia) via API export in August 2025. The export included patent family identifiers, bibliographic metadata, CPC classifications, and a text corpus used for term-based screening and tagging.[152]

Patent party names and locations were standardized and cross-validated using:

- USPTO PatentsView (party records and related normalization support),[153] and
- OECD patent datasets and products, including REGPAT, HAN/HARN, and TPF (for location standardization, name harmonization support, and cross-referencing).[154]
- A limited subset of parties was additionally cross-checked using Infobel to support selective ownership-related validation where subsidiary relationships or corporate restructuring were suspected.

Data processing and corpus construction were implemented primarily in R, using standard data wrangling and text processing libraries (e.g., data.table, dplyr, stringr) and hashing utilities to deduplicate text segments. Entity clustering for conservative name reconciliation was performed using OpenRefine. Non-Latin party names were transliterated and machine translated via the Google Translate API to produce Latinized strings suitable for matching.

B.2 Unit of analysis, family construction, and time assignment

The unit of analysis is the invention, operationalized as a patent family. Patent documents were grouped into inventions using Lens's INPADOC-defined "extended patent families," an inclusive family construct intended to deduplicate across jurisdictions and patent authorities.[155] This supports ecosystem analysis by reducing jurisdictional double-counting while retaining broad coverage of related filings pursued as part of an invention program.

Each invention is assigned to a year using the earliest priority date of the first filing in the family. This convention anchors activity to the earliest disclosed inventive event and reduces sensitivity to downstream publication and national-phase timing. The analysis focuses on inventions with earliest priority dates on or after January 1, 2010.

The study uses whole counts throughout (no fractional allocation). Whole counting is used intentionally to preserve visibility into overlap and convergence: a single invention may carry multiple CPC codes, match multiple domain vocabularies, involve multiple geographies, and list multiple applicants/assignees. *As a result, disaggregated totals (e.g., by domain, platform, sponsor, or geography) can exceed the count of unique inventions.*

B.3 Three-stage corpus construction

Quantum patent landscaping is highly sensitive to boundary choice. To define the global quantum technology landscape, this study adopts a multi-stage positive-unlabeled learning architecture. Unlike traditional Boolean patent searches, which are static and prone to human bias, this approach combines deterministic taxonomic filtering with iterative, probabilistic natural language processing (NLP). The retrieval process functions as a concentric expansion, starting from a nucleus of certainty and expanding outward to capture emerging and unclassified innovations until a point of mathematical stability is reached.

This construction of the final corpus entails three discrete stages:

Stage 1: High-recall candidate corpus

A candidate corpus is constructed by exporting, from Lens, inventions (extended patent families) meeting at least one of two criteria:

1. **CPC-title screen:** the patent family includes at least one patent document tagged with a CPC code whose official CPC title contains the term "quantum" (over 160 such CPC titles), supplemented by a curated list of adjacent CPC codes associated with quantum-enabling platforms and device classes (e.g., those that cover Raman scattering, atomic clocks, quantum key distribution, optical pumping, etc.); and/or
2. **Full-text seed screen:** the invention includes at least one patent document whose full text contains high-signal quantum terms (e.g., "quantum," "qubit", "entanglement," "superposition," "SQUID," "transmon," and other seed terms) gathered from controlled vocabularies/dictionaries provided by pure-play quantum technology companies, industry groups, and patent authorities.

The candidate corpus is intentionally over-inclusive. Its purpose is to bound downstream screening within a plausibly quantum-adjacent universe rather than the global corpus.

Stage 2: Taxonomic and semantic anchoring

From the candidate corpus, patent families that certainly relate to quantum computing, quantum communications, or quantum sensing are identified using two complementary algorithms that combine CPC code tags with text-based keyword searches, each specific to established quantum technology typologies. The combination of outputs from these two search pathways produces a high-confidence corpus of quantum inventions.[156]

Pathway A — Taxonomic and syntactical intersection. The foundational quantum corpus is established by a strict, high-precision filter that eliminates false positives entirely. This corpus is created by subsetting the candidate universe in two steps:

1. **Hierarchical classification:** Patent families labeled with CPC codes that strictly denote quantum hardware, quantum cryptography, and atomic physics are isolated and grouped into defined quantum categories. Categories are not mutually exclusive, so families can belong to more than one.
2. **Syntactical proximity:** The text of documents in these CPC-tagged patent families is then scanned for category-specific keywords and terms. A patent family is only accepted into the foundational corpus if specific constituent technologies (e.g., “Josephson junction,” “nitrogen-vacancy center”) appear within a precise word-distance of defining quantum terminology.

This pathway creates a “ground truth” corpus of patent families that are *definitionally* quantum technologies.

Pathway B — Context-aware semantic anchoring. A bounded semantic search is conducted to capture inventions that may lack a specific CPC classification but contain high-signal anchor terms. This corpus is constructed in two steps:

1. **Polysemy resolution:** A "negative lookahead" algorithm is used to filter out patent families in the candidate corpus that only use “quantum” in the context of conventional technologies (e.g., “quantum well efficiency” in standard LEDs). This ensures that the term “quantum” is used only in relevant physical contexts.
2. **Domain fingerprinting:** The text of documents in this “resolved” universe is then searched for “anchor terms”—phrases that are unique to the field (e.g., “Bell state,” “No-cloning theorem,” “Hamiltonian simulation”). Patent families that contain mentions of anchor terms and are tagged with CPC class codes (more general than the codes used in Pathway A) are retained.

This pathway bridges the gap between the rigid patent office classifications and the fluid, evolving language used by inventors.

These pathway counts provide interpretive transparency: they expose how much of the universe depends on CPC classification anchors versus text evidence.

Stage 3: Iterative probabilistic expansion

The final phase involves an iterative NLP loop that allows the corpus to define itself. The combined outputs of stages 1 and 2 are treated as a training set to discover relevant documents that human-defined or CPC-dependent queries might miss. The objective is to expand the analytic universe by bootstrapping from the unique vocabulary used to describe innovation in quantum technology.

1. **Lexical feature extraction:** The vocabulary of the training set is compared to the remainder of the candidate corpus. Using keyness statistics and log-odds ratios, terms that are over-represented in the training set are identified with high confidence for each type of quantum technology (computing, communications, and sensing).
2. **Dual scoring:** Each invention in the candidate corpus is scored on two dimensions:
    - **Breadth:** The diversity of quantum vocabulary present in the documents' text.
    - **Intensity:** The frequency of those quantum terms in the documents' text.
3. **Geometric thresholding:** Inventions that score above the geometric "elbow" of the score distribution for both breadth and intensity are added to the quantum corpus. This dynamically identifies the inflection point at which a high-relevance signal gives way to noise, creating a mathematically justified cutoff for inclusion.
4. **Convergence:** This process is iterative. The new inventions are added to the training set, and the vocabulary analysis is re-run. The loop repeats until the Jaccard similarity index stabilizes across iterations, indicating that the universe has fully converged and no new distinct lexical clusters remain.

This approach overcomes the "classification sparsity" and "lag" that complicate quantum technology studies. The algorithm dynamically identifies relevant inventions through their lexical signatures—capturing an invention even if it is classified under CPC subclasses unrelated to known quantum technology CPC groups.

Overall, this approach to boundary construction ensures a corpus that is both maximally precise (anchored in verified physics and classification codes) and maximally complete (capturing novel terminology and unclassified patents through statistical convergence). It removes the limitations of static keyword lists, allowing the analysis to capture the true, evolving edge of the quantum technology frontier.

This text-based screening and tagging are performed on English-language fields (titles, abstracts, and claims) when available. Inventions lacking English text remain eligible through CPC anchors. Because the invention is defined as a family, a non-English domestic filing can also be captured indirectly when at least one family member (filed through, e.g., WIPO/EPO/USPTO, or otherwise published with English fields) contains text matching the vocabulary. This substantially mitigates language bias; however, inventions that are both (i) domestic-only in non-English jurisdictions and (ii) not captured by the CPC title/anchor screens may be underrepresented. In practice, less than 1% of patent families in the candidate corpus lack English text and at least one known quantum technology CPC anchor.

B.4 Domain tagging and classification

Inventions are tagged into three domains—quantum sensing, quantum communications, and quantum computing—using a hybrid rule system applied at the invention (family) level:

- **CPC-based tagging:** domain membership is indicated by the presence of domain-relevant CPC subclasses (anchors and device-class patterns).
- **Text-based tagging:** domain membership is indicated by matches to domain-specific vocabularies (phrases and abbreviations) applied to the cleaned title–abstract–claim corpus.

Domain tags are non-exclusive. An invention may be tagged to multiple domains when it contains multi-domain CPC signals and/or matches multiple vocabularies. Domain totals, therefore, represent participation/overlap counts, not mutually exclusive partitions of unique inventions.

The analysis includes a cryptography-related vocabulary to identify inventions that reference cryptographic methods. Post-quantum cryptography (PQC) is considered out of scope as a standalone adaptation pathway. To exclude PQC-only activity while retaining crypto-adjacent inventions coupled to engineered quantum systems (especially QKD-adjacent work), the study applies a cryptography-only exclusion rule:

- Inventions that match the cryptography vocabulary but do not match sensing, communications, or computing vocabularies—and are not otherwise captured through quantum CPC anchors—are removed from the final dataset.
- Cryptography-related inventions remain eligible when they are also coupled to other quantum domains and/or quantum CPC anchors (e.g., QKD components, single-photon systems, quantum communications infrastructure).

Cryptography is therefore used as a screening variable, not reported as a fourth quantum domain.

B.5 Internationalization and collaboration lens

As mentioned in subsection A.3, recent reports on quantum patenting activity treat internationalization as an explicit analytic lens to distinguish domestically anchored activity from cross-border integrated activity. The OECD has done this by focusing its quantum analysis on “international patent families” (IPFs).

This report incorporates an explicit internationalization dimension conceptually adjacent to IPFs, while emphasizing ecosystem participation and cross-border integration. Specifically, inventions are separated into:

- **Multinational collaboration / internationalized inventions:** inventions that (i) have a multi-country nexus (inventors or applicants located in more than one country) and

(ii) show multi-jurisdiction protection (filings in more than one jurisdiction via family members' authorities); versus

- **Single-country origin inventions:** inventions whose nexus is confined to a single country.

This decomposition is used to interpret country-level portfolios not only by volume but by the degree to which inventive activity and protection strategy are internationally distributed. Because this study uses whole-count nexus assignment, inventions in the multinational category may contribute to multiple countries (each country linked by inventor/applicant nexus)—allowing for closer analysis of international collaboration—while single-country origin inventions contribute only to their single nexus country. In practical terms, this approach functions as a policy-relevant complement to the OECD–EPO IPF/non-IPF distinction: IPF status captures the breadth of *protection across authorities*, while the collaboration lens captures *cross-border participation in invention* and sponsorship, alongside filing breadth.

B.6 Geographic attribution and sponsor attribution

Unless otherwise stated, geographic results are based primarily on inventor geography. Inventor-based attribution is used to reflect the locus of inventive activity and technical capability. Geographies are derived from inventor addresses where available and geocoded through the standardization pipeline described below.

Patent families often link multiple countries and regions (international teams, multinational applicants, and multi-jurisdiction protection). Inventions are therefore assigned wholly to each geography with which they have a nexus, defined as the presence of at least one inventor address and/or applicant/assignee address in that geography. This convention supports ecosystem mapping by preserving visibility into cross-border collaboration and distributed invention activity.

As a result, geographic totals represent participation counts ("inventions with a nexus to geography X"), not mutually exclusive origin shares. Any table or figure that reports "share by country" should either (a) use language consistent with participation counts, or (b) provide a mutually exclusive view as a supplemental sensitivity analysis (not performed in scope).

Sponsor (applicant/assignee) reporting is tied to the inventor geography of the invention rather than the sponsor headquarters or the applicant address. Sponsor tables, therefore, answer: Which organizations are applicants/assignees on inventions invented in this geography? This convention separates "where invention occurs" from "who sponsors/owns the filings associated with that invention," which is often the policy-relevant distinction.

B.7 Party standardization, entity resolution, and ownership cross-checking

Applicant/assignee names were standardized to reduce duplication arising from language and script variation. Non-Latin spellings were transliterated and machine-translated into Latin characters (Google Translate API) to enable matching to Latin-script reference datasets and support consistent downstream cleaning.

Latinized party strings were matched where possible to standardized reference names in:

- OECD HAN/HARN resources, and
- USPTO PatentsView party records.

Not all names have matches in these reference datasets (particularly smaller firms, less-covered jurisdictions, and entities with recent renaming). Where a match exists, the standardized reference form is used as the canonical party name. Where no match exists, the best available Latinized spelling is retained and carried into deterministic cleaning.

Canonical and unmatched names were then standardized through deterministic cleaning:

- capitalization normalization,
- punctuation removal, and
- removal of legal suffixes and corporate designators (e.g., Inc., Ltd., GmbH, and equivalents).

The purpose of deterministic cleaning is to reduce superficial variation that would otherwise inflate counts and obscure participation patterns.

Names were then processed through OpenRefine clustering to reduce duplication from near-identical strings (spacing, punctuation, and abbreviation variants). Only conservative ("safe") clustering settings were used to minimize false merges (incorrectly consolidating distinct entities). This choice increases confidence that merged entities are genuinely the same, at the cost of leaving some true duplicates unresolved.

A limited subset of entities suspected to be subsidiaries or affected by corporate restructuring was cross-checked using Infobel to support ownership-related validation.

Sponsor results are reported using post-cleaning canonical names (not ultimate-parent roll-ups). Multi-applicant inventions are handled via whole-count participation: if an invention lists multiple applicants/assignees, each sponsor receives a count of 1 for that invention. Sponsor totals, therefore, reflect participation intensity rather than mutually exclusive ownership shares.

* * *

The methodological choices documented in Section B are intended to address known shortcomings of earlier approaches while remaining feasible within the project's scope. In particular, the study mitigates classification lag and terminology drift through a two-stage corpus design (high-recall candidate screen followed by hybrid refinement); improves comparability through family-level deduplication and priority-year assignment; preserves visibility into convergence by using non-exclusive tagging and whole-count participation measures; and treats internationalization explicitly, distinguishing domestically anchored activity from cross-border integrated invention and protection strategies.

These choices also define how results should be interpreted. The findings are best read as comparative, system-level signals—robust for identifying persistent patterns across domains, platforms, geographies, and actor types, and less suitable for precision claims at the boundary of field definition. Several constraints follow directly from the design:

- **Constructed field boundary.** The quantum corpus is constructed through a high-recall candidate screen and hybrid refinement (CPC anchors and text vocabularies). Boundary noise at the margin is expected; the corpus is intended to be directionally correct for ecosystem-level pattern analysis rather than definitive classification of every individual invention.
- **Non-exclusive counting and overlap.** Domain tags, CPC assignments, sponsor participation, and geographic attribution are non-exclusive and whole-counted. Disaggregated totals may therefore exceed unique invention counts; reported "shares" should be interpreted as participation/overlap measures unless explicitly stated otherwise.
- **Inventor-centric geography and sponsor-by-inventor attribution.** Geography is anchored primarily to inventor location (locus of inventive activity). Sponsor tables reflect which organizations appear on inventions invented in a geography, not sponsor headquarters or control location.
- **Language availability and family linkage.** CPC anchors and family linkage mitigate language bias, but domestic-only non-English families lacking quantum-specific CPC signals may be underrepresented.
- **Conservative entity resolution.** Party name standardization relies on transliteration/translation, external reference matching, deterministic cleaning, and conservative clustering; residual duplication is more likely among smaller entities and those with frequent renaming. Ownership roll-ups are not comprehensive.

Future work could increase confidence at the margin without changing the analytic approach by adding sensitivity checks (e.g., CPC-only vs text-only subsets; alternative family definitions), targeted manual audits on stratified samples to estimate boundary error rates, broader ownership roll-ups for sponsor analysis, and explicit quantification of English-field availability and jurisdiction coverage.

C. Generativity and emergence indices

This report introduces two related indices—Generativity and Emergence—to characterize the distribution of leverage among discrete technologies and platforms within the quantum technology corpus. The indices are designed to move beyond raw patent counts and provide interpretable signals about system structure and system change.

- **Generativity** identifies CPC-coded technologies that behave like enabling platforms: broadly connected to diverse adjacent technologies, positioned to bridge across the network, and not confined to a closed clique of near-neighbors.
- **Emergence** identifies CPC-coded technologies that appear nascent but accelerating: initially specialized/peripheral (not yet widely integrated) but showing rapid increases in activity and structural definition over time.

Both are constructed as composite indices of latent attributes that are not directly observable in patent data but can be observed by deriving metrics that describe the associations among technologies in the quantum technology patent corpus. In combination, these metrics are treated as observable proxies for the two latent attributes of interest.

This section documents how the component metrics are constructed and used to compute the two composite indices. It proceeds in the order the analysis is built: (i) constructing the CPC relatedness network from co-occurrence within inventions, (ii) deriving edge-level association metrics, (iii) aggregating these into CPC-level network statistics that capture distinct structural roles, and (iv) combining those statistics into the Generativity and Emergence indices.

C.1 Constructing the CPC relatedness network

Like the rest of the report, the base unit of analysis for generativity and emergence is the invention (patent family). In this section, however, the analytic focus shifts from invention-level attributes to the system-level role of CPC-coded technologies within the broader quantum technology space. The component metrics, therefore, create statistics at the level of individual CPC codes (i.e., technologies), derived from the co-occurrence of those codes across inventions.

To derive these component metrics, each invention is associated with one or more CPC codes. Both the generativity and emergence indices are built from component metrics that quantify attributes of the co-occurrence structure of CPC codes within each invention. In practice, this means that each component is computed for each CPC code based on its pattern of adjacency to other CPC codes across the invention corpus.

To reduce sparsity and stabilize network statistics, CPC codes are analyzed at the *subclass* level using a truncated CPC hierarchy, retaining only the portion before the "/". For example, G06N10/70 → G06N10. Furthermore, indexing scheme codes are assigned to their parent codes in the CPC hierarchy. For example, G06T2207 → G06N07. This aggregation yields approximately 1,800 unique CPC codes across the full quantum corpus (with lower counts within narrower platforms/domains).

This representation treats the set of 1,800 generalized CPC codes that appear on quantum technology inventions as a network whose nodes are technologies and whose edges reflect repeated co-classification within inventions. Both the nodes and edges are weighted by the count of inventions they represent in the corpus. (For edges, these weights are inverted in some measures so that larger weights represent shorter distances between nodes).

To begin, a CPC co-occurrence network is constructed as an adjacency table, and the following quantities are defined.

Let:

- T = total number of inventions in the quantum technology universe
- T_i = number of inventions in the universe that contain CPC i
- C_{ij} = number of inventions in the window that contain both CPC i and CPC j
- $N(i)$ = number of CPC js connected to CPC i (called the *degree* in network analysis)

From these:

$$P_{ij} = \frac{C_{ij}}{T}, \qquad P_i = \frac{T_i}{T}$$

are calculated to measure the share of inventions in the universe that contain each CPC i and in combination with CPC j.

Combinations of these core network metrics are used to compute the component measures defined in what follows.

C.2 Deriving component measures of association

The Generativity and Emergence indices each comprise component metrics that draw on multiple analytical traditions, including information theory (mutual information and entropy), normalized co-occurrence relatedness, and network science (centrality, transitivity, distance-based structure). Each component captures a distinct aspect of a technology's structural role in the quantum invention system—its strength of association with neighboring technologies, the breadth and diversity of its connections, its degree of local closure versus brokerage, and (for Emergence) the pace at which these properties and associated inventive activity are changing over time. Building on the CPC relatedness network described in Section C.1, this section introduces these component metrics, their mathematical and theoretical foundations, and their interpretation.

Association embeddedness

Two primary association measures are calculated for each CPC pair (i,j):

a. **Mutual information (MI)**, which is first calculated as **normalized pointwise mutual information (NPMI)**, given by

$$I_{ij} = \frac{log_2\left(\frac{P_{ij}}{P_i P_j}\right)}{-log_2\left(P_{ij}\right)}$$

This normalization of pairwise association reduces sensitivity to frequency and bounds the measure to a comparable scale (to $[-1,1]$).

From this, we can calculate **mutual information** (information aggregation), a weighted aggregation of NPMI across edges, as

$$MI_i = \sum_j I_{ij} \cdot P_{ij}$$

This captures how strongly CPC i is associated with its neighbors in information terms, while weighting by the prevalence of each co-occurrence. This term is bounded to $[0,1]$, where ≈ 0 indicates CPC i adds no unique information value to the network, and ≈ 1 indicates highly prevalent and highly specialized information value that signals structural importance.

b. **Relatedness**, and its several useful derivatives, is calculated by first finding a cosine-style co-occurrence relatedness, given by

$$R_{ij} = \frac{C_{ij}}{T_i \cdot T_j}$$

This captures the strength of association between CPC i and CPC j while normalizing for marginal prevalence.

From this, we can then define **mean relatedness** (R) as

$$R_i = \frac{1}{N(i)} \cdot \sum_j R_{ij} \cdot \mathrm{R}$$

This captures the relative *embeddedness* of CPC i in its local community—that is, among only the CPC js to which it is connected—as opposed to its embeddedness in the entire network, as measured by MI.

This can be extended to measure **relative density ($\boldsymbol{RD}$)**, where each co-occurrence R_{ij} is scaled relative to the typical connectivity of the neighbor j (i.e., co-occurrence strength relative to the neighbor's baseline), then averaged across neighbors. This results in a measure that is bounded to $[0, \infty]$, where a value ≥ 1 means i tends to connect to neighbors j more strongly than those neighbors typically connect to others, and a value ≤ 1 implies the opposite.

Ultimately, mutual information, mean relatedness, and relative density each signal the influence of a technology within the broader technology landscape. Mutual information reveals influence throughout the entire landscape, whereas mean relatedness and relative density do so within localized communities of connected nodes.

Association diversity

The procedure also computes entropy-like terms used to build a node-level diversity measure. This study uses a conditional form of this measure, given by

$$H_{ij} = -P_{ij} \cdot log_2\left(\frac{P_{ij}}{P_i}\right)$$

This term is used to characterize the dispersion of a CPC's adjacency distribution rather than its raw connectedness alone.

We can then calculate **normalized entropy ($\hat{H}$)**, where

$$H_i = -\sum_{j \in N(i)} H_{ij}$$

and

$$\widehat{H_i} = \frac{H_i}{log_2\big(N(i)\big)}$$

This term is bounded to $[0,1]$, where values ≈ 0 indicate that i's connections are highly concentrated (one/few dominant neighbors), and ≈ 1 indicate i's connections are broadly distributed (close to uniform across neighbors). This metric, therefore, describes the overall level of connectedness of CPC i to all js within its local network. In that way, it is similar to betweenness centrality, which is covered under the network-derived metrics.

Network-derived metrics

For each CPC i, the following node-level measures and metrics are derived from the co-occurrence network.

a. **Structural prevalence**: measures of relative size and overall connectedness:

  - **Degree:** number of distinct CPC neighbors (used in other metrics, above)
  - **Strength:** total co-occurrence volume across all neighbors
  - **Share:** share of inventions in the window that contain CPC i

b. **Graph position**: normalized graph-theoretic metrics of closure and brokerage:

  - **Transitivity ($\hat{T}$):** a weighted clustering measure capturing local closure (the extent to which a CPC's neighbors are themselves connected). High values indicate clique-like embedding; low values indicate more open neighborhoods.
  - **Betweenness (B):** computed on a distance transformation of weights (stronger co-occurrence implies shorter distance). High values indicate brokerage/bridging position between clusters or "cliques."

Change measures

Emergence is intended to capture not only a CPC-coded technology's current structural position but also whether it is changing rapidly—i.e., whether its association structure and activity are strengthening over time relative to peers. To represent this "first derivative" component, the methodology computes Δ change-rate measures for selected CPC-level metrics.

For a given component metric X, the Δ term is computed as the geometric mean of the most recent three year-over-year ratios, which is equivalent to a 3-year compounded annual growth factor (or CAGR)[157]:

$$\Delta X_t = \sqrt[3]{\left(\frac{X_t}{X_{t-3}}\right)} - 1$$

These component metrics translate the raw CPC co-occurrence structure into a set of interpretable descriptors of each CPC-coded technology's role in the quantum invention system. Pairwise association metrics (NPMI and relatedness) characterize the strength and informativeness of technological coupling; entropy-based metrics capture how concentrated or diversified a technology's adjacency profile is; network-position metrics distinguish locally closed, clique-like embedding from brokerage and system-level centrality; and change metrics provide a first-derivative signal of how quickly these properties—and associated inventive activity—are changing.

C.3 Subsetting by universe and time windows

The component measures defined in Section C.2 are not computed once for the quantum corpus as a whole. They are computed repeatedly within specific analytic universes and time windows, because the structural role of a CPC-coded technology is inherently contextual: a technology can be highly generative within one platform while relatively peripheral within another, and it can shift position over time as invention activity and technological coupling evolve. Section C.3 describes how the corpus is subset into these universes and windows, and how the resulting measures are normalized so they can be combined into composite indices in a consistent and interpretable way.

Analytic universes

Each of the metrics described in section C.2 is computed within multiple analytic universes defined by the report's clustering/segmentation scheme (e.g., the full quantum universe, each quantum domain, each platform/cluster, and selected sub-platforms such as lasers). This leads to the identification of more and less generative or emergent CPC-coded technologies within each universe.

Time-window regimes

Each of the metrics is also computed for multiple time windows, and two variants of the indices are generated:

- **Three-year trailing window (moving average, MA):** For year Y, the network is constructed from inventions with earliest priority year from $[Y-2, Y]$. This moving window is used to produce time-series measures that respond to changing structure and activity.
- **Cumulative window (since 2010):** For year Y, the network is constructed from inventions with earliest priority year $\leq Y$ (starting in 2010). This cumulative window produces a "long-run" view of network position and dampens year-to-year volatility.

The two regimes answer different questions:

- MA emphasizes recent structure and acceleration.
- Cumulative emphasizes persistent position and long-run embeddedness.

Where Δ ("change") metrics are used, they are meaningful primarily in the MA setting.

Percentile normalization

This universe-time window subsetting is directly relevant to the construction of the indices. Because the metrics described above vary with:

- corpus size,
- CPC prevalence,
- windowing regime, and
- platform/domain boundaries,

the analysis converts key CPC-level measures into within-universe percentile ranks (0–100).

For a metric X, the percentile rank X_P is computed from the rank ordering of CPCs in that universe. Percentiles represent relative standing within the universe. This is likewise done for change metrics, e.g., ΔX_P, with high Δ percentile values indicating CPCs whose structural measures (or activity) are increasing faster than peers within the universe.

These percentile rankings are computed within each universe and time window. Therefore, a score of 80 means “this CPC ranks in approximately the top 20% within this universe and time-window,” not “this CPC is absolutely more generative than CPCs in other universes.” These percentile ranks thereby allow comparisons over time within the same universe and provide a common scale for constructing composite indices. Cross-universe comparisons are conducted using contribution and intensity measures (described below in Section C.5), rather than directly comparing percentile values across universes.

In combination, universe subsetting, time-windowing, and within-universe percentile normalization define the comparison set against which “high” and “low” generativity or emergence are evaluated. They ensure that each CPC is assessed relative to the relevant platform/domain context and time horizon, rather than against raw magnitudes that are driven by corpus size, classification prevalence, or secular growth in patenting. The next section uses these within-universe percentile-ranked measures—computed under the moving-average and cumulative regimes—to construct the Generativity and Emergence indices reported throughout the report.

C.4 Composite index construction

Section C.4 combines the component measures defined in Sections C.2–C.3 into two composite indices using simple arithmetic. The objective is not to introduce additional complexity, but to make the interpretation of multi-dimensional network structure tractable: each index aggregates percentile-ranked measures that proxy distinct aspects of technological role (connectivity, diversity, brokerage, closure, and change). The resulting indices provide a compact way to compare CPC-coded technologies within a given platform and time window, while preserving the underlying intuition of the component measures.

Calculating the Generativity Index

Generativity is defined as an equal-weight composite of four percentile-ranked measures:

$$Generativity = \frac{\widehat{H_P} + R_P + B_P + \left(100 - \widehat{T_P}\right)}{4}$$

Following the intuition:

- $\widehat{H_P}$: diverse adjacency structure (broad recombination potential)
- R_P: strong overall association with neighbors (non-random integration)

- B_P: bridging position (cross-cutting leverage)
- $100 - \widehat{T_P}$: low clique closure (not trapped in a tight local subcommunity)

High generativity indicates a CPC that functions as a connector and enabler inside the platform/network.

Calculating the Emergence Index

Emergence is constructed in two steps. First, an “emergence potential” (EP) term captures specialization and early-stage positioning:

$$EP = \frac{MI_P + (100 - R_P) + (100 - B_P)}{3}$$

Following the intuition:

- MI_P: strong association structure (definition/specialization)
- $100 - R_P$ and $100 - B_P$: low integration and low brokerage (not yet widely embedded)

This is an intentionally “pre-integration” signal: a CPC can become emergent precisely because it is not yet central or broadly connected.

Emergence then combines emergence potential with multiple acceleration signals:

$$Emergence = \frac{EP + \Delta MI_P + \Delta RD_P + \Delta \widehat{H}_P + \Delta Inv_P}{5}$$

where ΔInv_P is the percentile rank of the invention-volume change for the CPC code.

This follows the intuition:

- ΔMI_P: increasing influence and specialization in the network
- ΔRD_P: increasing embeddedness in localized communities of technologies
- $\Delta \widehat{H}_P$: increasing diversity of connections (expansion of co-occuring technologies)
- ΔInv_P: relatively rapid growth in invention volume, consistent with intuitive concepts of emergence

A CPC appears emergent when it is initially specialized/peripheral and exhibits increasing activity and structural definition.

The novelty of this approach is that it treats a CPC-coded technology’s “strategic role” as a structural property of the ecosystem, inferred from patterns of co-classification and their evolution over time, rather than as a function of patent volume alone. Generativity and Emergence, therefore, enable a different class of insight: they distinguish technologies that matter because they are enabling connectors (high generativity) from those that matter because they are sharpening and accelerating (high emergence), even when both may have modest raw counts. In practical terms, this helps surface where leverage is likely to accumulate within and across platforms—identifying mature enabling foundations, emerging niches, and cross-cutting technologies that mediate recombination—providing decision-makers with a more interpretable map of system assembly than counts or growth rates can provide on their own.

C.5 Aggregation: platform/domain contribution and intensity

Percentile indices are CPC-level diagnostics. The report also requires platform/domain-level interpretation: which parts of the quantum universe disproportionately contribute to generativity or emergence relative to their volume. This is implemented through invention-weighted aggregation.

For a CPC i with invention count T_i in a universe-year window, define the **weighted mass** for an index Z_i as:

$$Z_i^{(w)} = Z_i \cdot T_i$$

Weighted masses are summed across CPCs in a group g (e.g., a domain or platform) to produce a group total

This permits the calculation of the **contribution share**. For group g relative to a reference universe U (e.g., the total quantum universe) in the same year/window:

$$ContributionShare_g = \frac{Z_g^{(w)}}{Z_U^{(w)}}$$

We can define the **invention share** as:

$$InventionShare_g = \frac{T_g}{T_U}$$

where T_g is total inventions in group g and T_U is total inventions in the reference universe.

With these quantities defined, we can now calculate the **intensity**:

$$Intensity_g = \frac{ContributionShare_g}{InventionShare_g}$$

The intensity metric is bounded to $[0, \infty]$, where values ≥ 1 indicate that the group contributes disproportionately to the index Z relative to its volume. This device is used to distinguish “large because large” from “strategically leveraged because structurally generative/emergent.”

* * *

The Generativity and Emergence indices provide a compact, system-level way to interpret quantum inventive activity as system assembly rather than merely as volume. They surface where leverage resides by distinguishing technologies that matter because they act as enabling connectors (high generativity)—supporting recombination across neighboring technology areas—from technologies that matter because they are sharpening and accelerating (high emergence)—gaining definition and activity even before they become broadly integrated. In this study, the indices are used to identify strategically positioned CPC-coded technologies within platforms and to compare how domains and platforms over- or under-contribute to system leverage relative to their invention volume through contribution and intensity measures. The result is a more interpretable map of the quantum technology landscape: not just what is large or fast-growing, but what appears structurally enabling, what is consolidating into distinct pathways, and where cross-cutting foundations may be accumulating.

These indices should be interpreted as structured proxies rather than definitive measures of technical merit, performance, or market readiness. They reflect patterns in patenting and classification behavior—co-classification practices, CPC schema evolution, and jurisdictional differences—as well as the corpus definition, CPC aggregation level, and time-windowing choices used to construct the relatedness network. The measures are therefore best read as comparative signals of role and trajectory within defined universes and time horizons. They are most persuasive when triangulated with domain knowledge and qualitative evidence elsewhere in the report.

Taken as a whole, the methodology is designed to produce comparative, system-level signals that are actionable for ecosystem interpretation: where inventive activity concentrates, how domains and platforms overlap, how participation varies across geographies and organizations, and which technologies appear structurally enabling or rapidly consolidating. The central contribution is to make boundary and counting choices explicit, and to complement scale-based reporting with structural measures that help distinguish enabling foundations from emerging niches and integration interfaces.

Readers should interpret results in light of three deliberate design features. First, the quantum corpus is constructed through a high-recall candidate screen and hybrid refinement; boundary noise at the margin is expected, but the corpus is designed to be directionally correct for ecosystem analysis. Second, many outputs use non-exclusive, whole-count participation (across domains, CPCs, sponsors, and geographies) to preserve overlap and convergence; disaggregated totals may therefore exceed unique invention counts. Third, the Generativity and Emergence indices are structured proxies derived from co-classification patterns and their evolution over time; they inform role and trajectory within defined universes and time horizons rather than technical merit, performance, or readiness.

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Endnotes

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[1] National Academies of Sciences, Engineering, and Medicine, *Quantum Computing: Progress and Prospects* (Washington, DC: The National Academies Press, 2019), 31–36. The report provides a definitive breakdown of these three non-classical phenomena (superposition, entanglement, interference) and how they fundamentally separate quantum computational paradigms from classical ones.

[2] Antonio D. Córcoles et al., "Challenges and Opportunities of Near-Term Quantum Computing Systems," *Proceedings of the IEEE* 108, no. 8 (August 2020): 1338–52. The authors detail the severe susceptibility of quantum states to environmental decoherence, framing the current era of quantum development largely around the complex "control problem" of shielding, manipulating, and measuring these states alongside classical electronics.

[3] National Science and Technology Council (NSTC), *National Strategic Overview for Quantum Information Science* (Washington, DC: Executive Office of the President, September 2018), 2–4. This policy document helped solidify the standard tripartite framework (computing, communications, and sensing) that currently organizes federal funding and strategic investment globally.

[4] National Institute of Standards and Technology (NIST), "Post-Quantum Cryptography," NIST Computer Security Resource Center. NIST clarifies the boundary between PQC (which relies on algorithmic, classical math defenses) and QKD (which utilizes the physical properties of quantum mechanics to secure communication channels).

[5] Kai Bongs et al., "Taking Quantum Sensors into the Real World," *Nature Reviews Physics* 1, no. 12 (December 2019): 731–39. The authors highlight that while quantum sensing is the most mature domain, the transition from lab to commercial deployment is bottlenecked entirely by the need for ruggedization, miniaturization, and systems integration.

[6] Stephanie Wehner, David Elkouss, and Ronald Hanson, "Quantum Internet: A Vision for the Road Ahead," Science 362, no. 6412 (October 19, 2018). The authors illustrate why computing and communications are fundamentally structurally linked, noting that distributed quantum computing and secure quantum networks rely on the exact same underlying entanglement generation, photonics, and repeater architectures.

[7] World Economic Forum (WEF), *State of Quantum Computing: Building a Quantum Economy* (Geneva: WEF, September 2022), 11–13. This report substantiates the concept of "enabling capabilities," documenting how innovations in precision measurement and algorithmic error mitigation recursively benefit sensing, communications, and computing simultaneously.

[8] Center for a New American Security (CNAS), *Quantum's Industrial Moment* (Washington, DC: CNAS, March 2026). From a policy and economic development perspective, the bottlenecks in this foundational layer represent a "self-reinforcing industrial gap." Because early-stage demand remains fragmented, private investment in specialized, quantum-grade component manufacturing is suppressed. Addressing this requires targeted public infrastructure investments—such as regional "Quantum Foundries" and the NSF-led National Quantum Virtual Laboratory—to provide startups with shared access to commercial-grade materials and microfabrication facilities, thereby lowering prohibitive capital barriers.

[9] Sandia National Laboratories, *Silicon Photonics: Leveraging CMOS Manufacturing for Quantum Information Science*, SAND2024-1104R (Albuquerque, NM: U.S. Department of Energy, 2024). Photonic Integrated Circuits (PICs) represent one of the highest-leverage investment areas. Because integrated photonics can largely leverage existing semiconductor manufacturing methodologies (CMOS compatibility), advances in this layer can scale rapidly.

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[10] U.S. Department of Energy, “Technical Areas,” DOE National Quantum Information Science Research Centers. The DOE and NSF consistently highlight precision metrology as the critical "calibration infrastructure" of the quantum economy. Without standardized, highly accurate optical stabilization and spectroscopy, it is incredibly difficult to independently benchmark custom quantum prototypes. Public investment in this layer effectively acts as a public good, establishing the shared testbeds and metrology standards that allow the entire industry to validate and commercialize their hardware.

[11] Future Markets Inc., *Quantum Sensors Market Report 2026-2046: Size, Share & Forecast* (February 2026). Magnetometry and interferometry are the most immediate vector for commercial return on investment (ROI). These technologies are actively transitioning out of the lab into dual-use markets, driven by immediate defense and aerospace demand for GPS-denied navigation, as well as civilian applications in environmental monitoring, resource extraction, and medical imaging. This establishes the near-term, high-volume contract pipelines necessary to sustain early-stage quantum hardware suppliers.

[12] National Science Foundation (NSF), *Expanding Capacity in Quantum Information Science and Engineering* (ExpandQISE) (Alexandria, VA: NSF, 2025). From a funding perspective, the explosive growth in quantum software startups often masks underlying hardware fragility. Because software avoids the massive capital expenditures (CapEx) of physical fabrication, it attracts private venture capital more easily. Economic developers must be careful not to mistake software-layer velocity for overall system maturity; public funding remains vital for the capital-intensive lower layers that private markets hesitate to de-risk.

[13] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies: Navigating the Valley of Death* (Washington, DC: The National Academies Press, 2024), 45–52. Systems integration and ruggedization are the primary bottlenecks for tech transfer. Initiatives like the NSF Convergence Accelerator are specifically designed to fund this exact interface work—forcing collaboration between quantum physicists and classical systems engineers to translate laboratory phenomena into deployable, field-ready hardware.

[14] Organisation for Economic Co-operation and Development (OECD), *Quantum Technology Policies: Fostering Innovation and Scale-up* (Paris: OECD Publishing, 2025). This structural reality dictates that smart regional economic development should avoid prematurely "picking winners" among vertical end-uses (e.g., funding a startup that only does quantum maritime navigation). Instead, regions build more resilient innovation ecosystems by funding horizontal, shared-platform infrastructure—such as quantum testbeds or microfabrication foundries—that support a wide array of downstream applications.

[15] NSTC, *National Quantum Initiative Supplement to the President's FY 2026 Budget* (Washington, DC: Executive Office of the President, 2025). This concept of overlapping dependencies is crucial for federal strategic planners. It means that targeted investments in shared components—like advanced photonics manufacturing or cryogenic cables—yield immense collateral benefits across computing, sensing, and communications simultaneously, effectively maximizing the return on public research dollars.

[16] Nathalie P. de Leon et al., ”Materials Challenges and Opportunities for Quantum Computing Hardware,” *Science* 372, no. 6539 (April 16, 2021): eabb2823. See also McKinsey & Company, *Quantum Technology Monitor* (New York: McKinsey & Company, April 2024), which highlights the intensive capital requirements of the foundational hardware layer.

[17] European Patent Office (EPO) and OECD, *Mapping the Global Quantum Ecosystem* (Munich: European Patent Office, 2025). This report tracks the centrality and exponential growth of foundational patent filings. See also Quantum Industry Consortium (QuIC), *A Portrait of the Global Patent Landscape in Quantum Technologies* (January 2024), 5–7.

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[18] de Leon et al., “Materials Challenges and Opportunities,” eabb2823. The authors extensively document how surface roughness, impurities, and material defects act as primary sources of noise and decoherence, severely limiting fabrication reproducibility across runs.
[19] McKinsey, *The Year of Quantum*: *From Concept to Reality in 2025* (New York: McKinsey & Company, June 2025), 4–6. The report emphasizes the current industry shift from simply maximizing qubit counts to stabilizing them, noting that precision manufacturing, regional infrastructure "clusters," and error-correction are the critical prerequisites for achieving commercial scalability.
[20] Christian L. Degen, F. Reinhard, and P. Cappellaro, “Quantum Sensing,” *Reviews of Modern Physics* 89, no. 3 (July 2017): 035002. This foundational review outlines how techniques like magnetometry and interferometry act as the bridge between fragile quantum states and macroscopic observability.
[21] European Patent Office and OECD, *Mapping the Global Quantum Ecosystem* (Munich: European Patent Office, 2025). The report specifically notes the high "degree of transversality" of measurement and optical readout patents, indicating their frequent co-assignment and cross-citation across computing, sensing, and cryptography domains.
[22] Kai Bongs et al., “Taking Quantum Sensors into the Real World.” The authors detail the severe engineering hurdles—specifically temperature fluctuations, vibration, and EMI—involved in transitioning quantum metrology equipment from highly controlled laboratory environments to field-deployable commercial devices.
[23] WEF, *Quantum Computing Governance Principles* (Geneva: WEF, January 2022), 14–17; and NIST, "Quantum Information Science and Technology (QIST) Standards," ongoing initiatives. Both sources underscore the critical bottleneck caused by the lack of globally standardized benchmarking protocols and qualification environments, which deters commercial adoption and risk assessment.
[24] McKinsey, *Quantum Technology Monitor*. The report highlights that quantum software and services consistently capture a growing share of startup creation, largely because they avoid the massive capital expenditure (CapEx) required for hardware fabrication facilities.
[25] National Academies of Sciences, Engineering, and Medicine, *Quantum Computing*: *Progress and Prospects*, 115–20. This consensus study emphasizes the absolute necessity of hybrid quantum-classical architectures, noting that quantum processors function effectively as co-processors requiring robust classical infrastructure for control and readout.
[26] Frederic T. Chong, Diana Franklin, and Margaret Martonosi, “Quantum Computing for Computer Architects,” *Communications of the ACM* 60, no. 10 (September 2017): 70–74. The authors detail the concept of “thin” or “leaky” abstractions in quantum computing, explaining how the lack of standardized architectures forces developers to perform intensive, hardware-specific optimization for every deployment.
[27] John Preskill, “Quantum Computing in the NISQ Era and Beyond,” *Quantum 2* (August 2018): 79. In this foundational paper, Preskill argues that while software-based error mitigation is vital for extracting value from Noisy Intermediate-Scale Quantum (NISQ) devices, it ultimately cannot overcome the fundamental physical constraints of hardware gate fidelity and coherence times.
[28] McKinsey, *Quantum Technology Monitor*. The report illustrates this asymmetry by tracking investment and startup proliferation, noting that software and systems companies scale rapidly due to comparatively low capital expenditure, while foundational hardware development remains bottlenecked by intense resource and fabrication demands.
[29] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology* (Santa Monica, CA: RAND Corporation, 2022).This analysis delves into the supply chain dynamics of quantum technology, highlighting how early dominance in specific hardware architectures creates profound path dependence and establishes strategic "chokepoints" that dictate broader technological trajectories.

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[30] NSTC, *National Strategic Overview for Quantum Information Science*. The NSTC extensively outlines how the transition from bespoke laboratory prototypes to economically viable, repeatable systems fundamentally relies on establishing rigorous, shared metrology frameworks and validation environments.
[31] Quantum Economic Development Consortium (QED-C), *Quantum Sensing for Position, Navigation and Timing Use Cases* (Arlington, VA: QED-C, 2024), 12–15. Moving quantum out of the lab requires funding traditional engineering disciplines—packaging, vibration isolation, and thermal management—to optimize the Size, Weight, Power, and Cost (SWaP-C) of devices. The "valley of death" here is fundamentally an engineering and ruggedization challenge, not just a physics one.
[32] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies* (Washington, DC: U.S. Department of Defense, 2023). Early public sector and infrastructure contracts for quantum sensors can act as a vital demand signal for the broader ecosystem. By establishing a near-term market for high-fidelity components (e.g., specialized lasers, photon detectors, and control electronics), sensing applications provide the revenue streams necessary to sustain the foundational supply chain that quantum computing will ultimately rely upon.
[33] NSF, *National Quantum Virtual Laboratory* (NQVL) *Program Solicitation*, NSF 23-604 (Alexandria, VA: NSF, 2023). Because sensing devices are the first to hit these real-world bottlenecks, they highlight the acute need for shared metrology and validation infrastructure. Public investment in accessible, standardized testbeds—where companies can qualify their hardware against rigorous benchmarks—directly lowers the barrier to entry for commercialization, turning a localized bottleneck into a regional competitive advantage.
[34] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. This paragraph defines the core challenge of technology transfer in quantum sensing: optimizing for SWaP-C (Size, Weight, Power, and Cost). Public funding that helps startups transition from tabletop physics experiments to miniaturized, robust, field-deployable units is a critical intervention point for bridging the commercialization "valley of death."
[35] NSF, *Convergence Accelerator: Quantum Technology* (Alexandria, VA: NSF, 2023). Framing sensing as a "deployable measurement stack" rather than a singular device highlights the need for convergent research. Advancing this stack requires regional talent ecosystems that blend quantum physicists with systems engineers, photonics technicians, and software developers. Regions that can cultivate this cross-disciplinary workforce are best positioned to capture the economic value of quantum manufacturing.
[36] NSF, *NSF Regional Innovation Engines* (NSF Engines) *Program*, NSF 22-583 (Alexandria, VA: NSF, 2022). This structural reality validates the strategic approach of place-based initiatives like ASCEND. By recognizing that climate and infrastructure applications rely on the exact same underlying platforms (photonics, control electronics) as defense or communications, regional hubs in the Mountain West can leverage dual-use supply chains. Economic development here isn't just about building an environmental sensor; it is about anchoring the deep-tech manufacturing base required to build any advanced quantum system.
[37] IDTechEx, *Quantum Sensors Market 2026–2046: Technology, Trends, Players, Forecasts* (Boston: IDTechEx, August 2025). The transition from laboratory phenomena to field-deployable sensors is dictated by strict SWaP-C (Size, Weight, Power, and Cost) requirements. Because sensing technologies must operate in dynamic, unshielded environments, moving them toward commercialization requires overcoming intensive mechanical and thermal engineering hurdles long before the underlying quantum physics reaches theoretical maturity.

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[38] QED-C, "QED-C Details Member Advances in Quantum Control Electronics," HPCwire, March 4, 2026; and "The Supply Chain Chokepoints in Quantum," *War on the Rocks*, October 20, 2025. This deep structural overlap indicates that regional technology ecosystems do not need to specialize narrowly in just computing or just sensing. Establishing robust manufacturing capabilities for foundational "enabling technologies"—such as photonic integrated circuits, optical filters, and specialized control electronics—creates a versatile supply chain that simultaneously de-risks all three major quantum application areas.

[39] Holland High Tech, *Quantum Technologies*: *Strategic Programme 2024–2027* (The Hague: Top Sector HTSM, 2024). Treating quantum technologies as isolated hardware components frequently masks the root causes of failure during deployment. Successful commercialization requires a "full-stack systems perspective," meaning that innovation policy and infrastructure investments must explicitly target the complex integration points between the fragile quantum processor, the classical control logic, and the end-user's legacy data systems.

[40] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*, 62–68. The distinction between scientific maturity (often measured by Technology Readiness Levels, or TRLs) and institutional maturity (Manufacturing Readiness Levels, or MRLs) is central to evaluating technology pipelines. Even if a quantum sensor achieves a high TRL in a laboratory, it cannot cross the "valley of death" without overcoming severe MRL deficits—such as the lack of standardized procurement pathways, shared calibration facilities, and reproducible supply chains for specialized components.

[41] NSF, ExpandQISE. The high reciprocal overlap between sensing, computing, and communications signals that public and private investments in sensing testbeds yield outsized structural returns. By forcing the development of robust control and readout electronics for environmental applications, these initiatives concurrently solve the signal integrity bottlenecks that currently limit the scalability of quantum computing architectures.

[42] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. Innovation policies that focus exclusively on counting end-use applications frequently misdiagnose the health of an emerging industry. The concentration of inventive effort in enabling platforms indicates that the primary barrier to commercialization is not a lack of use cases, but rather an underdeveloped horizontal supply chain for foundational components like single-photon detectors and specialized optical fibers.

[43] U.S. Department of Energy, "Quantum Information Science Centers," Office of Science. The integration of assembly work directly into the inventive core underscores the necessity of interdisciplinary funding models. Because sensing cannot rely on post-hoc software fixes to overcome hardware fragility, regional innovation hubs must foster deep, concurrent collaboration between quantum physicists, photonics engineers, and classical software developers to achieve fieldable systems.

[44] WEF, *State of Quantum Computing*, 14–18. This platform concentration indicates that the primary barriers to commercialization are found in the supply chain for enabling technologies, not in a lack of end-use discovery. Public investment strategies that focus heavily on accelerating these horizontal platforms—such as advanced photonics manufacturing—yield higher structural dividends because they de-risk multiple downstream applications simultaneously.

[45] Kai Bongs et al., "Taking Quantum Sensors into the Real World." The transition from laboratory demonstration to field deployment is almost entirely gated by physical hardware ruggedization. Securing signal fidelity against thermal, vibrational, and electromagnetic interference requires intensive mechanical and optical engineering, making these physical layers the true anchor points for any deployable sensing capability.

[46] National Academies of Sciences, Engineering, and Medicine, *Quantum Computing: Progress and Prospects*, 115–22. The substantial presence of software and systems patents within sensing demonstrates the field's necessary shift from pure physics to quantum engineering. Extracting a reliable signal from a noisy environment requires complex algorithmic error mitigation and control logic, meaning successful innovation hubs must tightly integrate quantum physicists with classical software and systems engineers.

[47] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*. The concept of "stack closure" is vital for assessing technology readiness. Isolated laboratory breakthroughs frequently fail to cross the "valley of death" because they lack the surrounding control, calibration, and software infrastructure. Evidence of concurrent development across these layers signals that the ecosystem is maturing toward holistic, field-ready systems capable of integrating into existing infrastructure.

[48] Hideki Tomoshige and Phillip Singerman, *Government as a Demand Creator for the Quantum Industry* (Washington, DC: CSIS, March 2026). Patent concentration in these foundational areas reflects the reality that while quantum sensors are technically mature in laboratory environments, a substantial capability gap remains for industrial deployment. Transitioning to end-use applications requires sustained, capital-intensive investment to miniaturize components and improve the durability of the underlying metrology and control systems.

[49] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. This concentration of effort highlights the engineering "valley of death" facing quantum sensors. Escaping the "lab-in-a-box" paradigm requires profound advances in key enabling technologies—such as low-noise electronics, vacuum components, and deployable optical architectures—which correctly absorb the bulk of current inventive capacity.

[50] McKinsey, *The Year of Quantum*, 8–12. The data clearly shows an industry shift from simply demonstrating quantum phenomena to actively stabilizing them. Because extracting a reliable signal requires complex error mitigation and interpretation pipelines, successful technology transfer fundamentally relies on hybrid integration, demanding equal innovation in the classical electronic control layers that surround the quantum core.

[51] CNAS, *Quantum's Industrial Moment* (Washington, DC: CNAS, March 2026). The persistent presence of materials chemistry in the patent record points to a critical "self-reinforcing industrial gap." Because quantum systems demand ultra-high-purity materials and tightly controlled microfabrication beyond the capabilities of standard foundries, scaling these technologies is impossible without dedicated domestic manufacturing infrastructure and specialized supply chains.

[52] WEF, *Quantum Technologies: Key Opportunities for Advanced Manufacturing and Supply Chains* (Geneva: WEF, October 2025). For strategic planners, this distribution is a clear signal: the most resilient regional innovation ecosystems will be those that anchor themselves in advanced manufacturing, materials engineering, and systems integration. Prematurely chasing niche downstream applications without first securing this upstream industrial base poses significant commercialization risk.

[53] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. The disproportionate influence of these platforms confirms that optical and photonic components function as the horizontal infrastructure of the quantum economy. For strategic planners and investors, this indicates that cultivating a robust, advanced manufacturing base in these specific layers offers one of the highest-leverage opportunities to capture structural value within the broader industry, regardless of which downstream application ultimately scales first.

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[54] NSTC, *National Strategic Overview for Quantum Information Science* (Washington, DC: Executive Office of the President, 2018), 7–10. Because these foundational platforms solve shared bottlenecks across all application domains, R&D investments in quantum sensing yield massive collateral benefits. A regional ecosystem that masters signal integrity and control interfaces for environmental sensors simultaneously builds the exact supply chain and specialized workforce required to support large-scale quantum computing and secure communication networks.

[55] NSF, *National Quantum Virtual Laboratory* (NQVL) *Program Solicitation*, NSF 23-604 (Alexandria, VA: NSF, 2023). This requirement for "stack closure" highlights why technology transfer so frequently stalls. Transforming a fragile prototype into a trusted, fieldable capability requires rigorous calibration and validation—which in turn requires shared, standardized testing environments. Public infrastructure investments that establish these benchmarking testbeds are the critical catalysts for moving advanced measurement platforms out of the laboratory and into operational workflows.

[56] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*, 22–26. Because GPS-denied environments pose an immediate, existential risk to defense and logistics operations, PNT is experiencing the strongest demand "pull." For program officers, this means funding mechanisms targeting atomic clocks and inertial sensors are less about discovering new physics and almost entirely about optimizing SWaP-C (Size, Weight, Power, and Cost) to fit inside existing aerospace platforms.

[57] Kai Bongs et al., "Taking Quantum Sensors into the Real World." Cold-atom systems exemplify the "integration-heavy" bottleneck. Translating this modality requires massive cross-disciplinary engineering, particularly in miniaturizing ultra-high vacuum (UHV) chambers and stabilized laser cooling systems. Regions that invest in shared optical and mechanical engineering foundries are uniquely positioned to capture value here.

[58] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. NV-center magnetometry highlights a critical materials bottleneck. High-fidelity sensors require isotopically pure, defect-engineered synthetic diamonds. Scaling this pathway therefore requires deep industrial investments in synthetic materials manufacturing, moving the capability out of bespoke university labs into repeatable, commercial-grade fabrication.

[59] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*, 45–52. The National Academies stress that the most chronic funding gap in quantum technology lies in mid-stage packaging and systems integration. Federal programs must aggressively target this "boring" engineering—such as photonic integrated circuits and thermal shielding—because it is the absolute prerequisite for any field deployment.

[60] NIST, *Quantum Information Science and Technology* (QIST) *Standards* (Gaithersburg, MD: U.S. Department of Commerce, 2023). Establishing trust in quantum sensors requires institutional, not just technical, innovation. Funding shared, regional testbeds where startups can independently validate their hardware against NIST-traceable standards is one of the highest-leverage public investments a region can make to accelerate commercialization.

[61] CNAS, *Quantum's Industrial Moment* (Washington, DC: CNAS, March 2026). The failure to plan for "classical integration" is a leading cause of commercial stall. An incredibly sensitive quantum device is functionally useless if its data output cannot be parsed by legacy classical infrastructure. Funding must mandate co-development between quantum hardware engineers and classical software/systems integrators.

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[62] Richard Hung et al., S*cience & Tech Spotlight: Quantum Sensors, GAO-25-107876* (Washington, DC: U.S. Government Accountability Office, 2025). The GAO explicitly warns against conflating Technology Readiness Levels (TRLs) with System or Manufacturing Readiness Levels (SRLs/MRLs). A laboratory sensor boasting record sensitivity (high TRL) cannot change operational decisions if it lacks the robust data fusion and physical maintainability required for field sustainment (low SRL/MRL).
[63] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*. The inherent dual-use nature of quantum sensing primitives—particularly in Positioning, Navigation, and Timing (PNT)—means that early defense procurement will likely subsidize the supply chain maturation required for civilian infrastructure applications. Regional economic strategies can leverage this dynamic by targeting Department of Defense (DoD) transition funds to build manufacturing hubs that will eventually serve the environmental monitoring market.
[64] CNAS, *Quantum's Industrial Moment*. Strategic planners must resist the temptation to view quantum commercialization as a disruptive, "flip-the-switch" event. Funding mechanisms that incentivize incremental, backward-compatible upgrades to existing legacy systems—such as integrating a quantum magnetometer into an existing geological survey drone—are far more likely to successfully cross the technology transfer gap than attempts to build entirely novel product categories from scratch.
[65] NSF, *Convergence Accelerator Track I: Sustainable Materials for Global Challenges* (Alexandria, VA: NSF, 2023). The "pre-invention" status of climate-focused quantum sensing highlights a classic market failure where the fundamental science is known, but the application-specific engineering lacks immediate commercial incentives. This validates the need for patient, place-based public capital to bridge the gap between abstract physics and highly specific environmental monitoring requirements.
[66] WEF, *Harnessing Quantum Technologies for Environmental Sustainability* (Geneva: WEF, 2025). Extracting actionable climate data from quantum sensors requires building an extensive, non-quantum data assimilation pipeline. Investments in environmental quantum technologies must therefore mandate co-development with classical climate modeling and geospatial intelligence sectors to ensure the resulting data can actually be ingested by end-users.
[67] NIST, *Quantum Information Science and Technology (QIST) Standards*. Standardized calibration is the foundational public good of the quantum economy. Funding shared metrology testbeds acts as a force multiplier for a regional ecosystem, dramatically lowering the capital barriers for startups attempting to qualify their devices for federal or industrial procurement.
[68] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*, 85–92. The transition from an R&D grant mindset to a procurement mindset is the ultimate indicator of ecosystem maturity. Federal and state agencies can accelerate this by utilizing Other Transaction Authorities (OTAs) or establishing clear qualification thresholds, giving the private sector concrete performance targets to engineer against.
[69] National Oceanic and Atmospheric Administration (NOAA), *Next-Generation Earth Observation Systems* (Washington, DC: U.S. Department of Commerce, 2024). A highly sensitive quantum gravimeter is operationally useless if its data format is incompatible with NOAA's hydrological models. Funding initiatives must explicitly require interoperability with legacy environmental decision-support systems to ensure that "better measurement" successfully translates into "better policy."
[70] Elsa Kania and John Costello, *Quantum Hegemony? China's Ambitions and the Challenge to U.S. Innovation Leadership* (Washington, DC: CNAS, 2018), 8–12. CNAS emphasizes that global leadership is no longer defined by achieving isolated "quantum supremacy" demonstrations, but rather by capturing the critical supply chain chokepoints—such as cryogenic cabling, specialized lasers, and error-correction software—that all operational systems will eventually require.

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[71] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*. RAND's structural analysis of the two ecosystems explicitly contrasts China's top-down, state-directed funding model, which excels at rapidly scaling mature architectures, with the U.S. model, which relies on a highly decentralized, venture-backed ecosystem that excels at exploring novel physics but frequently struggles to coordinate capital-intensive infrastructure buildouts.

[72] Australian Strategic Policy Institute (ASPI), *ASPI's Critical Technology Tracker: The Global Race for Future Power* (Canberra: ASPI, 2023). ASPI's data highlights the vulnerability of autarkic technology development. Because the quantum supply chain is so fragmented, attempting to onshore every component from raw materials to final assembly dramatically increases the risk of technological lock-in and failure; allied burden-sharing is a structural necessity for maintaining progress.

[73] NSF, ExpandQISE. In an unsettled technology landscape, raw scale functions as a hedge against architectural failure. The more parallel bets a national ecosystem can fund simultaneously, the higher the probability that one of those pathways will successfully clear the engineering "valley of death" and achieve commercial viability.

[74] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*, 34–38. The report details how China's integration of state-owned enterprises (like telecommunications and grid operators) directly into the R&D process creates guaranteed, large-scale domestic markets for quantum technologies, effectively bypassing the commercialization hurdles that often stall U.S. startups.

[75] Information Technology and Innovation Foundation (ITIF), How the United States Can Maintain Its Lead in Quantum Information Science (Washington, DC: ITIF, 2023). This decentralized U.S. structure—blending corporate R&D, university basic science, and agile startups—is highly adaptive but poses a unique policy challenge: it requires intentional, publicly funded "connective tissue" (like the NSF Regional Innovation Engines) to ensure these disparate actors can effectively integrate their subsystems into unified, deployable technologies.

[76] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. The U.S. advantage in sensing is deeply tied to its legacy aerospace and defense industrial base, which possesses unparalleled expertise in systems integration, miniaturization, and ruggedization—the exact engineering disciplines required to translate fragile quantum physics into field-deployable sensors.

[77] Wehner, Elkouss, and Hanson, "Quantum Internet: A Vision for the Road Ahead," Science 362, no. 6412 (2018). China's massive infrastructure rollout of the Micius satellite and the Beijing-Shanghai QKD fiber backbone exemplifies its competitive advantage in state-directed infrastructure. Conversely, the U.S. ecosystem has pivoted heavily toward the more complex, architecturally flexible challenge of developing entanglement-based quantum repeaters and interoperable networking standards.

[78] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*. The National Academies notes that while China's model is highly effective at executing known engineering roadmaps, the U.S. model's high tolerance for parallel, high-risk experimentation gives it a distinct advantage in architecturally unsettled fields like quantum computing, where the dominant hardware platform has yet to be determined.

[79] EPO, *Quantum Metrology and Sensing*, 30. The study identifies Germany as the primary European hub for quantum-enabling optics and laser stabilization. For the specific role of German industrial leaders (e.g., TOPTICA Photonics and Menlo Systems) in supplying the frequency combs and laser subsystems required for neutral-atom computing and atomic clocks, see Jeroen Groenewegen-Lau and Antonia Hmaidi, "China's Long View on Quantum Tech Has the US and EU Playing Catch-Up," MERICS, December 12, 2024. Both reports emphasize that while Germany may trail in aggregate qubit counts, it is a "foundational supplier" whose components are essential to the U.S., Chinese, and European quantum stacks alike.

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[80] Department for Science, Innovation and Technology (DSIT), *National Quantum Strategy* (London: HM Government, 2023). The strategy explicitly pivots the UK's focus toward "mission-led" programs and the "ruggedization" of quantum hardware for real-world deployment. For the specific role of the UK in bridging laboratory science and operational environments through the National Quantum Technologies Programme (NQTP), see National Physical Laboratory (NPL), *Quantum Metrology Institute: Review of Impact* (Teddington: NPL, 2024), 12–15.

[81] CNAS, Quantum's Industrial Moment (Washington, DC: CNAS, March 2026). Japan's deep integration into the classical semiconductor supply chain makes it an indispensable partner for the quantum transition. Because scaling quantum hardware ultimately requires leveraging advanced CMOS manufacturing techniques and specialized cryogenic packaging, Japan controls critical integration layers that bridge laboratory physics and industrial manufacturing.

[82] Adm. Michael S. Rogers, William Zeng, James Andrew Lewis, Taylar Rajic, and Jonah Force Hill, CSIS Commission on U.S. Quantum Leadership (Washington, DC: CSIS, 2025). CSIS distinguishes between the "monolithic scale" of the Chinese innovation model and the "distributed resilience" of the Allied system. It argues that the Allied advantage lies in "architectural adaptability"—the ability to integrate specialized components from a network of diverse, reciprocal partners—rather than the centralized pursuit of a single hardware standard.

[83] U.S. Department of State, "Joint Statement of the United States of America and the United Kingdom of Great Britain and Northern Ireland on Cooperation in Quantum Information Sciences and Technologies," November 2021. Bilateral and multilateral agreements in quantum technology are not merely diplomatic formalities; they are structural economic imperatives. By pooling research capital and aligning metrology standards, allied nations explicitly weaponize collaboration to counteract the raw scale advantages of centralized, state-directed systems.

[84] ASPI, *ASPI's Critical Technology Tracker: The Global Race for Future Power* (Canberra: ASPI, 2023). Innovation network theory demonstrates that highly distributed systems inherently de-risk early-stage technology development. For strategic funding agencies, this validates a portfolio approach: instead of attempting to build an autarkic, end-to-end domestic supply chain, public capital yields higher returns when it leverages specialized international partnerships to bypass known technical bottlenecks.

[85] Kania and Costello, *Quantum Hegemony?*, 14–18. The power of "brokerage" in deep tech cannot be overstated. By anchoring the central hubs of global collaboration, a nation ensures that emerging international standards—crucial for future procurement and market dominance—are natively compatible with its own domestic industrial base.

[86] NSF, ExpandQISE. The U.S. role as a "system integrator" is not accidental; it is heavily subsidized by federal programs designed explicitly to act as connective tissue. Initiatives that fund translational research and cross-sector partnerships effectively institutionalize this brokerage advantage, turning domestic research universities into the mandatory clearinghouses for global quantum advancement.

[87] Anne-Marie Slaughter, *The Chessboard and the Web: Strategies of Connection in a Networked World* (New Haven: Yale University Press, 2017). Slaughter argues that in a networked environment, "relational power" stems from centrality and connection rather than just sovereign command, allowing actors to influence systems by defining norms and coordinating diverse clusters.

[88] Slaughter, *The Chessboard and the Web*, 168. Slaughter contrasts "hub-and-spoke" networks, which are optimized for efficiency but prone to single-point failure, with "mesh" networks that derive power from redundancy and reciprocal resilience. For the strategic application of this mesh model to allied quantum development as a hedge against the prohibitive costs and "architectural risks" of national autarky, see Rogers et al., *CSIS Commission on U.S. Quantum Leadership*, 12–14.

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[89] U.S. Department of State, “Joint Statement on Cooperation in Quantum Information Sciences and Technologies.” The deep redundancy of the allied cluster serves as a structural defense mechanism against supply chain shocks. When regional economic developers build specialized hardware foundries or metrology testbeds, they are not just serving local startups; they are embedding their region into this resilient, multinational co-production web.

[90] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*. China’s low multinational co-production share reveals a profound vulnerability: the risk of architectural lock-in. While central planning accelerates the deployment of mature technologies, it fundamentally struggles to pivot when novel, disruptive architectures (e.g., neutral-atom computing unexpectedly leapfrogging superconducting qubits) emerge from outside its closed network.

[91] ITIF, *How the United States Can Maintain Its Lead in Quantum Information Science* (Washington, DC: ITIF, 2023). The "race" metaphor actively damages innovation policy by encouraging governments to chase vanity metrics (like qubit counts) rather than investing in the unglamorous enabling layers—like cryogenic packaging and control electronics—where true structural leverage resides.

[92] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*, 62–68. Shifting the strategic framework from "winning a race" to "controlling the bottlenecks" fundamentally changes how public R&D funds should be allocated. Economic power in the next decade will accrue to the regions that master systems integration and open-architecture standards, allowing them to rapidly absorb and commercialize breakthroughs regardless of where they were originally invented.

[93] Groenewegen-Lau and Hmaidi, “China’s Long View on Quantum Tech Has the US and EU Playing Catch-Up.” The authors detail the “sovereign deployment” of QKD hardware across China’s financial and energy sectors as a mandate of the 14th Five-Year Plan. This illustrates the system’s capacity for rapid, top-down diffusion once a technical architecture is prioritized by the state.

[94] Edward Parker et al., *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*. This analysis warns that China's top-down infrastructure model carries profound "architectural lock-in" risk. By heavily subsidizing specific physical modalities before the global scientific consensus has settled, the state-directed ecosystem risks building highly efficient supply chains for technologies that may ultimately be outpaced by more agile, disruptive physics paradigms developed elsewhere.

[95] Rogers et al., *CSIS Commission on U.S. Quantum Leadership*, 14–16. CSIS highlights that the “Allied advantage” is not found in raw production volume but in the United States’ role as the “aggregator of global talent and specialized inputs,” effectively functioning as the system’s primary integrator.

[96] ITIF, *How the United States Can Maintain Its Lead in Quantum Information Science* (Washington, DC: ITIF, 2023). This "messy coordination" is precisely what makes the U.S. ecosystem resilient. For public funders, the strategic imperative is not to force all actors onto a single roadmap, but to fund the "connective tissue"—such as translation hubs and shared user facilities—that allows diverse university, corporate, and allied researchers to recombine their disparate hardware and software breakthroughs.

[97] OECD, *OECD Science, Technology and Innovation Outlook 2024*. The OECD notes a persistent gap between the volume of Chinese patent filings and their “international impact,” as measured by citations from non-Chinese inventors. This supports the characterization of the Chinese system as “scale-dominant but network-thin.”

[98] Kania and Costello, *Quantum Hegemony?,* 22–25. Interoperability is a mechanism of market capture. Because the allied system co-develops technologies across heterogeneous national infrastructures, it naturally produces global standards. Technologies designed exclusively for closed, domestic procurement loops frequently struggle to export because they lack the necessary interfaces to plug into international legacy systems.

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[99] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*. The National Academies note that the U.S. venture-backed model excels at failing fast and cheaply. Distributed systems can absorb the collapse of a heavily funded hardware startup without stalling the entire national enterprise, because allied researchers are simultaneously advancing viable alternatives in adjacent platform layers.
[100] Mark Muro, et al, *Breaking Down an $80 Billion Surge in Place-Based Industrial Policy* (Washington, DC: Brookings, December 2022). See also Mark Muro and Joseph Parilla, *The Case for Growth Centers* (Washington, DC: Brookings, 2019). Brookings' research on modern place-based economic development stresses that emerging tech hubs maximize their return on investment by intervening in specific, localized gaps within the national "industrial commons." Rather than attempting to build a comprehensive industry from scratch, regions succeed by specializing deeply in specific supply chain chokepoints and exporting that capability to the broader national network.
[101] NSF, *NSF Regional Innovation Engines*. The strategic framing here directly aligns with the mandate of programs like the NSF Engines. By leveraging geographic and institutional advantages (such as the Mountain West's existing aerospace, defense, and environmental monitoring footprint), a region can establish itself as the premier "systems integration" node, capturing the high-value engineering work required to transition laboratory quantum physics into operational public infrastructure.
[102] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*, 15–22. The National Academies emphasize that public funding must pivot from supporting isolated scientific breakthroughs to subsidizing the unglamorous work of systems engineering. Because commercialization is entirely dependent on stack integration, regional technology hubs must prioritize cross-disciplinary facilities that force physicists, software developers, and mechanical engineers to co-develop these systems.
[103] Avi Goldfarb and Roger Wilkins, "The Economics of Quantum Technologies," *National Bureau of Economic Research* (NBER) Working Paper No. 31200 (May 2023). The lack of a "dominant design" in quantum hardware profoundly alters regional investment strategies. Because picking a singular winning qubit architecture is currently impossible, economic development initiatives are far more resilient when they invest in the horizontal, enabling platforms—such as cryogenic cooling, specialized optics, and control electronics—that all competing architectures will inevitably require.
[104] Tomoshige and Singerman, *Government as a Demand Creator for the Quantum Industry*. Strategic planners must recognize that the traditional consumer market pull does not yet exist for quantum. Consequently, public agencies (like the DoD, DOE, and NOAA) must act as aggressive "first buyers," using procurement contracts and Other Transaction Authorities (OTAs) to artificially sustain early-stage quantum hardware companies until commercial enterprise demand matures.
[105] McKinsey, *Quantum Technology Monitor*. While venture capital is highly visible, it skews heavily toward software and systems integration, avoiding the massive Capital Expenditure (CapEx) required for fundamental hardware fabrication. Public and philanthropic capital remains absolutely vital for underwriting the foundational layers of the stack that private venture markets deem too risky or slow to yield returns.
[106] Boston Consulting Group (BCG), *The Long-Term Forecast for Quantum Computing Still Looks Bright* (Boston: BCG, 2024). The rapidly advancing classical frontier (particularly GPU-accelerated AI and tensor processing units) means that quantum commercialization cannot rely on generalized performance claims. To successfully commercialize, quantum systems must target highly specific, intractable computational bottlenecks (e.g., specific molecular simulations or complex optimization routing) where classical emulation is mathematically impossible, driving the need for hybrid quantum-classical data centers.

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[107] National Academies of Sciences, Engineering, and Medicine, *Commercializing Quantum Technologies*, 62–68. The National Academies formally define this transition as moving from Technology Readiness Levels (TRLs) to Manufacturing and System Readiness Levels (MRLs/SRLs). A laboratory device may possess a high TRL, but it has zero commercial value until it achieves a high SRL through rigorous systems engineering and environmental hardening.

[108] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. This interdependent nature of the stack means that public funding strategies must be holistic. Investing heavily in quantum processor development while ignoring the supply chain for cryogenic cooling or low-noise control electronics will inevitably result in a stranded, un-commercializable asset.

[109] McKinsey, *Quantum Technology Monitor*. The concentration of venture capital in the software and integration layers is a rational market response to the massive capital requirements of hardware fabrication. Because VC firms generally cannot underwrite the decadal, multi-hundred-million-dollar timelines required to build physical quantum foundries, public sector intervention remains the only viable mechanism for de-risking the foundational hardware layer.

[110] CNAS, *Quantum's Industrial Moment*. Quantum-as-a-Service (QaaS) allows the industry to generate early revenue and build user familiarity without solving the profound engineering challenges of miniaturization and ruggedization. However, strategic planners must recognize that QaaS inherently relies on centralized, easily accessible cloud infrastructure, making it unsuitable for edge deployments (like defense or remote environmental sensing) which still require localized, hardened hardware.

[111] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*. The DoD explicitly operates as the "first buyer" in these high-pressure arenas. Because the military cannot defer integration—a sensor must work on a vibrating aircraft today—defense contracts force the quantum industry to prioritize SWaP-C (Size, Weight, Power, and Cost) optimization far earlier than civilian markets would demand.

[112] Hung et al., S*cience & Tech Spotlight: Quantum Sensors*. PNT is the vanguard of quantum commercialization specifically because the baseline classical technology (GPS) is actively degrading in contested environments. This operational vulnerability creates an immediate market for quantum inertial sensors and atomic clocks, effectively subsidizing the manufacturing base that will later support civilian applications.

[113] NIST, "Post-Quantum Cryptography." The commercialization of PQC is a prime example of institution-led market formation. The market exists not because of spontaneous consumer demand, but because federal mandates (such as NSM-10) compel agencies and contractors to adopt these new mathematical standards to mitigate future strategic risk.

[114] WEF, *Quantum for Society*. In infrastructure sensing, the barrier to entry is institutional trust, not just technical capability. Commercialization depends on proving to risk-averse entities (like utility companies or hydrological surveyors) that quantum-derived data is statistically reliable enough to replace decades of legacy operational procedures.

[115] BCG, *The Long-Term Forecast for Quantum Computing Still Looks Bright*. The lack of a "dominant design" in quantum architectures severely paralyzes private capital. Because investors cannot yet determine whether superconducting circuits, trapped ions, or neutral atoms will ultimately scale, they are hesitant to fund the massive, specialized supply chains required for any single modality, trapping the entire industry in an expensive holding pattern.

[116] GAO, *Quantum Computing and Communications: Status and Prospects*, GAO-22-104422 (Washington, DC: GAO, 2021). GAO explicitly identifies cryogenic cooling and specialized microfabrication as critical supply chain chokepoints. A top-heavy supplier base in these areas means that a disruption at a single vendor can halt R&D across dozens of downstream startups, demonstrating why commercial scaling cannot occur without state-backed investments in industrial resilience.

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[117] National Academies of Sciences, Engineering, and Medicine, *Quantum Computing: Progress and Prospects*. The transition from "can it work" to "can it keep working" fundamentally changes the engineering priority from peak sensitivity to SWaP-C (Size, Weight, Power, and Cost) optimization and environmental hardening, marking the true beginning of the commercialization phase.

[118] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. Without shared metrological standards, every procurement contract becomes an exhaustive, custom R&D project. Establishing independent, NIST-traceable validation regimes is the only way to commoditize quantum components and accelerate federal and commercial acquisition cycles.

[119] NSF, *NQVL Program Solicitation*. The NQVL and similar DOE National QIS Research Centers represent the exact institutional intervention required to overcome integration risk. By underwriting the exorbitant CapEx of shared fabrication and cryogenic facilities, public institutions allow regional startups to iterate and fail cheaply, turning what would be prohibitive corporate expenses into a regional public good.

[120] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*. The DoD and allied defense ministries are the ultimate "anchor customers." Their willingness to fund the ruggedization of quantum inertial sensors for GPS-denied environments effectively subsidizes the manufacturing learning curves that will eventually make civilian applications economically viable.

[121] NIST, "Post-Quantum Cryptography Standardization.” NIST's multi-year standardization competition for PQC is the textbook example of institution-led market making. The commercial cybersecurity sector did not spontaneously transition out of consumer demand; it shifted because a centralized public institution provided the cryptographic benchmarks required to define the new market.

[122] Mark Muro et al., *Breaking Down an $80 Billion Surge in Place-Based Industrial Policy*. The geographic distribution of validation infrastructure dictates the geography of economic power. Regional hubs that secure federal funding to build shared quantum testbeds inherently force the national supply chain to orbit around their local standards, thereby capturing the high-value systems integration work that defines the industry's future.

[123] Tomoshige and Singerman, *Government as a Demand Creator for the Quantum Industry*. The structural unevenness of the stack dictates where private capital flows. Software and orchestration layers attract intense, early-stage venture funding precisely because they can iterate rapidly without the decadal, multi-million-dollar capital expenditures required to build physical quantum hardware foundries.

[124] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. Sensing achieves commercial viability earlier than computing almost entirely due to institutional pull. Agencies managing critical infrastructure and defense operations are willing to absorb high early-adopter costs to secure Positioning, Navigation, and Timing (PNT) resilience in GPS-denied environments, effectively subsidizing the ruggedization of the underlying hardware.

[125] Tomoshige and Singerman, *Government as a Demand Creator*. To cross the commercial "valley of death," the government must act as a "wise buyer." Public institutions are not just funding research; they are the primary market mechanism. By underwriting the exorbitant costs of shared fabrication facilities and acting as the anchor customer for early, bespoke systems, institutions artificially sustain the industry until broad enterprise demand can materialize.

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[126] Mark Muro, Joseph Parilla, and Francesca Ioffreda, "New Tech Hub Investments Aim to Unleash Diverse Regional Tech Clusters," *Brookings*, July 2, 2024. The U.S. Economic Development Administration's designation of the Elevate Quantum Tech Hub exemplifies this shift in defining regional advantage. Regions are no longer evaluated merely by their academic output; federal funding now flows to ecosystems that can prove they possess the inclusive workforce, shared open-access fabrication labs, and public-private partnerships necessary to translate discrete quantum inventions into deployable, commercial-grade systems.

[127] Mark Muro et al., *Breaking Down an $80 Billion Surge in Place-Based Industrial Policy*. This frames the core thesis of regional economic strategy under the CHIPS and Science Act: emerging tech hubs must abandon the goal of total autarky and instead cultivate deep specialization in a critical node of the national supply chain. The Mountain West's focus on the measurement and validation stack perfectly embodies this "place-based" competitive logic.

[128] NIST, "Quantum Physics Division (JILA)," U.S. Department of Commerce. NIST and JILA represent a near-unmatched concentration of atomic physics and precision metrology talent globally. For regional planners, these institutions act as structural anchors; their presence guarantees that the Mountain West will permanently reside at the forefront of the foundational enabling platforms required for quantum sensing and atomic clock miniaturization.

[129] QED-C, *Quantum Sensing for Position, Navigation and Timing Use Cases*. The region's disproportionate concentration in the measurement stack—specifically photonics, optics, and magnetometry—signals a highly mature hardware ecosystem. Unlike regions heavily skewed toward software (which can be geographically diffuse), the Mountain West holds physical capabilities that are intensely difficult to replicate, requiring capital-heavy, specialized foundries and cleanrooms.

[130] U.S. Economic Development Administration (EDA), "Elevate Quantum Tech Hub Designation," U.S. Department of Commerce, October 2023. This normalized concentration justifies the EDA's designation of Elevate Quantum as an official federal Tech Hub. It provides empirical proof that the Mountain West's quantum cluster is not a marketing artifact, but a structurally embedded industrial asset generating economic impact at a rate far exceeding its raw population size.

[131] NSF, Quantum Systems through Entangled Science and Engineering (Q-SEnSE) (Alexandria, VA: NSF, 2020). The high concentration in sensing is directly validated by the NSF's decision to establish Q-SEnSE as a Quantum Leap Challenge Institute anchored at CU Boulder. This federal investment specifically tasks the Mountain West with bridging the gap between theoretical quantum physics and the engineered deployment of ultra-precise sensors, cementing the region's national mandate in the measurement layer.

[132] Defense Science Board, *Report of the Defense Science Board Task Force on Applications of Quantum Technologies*. The extreme specialization in quantum gyroscopes (8.86x the U.S. average) directly aligns the Mountain West with the DoD's most pressing quantum priority: resilient Positioning, Navigation, and Timing (PNT) for GPS-denied environments. This gives the region an immediate, high-volume defense procurement pathway that civilian-only clusters lack.

[133] Sandia National Laboratories, "Quantum Computer Science," *U.S. Department of Energy*. The synergistic pairing of Boulder's basic science and metrology with New Mexico's defense-oriented national labs creates a complete "lab-to-fab" pipeline. Sandia's deep expertise in ruggedizing components for harsh environments provides the exact systems-engineering capabilities required to transition Boulder's quantum prototypes into fieldable technology.

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[134] Elevate Quantum, Elevate Quantum Secures $40.5 Million in Phase 2 Tech Hubs Funding (Denver, CO: Elevate Quantum Consortium, July 2024). The recent acceleration in regional momentum is not coincidental; it is being deliberately catalyzed. Initiatives funded by this EDA award are designed specifically to provide the physical testbeds required for startups to empirically validate their hardware, effectively acting as an accelerator for regional IP generation.

[135] NSF, ExpandQISE. The parallel acceleration in both enabling hardware (photonics) and organizing software (quantum programming) suggests the Mountain West is successfully executing a "full-stack" innovation strategy. By advancing the control logic in tandem with the physical sensor, the region is actively resolving the bespoke integration bottlenecks that cripple less diverse ecosystems.

[136] The University of New Mexico, "The University of New Mexico Launches The Quantum New Mexico Institute," UNM Newsroom, January 2024. The post-2020 surge highlights the critical importance of institutional translation layers. The formal launch of QNM-I addresses the primary chokepoint of technology transfer: producing the specialized, mid-level technicians and systems engineers required to scale production beyond the capabilities of PhD physicists alone.

[137] Tomoshige and Singerman, *Government as a Demand Creator for the Quantum*. The unusually high government sponsorship rate (18.5%) provides the Mountain West with a profound structural advantage: access to patient capital. Because national labs are not bound by the short-term ROI requirements of venture capital, they can subsidize the decadal development timelines necessary for complex quantum hardware, effectively de-risking the foundational IP before it is spun out to the private sector.

[138] Elevate Quantum, *Elevate Quantum Secures $40.5 Million in Phase 2 Tech Hubs Funding* (Denver, CO: Elevate Quantum Consortium, July 2024). The deployment of substantial federal and state capital toward shared infrastructure directly attacks the "bespoke prototyping" problem. By providing startups with subsidized access to dilution refrigerators and cleanrooms, the Mountain West is drastically lowering the barrier to entry, transforming quantum entrepreneurship from a capital-prohibitive endeavor into a scalable regional engine.

[139] Mark Muro and Joseph Parilla, "New Tech Hub Investments Aim to Unleash Diverse Regional Tech Clusters," *Brookings*, July 2, 2024. The Mountain West's accumulation of major federal quantum investments transforms it from a regional participant into a national "node." The strategic imperative for the region is now outward connectivity: utilizing this critical mass of validation and testbed infrastructure to attract startups and R&D capital from across the broader U.S. allied network.

[140] See: European Quantum Industry Consortium (QuIC), *A Portrait of the Global Patent Landscape in Quantum Technologies* (Brussels: QuIC, January 2025); UK Intellectual Property Office, *Eight Great Technologies*: *Quantum Technologies—A Patent Overview* (Newport: UK IPO, August 2014); European Patent Office, *Quantum Metrology and Sensing*: *Landscape Study on Patent Filing* (Munich: EPO, 2019); Martino Travagnin, *Patent Analysis of Selected Quantum Technologies* (Luxembourg: Publications Office of the European Union, Joint Research Centre, 2019); OECD, *Mapping the global quantum ecosystem*: *A comprehensive analysis based on innovation, firm, investment, skills, trade, and policy data*, EPO and OECD, 2025.

[141] QuIC, *A Portrait of the Global Patent Landscape in Quantum Technologies.* For example, according to the European Patent Office's CPC scheme (Revision 2022.08), subclass G04F 5/145 — "using coherent population trapping (CPT)" was introduced as part of recent CPC refinements distinguishing quantum-based atomic clocks from earlier resonance types (EPO, Cooperative Patent Classification Scheme, Section G04F 5/14*)*.

[142] UK IPO, *Eight Great Technologies*.

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[143] See the EPO's explainer on patent families: https://www.epo.org/en/searching-for-patents/helpful-resources/first-time-here/patent-families.
[144] OECD and EPO, *Mapping the global quantum ecosystem*.
[145] Ibid.
[146] UK IPO, *Eight Great Technologies*.
[147] Ibid.
[148] OECD, *Mapping the global quantum ecosystem*; UK IPO, *Eight Great Technologies*.
[149] OECD and EPO, *Mapping the global quantum ecosystem*.
[150] QuIC, *A Portrait of the Global Patent Landscape in Quantum Technologies*; UK IPO, *Eight Great Technologies*.
[151] OECD and EPO, *Mapping the global quantum ecosystem*.
[152] The Lens, https://about.lens.org/; and O. A. Jefferson et al., "The Lens MetaRecord and LensID: An Open Identifier System for Aggregated Metadata and Versioning of Knowledge Artefacts," *The Lens*, 2019, https://about.lens.org/the-lens-metarecord/.
[153] U.S. Patent and Trademark Office, "Data Download Tables," *PatentsView* (www.patentsview.org).
[154] OECD, *REGPAT database*, May 2025; OECD, *HAN database*, February 2025; and OECD, *Triadic Patent Families database*, February 2025.
[155] See: European Patent Office, *Patent families at the EPO* (Munich: European Patent Office), 22. According to the EPO, "The INPADOC extended patent family is covering a technology rather than one single invention and will generally contain more than one invention." INPADOC families contain "applications that are members of an extended patent family" and "cover technical content that is similar but not necessarily the same."
[156] This two-pathway approach entailing CPC- and keyword-based definitions has been piloted in other quantum landscape studies cited earlier and in a recent OECD study of artificial intelligence patenting: OECD, *Identifying emerging AI technologies using patent data: A semi-automated approach* (Paris: Organisation for Economic Cooperation and Development, 2025).
[157] In this study, values are subsequently converted to within-universe percentile ranks; therefore, using the growth factor vs. the growth rate does not affect rankings.

The NSF ASCEND Engine connects research, capital, and industry to develop and deploy technologies that help communities better anticipate risk, protect lives, and adapt to the growing impacts of natural hazards across the Colorado and Wyoming region.

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