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A Report of CSIS Renewing American Innovation

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Contents

Introduction

Quantum technologies have long served as the foundation for the development of key modern technologies, including lasers, atomic clocks, transistors, and semiconductor devices. New advancements in quantum information science and technology (QIST) are now enabling the creation of devices that can utilize, generate, manipulate, and read quantum states of matter, particularly quantum phenomena such as superposition and entanglement. With these advancements, QIST is expected to serve as a major platform technology on par with artificial intelligence (AI), underpinning advances in defense, finance, materials discovery, pharmaceuticals, and engineering.

As home to one of the world's leading research centers in the field of precision time and electrical metrology, Colorado has consistently driven these advancements. The state's world-class research and development (R&D) ecosystem evolved over decades, centering around JILA, originally established as the Joint Institute for Laboratory Astrophysics, a research institute established by the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder. As the United States faces growing global competition for quantum superiority, the sustained growth of these capabilities—including the R&D ecosystem that it has fostered—becomes strategically important.

This CSIS study—requested by NIST and organized in cooperation with the Quantum Economic Development Consortium (QED-C)—aims to identify policies to support and grow a competitive quantum industry that is both grounded in the United States and connected with leading quantum companies and organizations among allied countries and U.S. strategic partners. The study also

explores cooperative approaches to accelerate U.S.-based quantum technology development and deployment, identify means to address engineering and technology challenges to the development of utility-scale quantum technology systems, and encourage mutually beneficial collaboration in quantum among like-minded countries.

This report documents the growth of the Colorado quantum cluster, built around the nucleus of the JILA and NIST research efforts, and now broadening to include federal laboratories and universities across the wider Mountain West region. Critically, this cluster includes the myriad startups and firms specializing in building quantum computers, harnessing their remarkable capabilities for a variety of applications. This report highlights both (1) the importance of sustained and substantial federal and state support in the growth of this ecosystem and (2) the role of regional partnership organizations in creating cross-supporting networks within the cluster to solve emerging challenges related to achieving scale through building shared infrastructure, upskilling the workforce, and fostering technical cooperation.

The Regional and National Stakes in the Quantum Competition

While the science underpinning quantum technologies may be difficult to grasp, it has been repeatedly tested and validated by the scientific community, and quantum principles are rapidly becoming accepted by the scientific community as basic laws of nature—to be exploited by human actors for good or ill.[1]

Quantum technology-based applications are significant, and potentially disruptive. In addition to applications in computing and communications, quantum technology can be employed to deliver vast improvements in sensing the existence of and detecting changes in electric and magnetic fields, motion, gravity, the passage of time, brain activity, and other phenomena with a precision unmatched by current sensor technologies. Some current sensors already use quantum effects, including magnetic resonance imaging (MRI) scanners and atomic clocks that underpin the Global Positioning System (GPS). In addition, quantum technologies have multiple—and potentially disruptive—applications in the defense realm. Recent surveys have identified major potential uses of quantum science in cryptanalysis, secure communications and networking, optimization of logistics, AI, simulations, satellites, sensing for detection, navigation, and stealth.[2] Universities, research organizations, and companies across Colorado are pursuing these and other practical applications of quantum principles.

Colorado's leaders understand the stakes involved in U.S. leadership in this technology. In a joint editorial on April 6, 2025, Governor Jared Polis and Justin Schwartz, the chancellor of the University of Colorado Boulder, warned that "the United States is in a race with China for quantum supremacy, and the outcome could have profound implications for the global balance of power. While the U.S.

currently leads in quantum computing, China and other countries are rapidly catching up, investing heavily in research and development. . . . If China wins the quantum race, it could gain a significant strategic advantage, potentially undermining U.S. economic and military dominance."[3]

Colorado's quantum regional innovation ecosystem is a national asset already contributing significantly to U.S. quantum R&D efforts, job creation, economic growth, and networking activities. The next challenge is to sustain this growth and build scale.

To sustain its leadership in science, manufacturing, and innovation, therefore, the United States needs to grow regional quantum innovation ecosystems—such as that which is emerging in the Mountain West—that connect national laboratories, educational institutions, technical workers, investors, large and small quantum firms, and supportive state and federal economic development efforts.

Substantial progress has already been made. Colorado's quantum regional innovation ecosystem is a national asset already contributing significantly to U.S. quantum R&D efforts, job creation, economic growth, and networking activities. The next challenge is to sustain this growth and build scale by intensifying regional assets and by collaborating with other quantum ecosystems, both U.S.-based and foreign.

Colorado's Quantum Innovation Ecosystem

Building on the existing unparalleled scientific core, Colorado and the Mountain West region overall are emerging as the national epicenter of the QIST (quantum information science and technology) industry. The area is currently home to more quantum organizations, companies, and jobs than anywhere else in the country.[4]

Presence of Federal Agencies in Colorado as an Enabler of Colorado's Quantum Ecosystem

The Mountain West region has an unusually dense array of federal laboratories and research undertakings. These organizations are a legacy of the Cold War, when U.S. planners saw the area around Boulder—just east of the Rocky Mountains (the Front Range)—as protected from Soviet missile strikes. Strategic considerations, including being far from the U.S. borders and from any highly built-up areas, led to the establishment of major research and military facilities, including Los Alamos National Laboratory and Sandia National Laboratories, both in New Mexico.[5] National laboratories and federal agencies were established in Colorado, New Mexico, and the surrounding environs during the Truman and Eisenhower presidencies, and a number of those organizations have maintained an active presence to the present day, augmented and reinforced by new federal initiatives in quantum science within the state.[6]

Colorado stands out for its remarkable geographic density and wide range of subject areas, with over 30 federally funded research and military facilities, which are listed below.[7]

The Mountain West region has an unusually dense array of federal laboratories and research undertakings.

Box 1: Federally Funded Research and Military Facilities in Colorado

- Bureau of Reclamation
- Division of Vector-Borne Diseases
- Cooperative Institute for Research in the Atmosphere
- Cooperative Institute for Research in Environmental Sciences
- Colorado State University Energy Institute
- Transportation Technology Center
- Laboratory for Atmospheric and Space Physics
- National Center for Atmospheric Research
- National Ecological Observatory Network
- Communications Technology Laboratory
- Physical Measurement Laboratory Boulder
- Earth System Research Laboratories
- National Centers for Environmental Information
- National Weather Service
- Space Weather Prediction Center
- National Renewable Energy Laboratory
- National Solar Observatory
- First Responder Network Authority Innovation and Test Lab
- Institute for Telecommunication Sciences
- Agricultural Research Service
- Agricultural Genetic Resources Preservation Research
- Center for Agricultural Resources Research
- Central Great Plains Research Station
- National Wildlife Research Center
- Rocky Mountain Research Station
- USGS Core Research Center

- National Science Foundation Ice Core Facility
- Fort Collins Science Center
- North Central Climate Adaptation Science Center
- U.S. Air Force Academy Research Laboratories
- Department of Veterans Affairs Research Laboratory

- **The National Institute for Standards and Technology (NIST)** has operated a major research facility in Colorado since 1954 and has done more than any other agency to promote the state's efforts in quantum science.[8] NIST formed the nation's first government-university research center, JILA, at the University of Colorado (CU) Boulder. In combination, NIST, CU Boulder, and JILA have become a world-leading center of precision measurement, driving international measurement standards. For example, NIST has established the world's most accurate time standards, such as atomic clocks, cesium atomic clocks, and optical lattice clocks, which have been key in the development of the Global Positioning System (GPS), communication networks, and the internet. NIST has also developed a frequency comb, which enables high-precision measurement of laser frequencies.[9] This has revolutionized technologies that support navigation, communication, finance, and environmental monitoring.
- JILA has emerged as an institution with an extraordinary track record of breakthrough innovations, and whose alumni feature prominently across the spectrum of public, private, and academic quantum activity in Colorado.
- In 1995, Colorado-based NIST scientists, led by Nobel Laureate David Wineland, demonstrated the world's first experimental quantum logic gate using trapped ions as qubits.[10]
- In 2009, Colorado-based NIST scientists demonstrated the world's first ion trap–based quantum processor capable of performing arbitrary quantum computations.[11]
- In 2024, NIST scientists at JILA demonstrated a new kind of clock based on nuclear energy levels, enabling a next-generation platform for precision metrology and the study of fundamental physics.[12]
- Universities, companies, and federal labs in Colorado have been engaged in quantum research for over 60 years, resulting in advanced research capabilities and accumulated expertise in the quantum domain. Colorado's world-class research infrastructure and know-how enables researchers to carry out advanced experimental research into quantum technologies. For example:
  - Colorado is home to the Boulder Microfabrication Facility at NIST Boulder, a 1,700 m^2 (18,000 ft^2) cleanroom with ISO Class 5 (Class 100), which is much larger than any other facility currently available at universities.[13] This facility allows staff at NIST Boulder and their co-researchers to investigate questions related to microelectronics, quantum technology, and associated fields. As one example of how this facility is enabling

important breakthroughs in the quantum sector, David Wineland, who received the 2012 Nobel Prize in Physics for his work on trapped ions, benefited directly from access to the NIST cleanroom.[14]

  - NIST operates a technology transfer program called the Professional Research Experience Program (PREP), which allows students and university researchers from
  - CU Boulder, CU Denver, and New Mexico State University carry out research at NIST Boulder.[15]

- In 2024, the **National Science Foundation (NSF)** announced its commitment of $20 million to establish a National Quantum Nanofab at CU Boulder, a site which will feature the design and construction of nanoscale quantum devices.[16] In addition,
  - In 2024, the NSF awarded a $1 million grant to support efforts by a collaborative research team to build a high-performance quantum networking testbed. This research team, led by researchers at the University of Oregon, also included experts at CU Boulder, NIST, Boeing, and other universities and research institutions.[17]
  - In 2020, the NSF announced a $25 million award for CU Boulder to launch a new quantum science and engineering research center called the Quantum Systems through Entangled Science and Engineering (Q-SEnSE) Institute.[18] The center is led by JILA Fellow Jun Ye and operates in collaboration with 13 other research institutions in the United States and overseas.
- **The Department of Energy's Sandia National Laboratories** have a research partnership with CU Boulder that addresses four thematic areas, one of which is quantum science. Over 200 Sandia employees are graduates of CU Boulder.[19]
- **The Defense Advanced Research Projects Agency** (DARPA) has selected three Colorado-based quantum companies—Quantinuum, Atom Computing, and Oxford Ionics (the latter of which was acquired by IonQ)—to participate in Stage A of the Quantum Benchmarking Initiative, which seeks to assess the feasibility of creating an industrially useful quantum computer by 2033.[20] Stage A includes $1 million of funding, with this amount potentially expanding to up to $300 million in Stage C.
- **The Department of Defense** (DOD) has funded numerous research projects by Colorado-based entities. For example, in 2024, the local quantum enterprise Infleqtion received $11 million from the DOD pursuant to the Accelerate the Procurement and Fielding of Innovative Technologies (APFIT) program to support the company's work on the Rack-Mounted Optical Clocks project.[21]
- **Small Business Innovation Research** (SBIR) awards have substantially benefited Colorado-based startups. To give one example, the Colorado-based company Vescent Technologies, which manufactures lasers with quantum applications, has received 78 SBIR Phase I and Phase II awards since its founding in 2002—totaling over $250 million—in support of practical applications for this key technology.[22]

University-Based Research

Colorado's research universities are working in concert with federal agencies to advance quantum technologies. CU Boulder and NIST Boulder have "been a stronghold of quantum research for decades."[23] The universities have generated successive breakthroughs in quantum science that are being translated into commercial applications by local quantum companies, a number of which originated as university spin-offs.

Rather than require startups to own expensive infrastructure themselves, quantum incubators in Colorado give startups access to state-of-the-art laboratory facilities and specialized equipment. In practice, this approach serves as a critical bridge between proof-of-concept research and scalable commercial manufacturing.

The universities have trained generations of top-level students who are now working at local companies and research organizations and tackling difficult problems in complex environments in quantum technology.

The universities have generated successive breakthroughs in quantum science that are being translated into commercial applications by local quantum companies, a number of which originated as university spin-offs.

The high quality of the state's research infrastructure and faculty enables Colorado to compete for the very best students from around the world. The University of Colorado (CU) has one of the largest physics programs in the country, while Colorado School of Mines was the first university to offer a master's degree in Quantum Engineering. The Colorado School of Mines campus is also home to the largest Society of Women Engineers in the United States.[24]

The University of Colorado at Boulder (CU Boulder)

The University of Colorado at Boulder arguably constitutes the world's leading epicenter of quantum ecosystem. CU Boulder has one of the preeminent physics departments in the world and has produced four Nobel Laureates in physics—close to half of the Nobel winners in quantum science globally. In fiscal year 2023-24, university researchers at CU Boulder secured a record $742 million in research funding.[25] In addition, CU Boulder is the site of JILA, a longstanding and extraordinarily productive research partnership between NIST and CU Boulder. CU Boulder is also home to the CUBit Quantum Initiative, an interdisciplinary hub formed collaboratively by a local triad of CU Boulder, the NIST Quantum Physics Division, and Front Range companies.[26] Furthermore, CU Boulder is taking the lead role in the establishment of the Boulder Quantum Incubator, a site supporting the launch of startup quantum companies.[27]

EXCELLENCE IN SCIENCE

Colorado has "long been positioned at the tip of the quantum spear."[28] The state has produced four Nobel laureates in quantum physics research, all of them working at CU Boulder and NIST.

- Carl Wieman and Eric Cornell (2001), along with another colleague, won the prize for identifying an exotic form of quantum matter, the Bose-Einstein condensate (BEC), whose molecular form may be used to develop various types of superfluidity, a state of matter which flows without experiencing any friction.[29]
- John "Jan" Hall (2005) shared the prize in physics with two others for his work on laser-based precision spectroscopy and the optical frequency cone technique.[30]
- David J. Wineland (2012) won the prize jointly with a colleague for "ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems."[31]

The presence of Nobel laureates at CU Boulder has exercised a gravitational pull, drawing in promising students from around the world and laying the groundwork for subsequent generations of talented research at the university. Dr. Jun Ye, for example, who has conducted groundbreaking research in laser precision measurement in ultracold atoms, was born in China but emigrated to the United States and entered the physics doctoral program at CU Boulder, becoming the last graduate student of the eventual Nobel Prize Laureate John "Jan" Hall. Dr. Ye remains at NIST and CU Boulder and is now one of the most highly cited researchers in experimental atomic physics in the world.[32] In 2015, President Obama picked Dr. Ye for a Presidential Rank Award for his work in quantum physics, ultracold matter, and precision measurement.[33]

JILA

JILA is a joint institute of CU Boulder and NIST physically located on the CU Boulder campus. JILA is one of the country's leading research institutes in the physical sciences.[34] Founded in 1962, JILA has been the principal driver in the development of Colorado's quantum ecosystem and represents the country's first and most successful research collaborations between the federal government and a university.[35]

Founded in 1962, JILA has been the principal driver in the development of Colorado's quantum ecosystem and represents the country's first and most successful research collaborations between the federal government and a university.

JILA enjoys recognition as one of the world's premier research and training organizations in atomic, molecular, and optical physics (AMO). JILA's scientific work is led by 28 JILA fellows and NIST employees, each of which heads a thematic research group that collaborates across JILA and with NIST, CU Boulder, and external partners. JILA does not have a director; authority is distributed among the JILA fellows. In this organizational structure, fellows serve as the heads of each research group, and they are responsible for determining the direction of research and hiring top talent.

- The JILA research groups average about 10 people, comprising primarily CU Boulder graduate students and postdocs, but also CU Boulder employee technicians and visiting international scientists. They are from countries across Europe, Asia, and the Americas.
- JILA has about 300 staff, including 150 CU Boulder graduate students and postdoctoral fellows and 70 CU Boulder administrative and technical support staff. The collaboration between NIST and CU Boulder within JILA has been so close that it is difficult to distinguish the NIST researchers from the CU Boulder fellows.
- JILA scientists include three with Nobel Prizes in physics, three MacArthur Foundation Fellows ("Genius Grant" winners), and eight members of the National Academy of Sciences.[36]
- JILA fellows are not limited to research in the area of quantum physics. In fact, they easily conduct interdisciplinary research with a high degree of freedom.

JILA has been responsible for numerous scientific breakthroughs in AMO physics, including the first cooling to the quantum ground state of a macroscopic object, the first evaporative cooling of molecules, the first quantum degenerate gas of polar molecules, the first Fermi condensate, and the first Bose-Einstein condensate. The NIST component of JILA, the Quantum Physics Division, developed the world's first self-referenced femtosecond laser frequency comb, one of the most powerful research and metrology tools since the 1960 invention of the laser.[37]

- About 400 of NIST's scientists and metrologists were trained at JILA and include top scientific leaders at the federal agency.
- JILA alumni enjoy leadership roles in the U.S. national laboratories outside NIST, in industry research labs, and in U.S. universities.[38]
- JILA's success has fostered at least one comparable government-university collaboration, the Joint Quantum Institute, a partnership between NIST and the University of Maryland launched in 2006.[39]
- JILA fellows have access to research infrastructure, including NIST cleanrooms, which are expensive and difficult for any single company or organization to fund by itself. It is important to note that to maintain this regional strength, JILA spaces need to be constantly updated with new facilities and equipment to meet the changing needs of today's cutting-edge research.

Significantly for the growth of the region's quantum ecosystem, JILA alumni are leaders in a number of Colorado's quantum companies:

- **Stable Laser Systems**, a maker of quantum stabilization technology, was founded in 2009 by Mark Notcutt, who trained at JILA under Nobel Laureate Jan Hall, who serves as a consultant to the company.
- **Infleqtion**, a developer of neutral atom quantum computing technology, was cofounded by Dana Anderson, a JILA fellow.
- **KMLabs**, a maker of tabletop laser systems, was spun out of the Kapteyne-Murnane group at JILA, and its cofounder, Henry Kapteyn, is a fellow at JILA.
- **Atom Computing**, a maker of quantum computers, was co-founded by a graduate student supervised by Dr. Jun Ye and is advised by him, who, as noted above, is a JILA fellow and advisor to Atom Computing with extensive achievements in the field of quantum measurement.[40]
- **Vescent Technologies**, which makes precision lasers with quantum applications, was spun out of JILA and NIST.[41]

CUBIT QUANTUM INITIATIVE

The CUbit Quantum Initiative is a partnership between CU Boulder, NIST's Quantum Physics Division, and local companies aimed at catalyzing the quantum activities of the University of Colorado (CU), including those of JILA.[42] CUBit partners with Boeing, ColdQuanta, Lockheed Martin, Atom Computing, SPIE (the international society for optics and photonics), and other entities.[43] CUbit has three research focus areas:

- **Quantum Computing and Simulation** manipulates many quantum particles with the hope of enabling exponentially greater speeds than conventional high-speed computers.
- **Quantum Networks and Communications** seeks to develop the ability to transmit and store quantum information over long distances.

- **Quantum Sensing and Measurement** develops ultraprecise measurement and sensing techniques with numerous potential applications, including navigation without GPS.[44]

CUbit oversees four quantum research centers at CU Boulder addressing three focus areas:

- **Q-SEnSE:** Quantum Systems through Entangled Science and Engineering (Q-SEnSE) is a Quantum Leap Challenge Institute, founded originally with funding from the NSF. It is led by CU Boulder in partnership with seven research universities, three national labs, and NIST. The institute is exploring how advanced quantum sensing can develop and apply novel quantum technologies, provide tools to support a national quantum infrastructure, and train a workforce with quantum skills.[45]
- **Quantum Systems Accelerator (QSE):** Originally funded by the Department of Energy (DOE), QSE is a multi-organizational entity aiming to successfully design and make scalable quantum computers modeled on JILA. QSA includes scientists from both JILA and NIST and is seeking to demonstrate quantum control of more than 50 ions, display an entangled many-body system with over 1000 atoms, and generate quantum algorithms for high-level quantum computing and simulation.[46]
- **Quantum Engineering Initiative (QEI):** The QEI is a new research center in which scientists from the CU College of Engineering and Applied Science and NIST Boulder Labs are collaborating to develop next-generation, field-deployable, ultra-stable clocks; to translate quantum sensors into quantum systems and networks; and to promote engineering students' engagement in quantum science.[47]

COLORADO SHARED INSTRUMENTATION IN NANOFABRICATION AND CHARACTERIZATION (COSINC)

CU Boulder's College of Engineering and Applied Science operates COSINC, a multidisciplinary shared user facility providing state-of-the-art access to instruments in a variety of disciplines, including micro and nano fabrication, metrology, and materials characterization. The tools have quantum systems applications.[48]

NATIONAL QUANTUM NANOFAB

In June 2024, the NSF announced a new $20 million facility—the National Quantum Nanofab—which will be established on the CU Boulder campus.[49] Characterized by CU Boulder researchers as the "'quantum machine shop' of the 21st century," the Nanofab will gather researchers from CU and around the country to develop the capability "to invent devices at the nano level."[50] Construction of the facility, which will comprise a cleanroom and nanofabrication tools, will take an estimated five years. The effort will be supported by, and connected to, the existing Colorado Shared Instrumentation in Nanofabrication and Characterization (COSINC) characterization and cleanroom facilities.[51]

BOULDER QUANTUM INCUBATOR

In January 2025, CU Boulder, Colorado State University, Colorado School of Mines, and Elevate Quantum announced a joint effort to establish the Boulder Quantum Incubator, a 13,000 square foot facility in east Boulder. The site will feature a collaborative office environment for early-stage

quantum companies supported by state-of-the-art scientific equipment, allowing scientists to test their ideas in the real world and turn quantum technologies into useful products for consumers. CU Boulder is providing leadership and staff resources to enable the creation of a robust testbed on its campus.[52]

Colorado School of Mines (Mines)

Colorado School of Mines in Golden, Colorado, is a public research university focusing on applied science and engineering. Mines has approximately 8,000 students, with 25 percent being graduate students pursuing doctoral or master's degrees. In addition, Mines is the home of one of the nation's first quantum engineering programs, launched in 2020.[53]

- Mines has designated quantum technologies as one of its areas of focus, and it is the first U.S. university to offer both master's and doctoral degrees in quantum engineering.
- Mines offers undergraduate and master's degrees in hardware and software, and doctorates in quantum engineering.
- The NSF awarded Mines a $3 million grant to develop intensive interdisciplinary training programs for master's and doctoral students in quantum information science (QIS).[54]
- Mines is playing a key role, as developer and landlord, in the creation of the research center and incubator, Quantum Commons, under the auspices of Elevate Quantum Arvada, Colorado.[55]
- Mines offers students who have completed a two-year Associate of Engineering Studies (AES) degree at a Colorado community college the opportunity to transfer their credits directly to Mines and seamlessly advance to a four-year degree program, including for the university's quantum engineering program.[56]

COLORADO UNDERGROUND RESEARCH INSTITUTE (CURIE)

Colorado School of Mines is developing a quantum research facility in the Edgar Experimental Mine in Idaho Springs as part of the school's participation in Elevate Quantum. When the facility is completed, it will be open for use by members of Elevate Quantum. The establishment of this facility deep inside a mine will enable researchers to test very sensitive equipment–such as quantum sensors and devices–in an environment shielded from the cosmic rays and electromagnetic noise present on the surface. The Mining Engineering Department at Mines is providing operational support and preparing the necessary tunnels and chambers.[57]

LABRIOLA INNOVATION HUB

The Labriola Innovation Hub, formed in 2024, is the "crown jewel of the Entrepreneurship and Innovation Ecosystem" at Mines.[58] Among other facilities, the Hub houses the Maybell Quantum Big Fridge, which can create an ultralow environment to enable the function of many quantum systems. The Big Fridge can create an environment 270 times colder than deep space and about 180,00 times colder than the coldest temperature ever recorded on earth. Maybell is renting the space for this project from Mines, which represents "exactly the kind of support Colorado School of Mines hopes to provide Colorado's quantum industry," according to Mines President Paul C. Johnson.[59]

BECK VENTURE CENTER

Colorado School of Mines is home to the Beck Venture Center, providing access to business incubation facilities and support resources for startups established using technology developed at Mines.[60] The 31,000-square-foot Venture Center represents an important part of the expanding innovation ecosystem for startups, investors, and service providers engaged with quantum technologies in Colorado. The Venture Center also is home to the Mines Venture Capital Fund, which is deeply integrated with Mines research and emerging technology investment opportunities.[61]

MINES SHARED INSTRUMENTATION FACILITY

The Shared Instrumentation Facility (SIF) at Mines serves as a regional analytical, fabrication, and testing resource that supports university, federal lab, and industry research. With cleanroom facilities for nanofabrication, characterization, and materials analysis, SIF serves as a partner to the expanding quantum R&D base for the public- and private-sector organizations in Colorado.[62]

Colorado State University (CSU)

CSU's quantum physics department is engaged in research into a variety of quantum themes, including atomic clocks, quantum computing, ultracold neutral atom plasmas, single atom detection, and laser spectroscopy of trapped ions.[63] For example, the school's W. M. Keck Laboratory for Quantum Computing is exploring—and already utilizing—the interaction between coherent optical radiation and neutral atoms through cutting-edge research techniques.[64] The DOE has awarded $16 million to CSU over four years to co-lead the establishment of the Research on Inertial Stability in Energy (RISE) Hub, alongside other partners. RISE aims to develop high-end laser technologies and make them more accessible to researchers.[65]

University of Denver (U Denver)

U Denver offers undergraduate, master's, and doctoral degrees in physics. In 2019, the W. M. Keck Foundation awarded a $1 million grant to fund a research collaboration between U Denver's Mark Siemens and Mines' Mark Lusk to explore possible uses of laser technology to conduct quantum experiments at room temperature rather than extreme cold temperatures.[66]

State-Level Policies and Initiatives

The state government of Colorado has solidly backed the development of quantum science and industry in the state, and the effort enjoys broad bipartisan support. Elevate Quantum's CEO, Zachary Yerushalmi, observes that "Democrat, Republican, Independent, sideways, whatever it is, everybody sees quantum as just this incredible, important swim lane that we can't afford to lose."[67]

Despite legal constraints imposed by Colorado's "Taxpayer"s Bill of Rights Law" that have made it difficult for the state government to spend large amounts of money to support the quantum sector, local communities, the governor, and the state legislature collectively have provided significant support for investment in quantum technology. This factor has been extremely important in growing the region's quantum innovation ecosystem.

The state government's promotional policies emphasize the sharing of research facilities and the creation of state-of-the art research centers available for use by academic and industrial actors on a shared basis.

Collaborations, and the spirit of cooperation, are pervasive throughout Colorado's quantum ecosystem. Government organizations, universities, and companies collaborate between and

among each other in so many ways that the boundaries between spheres are indistinct at best. This is a necessity because developing specialized quantum technologies and knowledge across multiple components is challenging for a single company.[68] The state government's promotional policies emphasize the sharing of research facilities and the creation of state-of-the art research centers available for use by academic and industrial actors on a shared basis.

Financial Support Through the Colorado Quantum Fund

In May 2024, the state of Colorado enacted HB24-1325, Tax Credits for Quantum Industry Support, which established the Colorado Quantum Fund.[69] This legislation created two tax incentives aimed at stimulating the development of the state's quantum ecosystem. Neither credit is available unless a Colorado-based entity receives either a multimillion-dollar federal grant from the Department of Commerce's Economic Development Agency (EDA) for the regional technology and innovation program or a comparable grant from another federal agency.

- **Tax Credit:** Section 2 creates a 100 percent refundable income tax credit for qualifying investments in fixed assets pursuant to a coordinated plan to create a shared quantum facility between 2025 and 2033. The amount of the credit is equal to the amount of the investment made by the applicant, subject to a cap of $44 million.
- **Loan Guarantee:** Section 3 offers a 100 percent refundable income tax credit to offset losses incurred by an applicant in connection with a loan to a quantum company—in effect, a loan guarantee. Qualified applicants include banks, private lending funds, and other entities that make loans to quantum companies. The maximum aggregate amount of all loan-loss credits is $30 million. The loan-loss reserve, based on a similar program at the DOE, is expected to leverage up to $1 billion in private capital for the local quantum industry.[70]
- **Elevate Quantum:** This 501(c)(3) nonprofit coalition designed to foster quantum-based growth in Colorado succeeded in securing a multimillion-dollar grant from the EDA for quantum-based economic development in 2023, enabling the state to use the Colorado Quantum Fund to support two projects: Quantum Commons, a research center in Arvada, and the Boulder Quantum Incubator in East Boulder.

The Colorado Office for Economic Development and Trade (OEDIT): The state's economic development organization administers the Section 3 quantum tax credits. In addition:

- In partnership with CU Boulder, OEDIT offers seed grants of $50,000 for translational quantum research, which are open to any Colorado research institution or industry partners, to move research out of the lab and into the marketplace.[71] In 2023, $1.5 million was allocated to funding this program.
- OEDIT awards Proof of Concept and Early Stage Capital Extension Grants through the Advanced Industries Accelerator (AIA) program, commonly referred to as Colorado's SBIR grants. Local quantum companies that have benefitted from this program include Maybell Quantum Industries and Resilient Entanglement.[72] Since 2013, more than $50 million has been granted to companies under the AIA program.

- In 2024, OEDIT sponsored a study led by CU Boulder on Colorado's quantum workforce needs, which was released as the state's "Quantum Workforce Roadmap" in 2024.[73]

Foreign Outreach

The state is reaching out to counterparts in like-minded countries that are also engaged in quantum research and industrial development. As international competition in the quantum field intensifies, Colorado is working to strengthen its position as a globally recognized location for quantum researchers and companies. Efforts are underway to establish multi-layered partnerships with foreign governments and institutions, between states and with local authorities, and with specific federal government agencies and research institutes.

- In 2024, a high-level Colorado delegation visited Denmark, Sweden, and Finland to encourage investment by those countries in the state's quantum and other high-tech sectors.[74]
- Colorado has signed memoranda of cooperation (MoCs) with respect to sectors like quantum and several other technology-intensive sectors with Finland (2022), the United Kingdom (2025), and New Zealand (2025).[75] The MoCs spell out thematic areas of planned collaboration—the Finland MoU, for example, specifies quantum high-performance computing and photonics.[76]

The Role of Elevate Quantum

Elevate Quantum (EQ) is a 501(c)(3) nonprofit coalition designed to foster quantum-based growth in Colorado, New Mexico, and Wyoming. The coalition was founded by Corban Tillermann-Dick and Zachary Yerushalmi to compete for, and win, funds from the federal CHIPS and Science Act of 2022 to make the region an officially designated regional quantum innovation hub. EQ is composed of 120 organizations, including companies, universities, educational and workforce organizations, and state and local government entities. Tillerman-Dick is the founder and CEO of Maybell Quantum, a company which specializes in advanced cryogenics, a refrigeration technology that is essential for certain quantum computers.

EQ and the state's efforts to win CHIPS Act funding were supported by Colorado Senators Michael Bennet and John Hickenlooper, Governor Jared Polis, Congressman Joe Neguse, other state officials, and university and industry leaders—a whole-of-state effort that ultimately succeeded.[77]

- In 2023, the Department of Commerce designated EQ as a regional tech hub and awarded a grant of $40.5 million to the group.[78]
- EQ qualified for $40.5 million in federal funding, thereby activating $74 million in matching state support and $1 billion in private capital. EQ, which has been active for only a few years, has already been positively characterized as the "local quantum industry's glue," providing the critical services to cross the divide between research coming out of a lab and commercialization for manufacturing at scale.[79]

- EQ's core expertise area is Quantum Information Technology (QIT), focusing on commercial applications in networking, computing, sensing, and enabling hardware.[80]

Cooperating on the Quantum COmmons

In September 2024, Colorado School of Mines announced the $14 million purchase of a research and startup campus in Arvada, Colorado, to advance the development of the region's quantum ecosystem.[81] This project combines several initiatives, including state tax credits, federal grants, land acquisition by Colorado Mesa University (CMU), and operations by EQ. Once developed, the 70-acre quantum research center will feature a 10,000-square-foot fabrication lab (fab) and cleanroom that will enable rapid prototyping and low-volume manufacturing of quantum technologies, while also serving as a base to train the necessary quantum workforce.[82]

The commons allows for shared and iterative R&D and the manufacturing of quantum-related technologies. Increasing the manufacture of photonic-integrated chips is one near-term goal of the partnership. Currently, this type of chip can take three to twelve months to procure for startup companies. The Quantum COmmons aims to establish a low-volume manufacturing line capable of the rapid production of such chips. The next step will be for the commons to collaborate with chip foundries and other manufacturing facilities to move from prototyping to mass production, thereby transferring knowledge, skills, and processes developed at Quantum COmmons.

Alongside the fab will be a 17,000-square-foot open innovation lab for collaborative R&D, and 70 acres available for open-access facilities expansion and co-location of quantum startups and scale-ups.[83] As of April 2025, the designs for these three project components had been completed, and construction is underway. Progress has been rapid, with companies expected to be able to move into the open innovations lab by July 2025.

This project will utilize half of the $40.5 million in federal funding allocated to EQ pursuant to its establishment as a regional tech hub. This federal funding activates a local ecosystem through matching funds, state commitment, and alignment with academic and industrial actors. In addition, Quantum COmmons qualifies as an "Enterprise Zone" as established by Jefferson County, Colorado, enabling it to access preferential measures such as investment tax credits, new employment credits, and R&D tax credits.[84]

Colorado-Based Quantum Companies

Over 50 Colorado-based companies are currently doing business in various applications of quantum technology, and Colorado is the only state with significant quantum infrastructure companies in quantum optics and low-temperature quantum systems.[85] There are more organizations in Colorado doing quantum work than anywhere else in the country.[86] Between 2020 and April 14, 2025, Colorado-based quantum companies attracted $596 million from investors.[87] Colorado has the highest concentration of companies in computer hardware, sensing, and quantum infrastructure and tools in the United States, and the state is the only place in the world where three world-class quantum computing companies are headquartered within a few miles of each other.[88]

Colorado's quantum companies benefit from the proximity of other technology-intensive industries in the state, including aerospace, semiconductors, life sciences, and clean energy.[89] Companies in these sectors represent an actual and potential customer base for quantum products and services, and also possess technical skills with potential applications for the manufacturing of quantum products. Furthermore, Colorado's quantum cluster enables quantum companies and end users to collaborate closely to advance practical applications of quantum technologies. As the quantum industry requires workers skilled in parts processing and assembly, engineers and technicians from the mature aerospace industry in Colorado are valuable assets.

In particular, Colorado is home to the second-largest aerospace industry in the United States. Several Space Force bases, including Schriever Space Force Base, Buckley Space Force Base, and Peterson Space Force Base, are located in the state. Colorado is also home to the headquarters of

the Space Operations Command. In addition, major aerospace companies such as Lockheed Martin, Northrop Grumman, Boeing, and United Launch Alliance, as well as a variety of aerospace-related startups, have established their operations in Colorado.

[Colorado] is the only place in the world where three world-class quantum computing companies are headquartered within a few miles of each other.

Leveraging its strengths in the aerospace and defense industries, the Colorado quantum ecosystem is expected to identify and be involved in a range of national security–related challenge areas to develop quantum technology use cases and secure funding from government agencies and private companies.

Quantinuum

Based in Broomfield, Colorado, Quantinuum is one of the world's largest integrated quantum companies, with over 550 employees and 420 PhD and MA-degree employees. The company is the result of the 2023 merger of Honeywell Quantum Solutions (HQS) and Cambridge Quantum (CQ) and operates out of eight locations in North America, Asia, and Europe.

- Quantinuum precursor HQS was formed in 2015 as a business unit of Honeywell International, specializing in hardware using trapped ions for quantum computing.
- The Honeywell executive who conceived of HQS believed that quantum computing would evolve to the point that it would be needed by almost all customers of Honeywell's business units, which then included aerospace, safety, performance materials, and building technology.
- Honeywell retained a 55 percent equity stake in Quantinuum and committed to invest $300 million in the merged company.
- CQ specializes in quantum software for numerous disciplines, including quantum chemistry, machine learning, and augmented cybersecurity.[90]
- The merged organization of Quantinuum plans to establish a cutting-edge R&D hub in neighboring New Mexico.

Quantinuum utilizes trapped-ion and other quantum technologies in quantum chemistry, cybersecurity, AI, machine learning, quantum Monte Carlo integration, and encryption applications.[91]

HQS launched the first H-series quantum computer in 2020, featuring a technology that allowed full connectivity between 12 identical high-fidelity qubits.[92] Quantinuum has subsequently released new iterations of the H-series computers featuring continuous improvements in performance and qubit volume.

- The H-2 series, introduced in 2023, featured 32 qubits, at the time representing the highest-performing quantum computer ever built.[93]
- In a Quantinuum-Microsoft collaboration, the two firms devised a technique to reduce the number of errors made by quantum computers—a principal challenge for this technology. With their new method, the companies ran 14,000 experiments on the H-2 without a single detectable error.[94]
- Quantinuum is introducing its Helios quantum computer in 2025, featuring 96 quibits, and its Sol computer in 2027, with 192 qubits.[95]
- Quantinuum's fifth-generation computer, Apollo, is expected to be available by 2030, featuring thousands of physical qubits, hundreds of logic qubits, and extraordinarily low physical error rates.[96]

Quantinuum has already developed a substantial customer base, providing a broad array of quantum-based applications, as listed in Table 1.

Table 1: Examples of Quantinuum's Customers and Applications

Customer	Application
Airbus	Hydrogen fuel fells
Thales	Cryptography
HSBC	Fraud detection
Chevron	LNG routing
DHL	Scheduling
JSR	Semiconductor defects
Amgen	Computational biology
Nippon Steel	Modeling iron crystals
Hess	Pipeline construction
Honeywell	Refrigerants
IDB	Blockchain
TotalEnergies	Carbon capture

Source: Harry Burhman, "Technical Perspective: By the End of the Decade, We Will Deliver Universal, Fully Fault-Tolerant Quantum Computing," Quantinuum (blog), September 17, 2024, https://www.quantinuum.com/blog/technical-perspective-by-the-end-of-the-decade-we-will-deliver-universal-fault-tolerant-quantum-computing.

Atom Computing

In 2018, two academics founded Atom Computing with only $5 million in seed funds, and the pair developed the world's first nuclear-spin-qubit quantum computer.[97] Today, Atom Computing builds gate-based quantum computers using optically trapped neutral atoms by means of optical tweezers—highly focused lasers that hold individual atoms in place—enabling other lasers to control more information. In contrast to other neutral-atom companies, Atom Computing uses the nuclear spin as its qubit, rather than electron spin, thereby providing it with various advantages, such as huge scalability, reduced complexity, long coherence times, and high fidelity.[98]

- In collaboration with Microsoft, Atom Computing has developed a commercial quantum system featuring 24 logic qubits, the largest number of entangled logic qubits to date, scheduled to be available for delivery in 2025.[99]
- Atom Computing holds the world record for neutral atom qubits with a 40-second coherence time (the longer quantum states can be sustained, the longer and more complex algorithms can be run).[100]
- Atom Computing is establishing its European headquarters in Copenhagen, supported by a 70 million DKK investment by the Danish government-owned Export and Investment Fund.[101]

Infleqtion

Infleqtion specializes in quantum-based products and services such as quantum sensing and neutral-atom-based quantum computing for applications in AI, energy, and defense. It uses lasers to precisely control atoms, then layers software on top to make the atoms work for various quantum technologies. The company was founded in 2007 under the name of ColdQuanta by Professor Dana Anderson at CU Boulder, who pioneered small-scale systems for cooling atoms to near absolute zero temperatures using revolutionary techniques such as magnetic trapping and laser cooling.

- Dr. Dana Anderson was a collaborator at CU Boulder with Drs. Eric Cornell and Carl Weiman, who created the first Bose-Einstein condensate (BEC), a new form of matter which is generated when atoms are cooled to near absolute zero, a feat for which they won the Nobel Prize.
- Building on these discoveries, Infleqtion uses lasers to arrange cesium or rubidium atoms in an extreme cold environment and to hold them in place, a method they employ across multiple quantum applications, such as computing, signal processing, sensing, and networking.[102]
- Infleqtion prides itself "on its longstanding history of developing deployable compact quantum hardware."[103] It is partnering with CU Boulder to develop quantum sensing using machine learning techniques with an eye to unprecedented navigation and positioning capabilities in real-world environments.[104]

Maybell Quantum

Maybell develops and produces cryogenic platforms that enable quantum computing technologies. It has offices in Denver and Copenhagen, and its CEO, Corban Tillemann-Dick, provided the strategic vision that led to the formation of Elevate Quantum.

- Maybell developed the Maybell Quantum Big Fridge, a quantum dilution refrigerator that is able to create conditions near absolute zero—more than 400 degrees Fahrenheit below zero—generating one of the coldest places on earth. Maybell developed the "Big Fridge" in collaboration with Colorado School of Mines. The fridge, which is currently being shipped to customers, is easier to use, more reliable, and much smaller than prior models.[105]
- Maybell has launched MayQ Labs, with quantum research centers in Denver and Copenhagen, to provide cutting-edge quantum tools to entrepreneurs.
- Maybell has signed a memorandum of understanding with South Korea-based Norma, a company specializing in quantum computing and security, to introduce an integrated quantum computing system in South Korea.[106]

Vescent Technologies

Vescent Technologies develops and manufactures precision laser and electro-optic technologies with applications in quantum computing, atomic clocks, and quantum sensing. Founded in 2002 by three scientists, Vescent began as a small company built on laser control research at NIST by Nobel Laureate Dr. Jan Hall, and one of the company founders worked at JILA as a graduate student. As of 2025, the company employs 45 people and generates about $11 million in annual revenues.

As companies look to scale and drive revenue growth, they need to establish a solid foundation of practical applications, engaged users, and resilient supply chains, while simultaneously advancing scalable quantum-related products.

These quantum-related companies have developed strong competitive advantages by tapping into Colorado's robust quantum ecosystem, characterized by national laboratories, educational institutions, workers, investors, private sector firms, and the state and federal governments.

As companies look to scale and drive revenue growth, they need to establish a solid foundation of practical applications, engaged users, and resilient supply chains, while simultaneously advancing scalable quantum-related products.

In order to achieve those goals, sustained, long-term support from government agencies remains critical to move innovative products up the entire innovation pipeline, from early-stage research to commercialization. Government agencies can play crucial roles in supporting early adopters of

quantum technologies. For example, agencies with missions that can be supported by quantum applications can catalyze market attention by purchasing products, investing in supply chains, and collaborating on broader challenges through initiatives like hackathons, proof-of-concept projects, and prizes, as well as steady support through programs like SBIR for incremental progress and DARPA for game-changing technological advances. Programs that encourage cooperation between large and small companies to develop new products to meet market needs can also play a major role.

Workforce Initiatives

Colorado is renowned as a world-leading hub for training quantum experts, and its universities offer advanced degree programs in quantum physics and engineering.[107] In fact, "many generations of graduates from Colorado universities have gone on either to found leading quantum companies or to hold prestigious positions at universities around the world."[108] Colorado already has 3,000 people working in quantum-related jobs, more than any other state, and Elevate Quantum estimates that the need for quantum-proficient workers may well rise to 10,000 by 2035, a daunting challenge even for a state with deep educational and training capabilities.[109] More trained manpower is essential. Indeed, such a workforce can help generate innovative solutions. To meet the opportunity and the challenge of growing an ever-more-robust quantum ecosystem, it will be important to increase quantity while maintaining quality. The Mountain West region needs to avoid the "tyranny of small scale," a challenge many regional leaders seem to fully appreciate.

Quantum Workforce Roadmap

Reflecting the recognized need for growing the workforce, two organizations at CU Boulder—CUbit Quantum and the university's Workforce Development Hub—led a collective effort to develop a Colorado quantum workforce roadmap, which was released in the fall of 2024. The roadmap identified the state's workforce strengths and gaps and included recommendations to address anticipated workforce challenges. The effort engaged over 200 representatives from the state's educational institutions, businesses, and other groups, as well as NIST and Sandia National Laboratories.[110] The roadmap found that the Colorado ecosystem has "well-established programs

for training a quantum-ready workforce at multiple institutions of higher education," but that "a more comprehensive focus on workforce development is essential, building on and aligning with the strategies proposed by Elevate Quantum."[111]

An estimated 80–90 percent of the jobs created by quantum capabilities will not require doctoral-level qualifications and instead call for skilled technical workers to fill positions such as lab technicians, engineers, welders, salespeople, financial professionals, and other competencies.

A key finding of the 2024 study is that an estimated 80–90 percent of the jobs created by quantum capabilities will not require doctoral-level qualifications and instead call for skilled technical workers to fill positions such as lab technicians, engineers, welders, salespeople, financial professionals, and other competencies. Thus, the roadmap calls for "a robust system of high schools, two- and four-year colleges, and workforce training programs."[112]

The roadmap emphasizes the need to break down the arcane science underlying quantum physics and information science into easily understandable terms. It recommends providing K-12 teachers with resources to explain quantum physics to students and to describe how it is becoming part of students' everyday lives. Furthermore, the roadmap advises expanding curricula at the state's community colleges to teach practical quantum-relevant skills such as welding, programming, and electronics. Finally, it advocates expanding career pathways for rural residents, women, and other groups historically underrepresented in physics to enter the quantum field.[113]

K-12 QUANTUM BLUEPRINT

On April 14, 2025—World Quantum Day—Colorado released *Advancing K-12 Quantum Education—A Blueprint for State Leaders*, which details a long-range plan to prepare students for careers in quantum science and industry. The state's objective is to integrate quantum concepts and competencies into a well-rounded science, technology, and math (STEM) curriculum to ensure that all Colorado students are familiar with quantum science and prepared to pursue careers in the field.[114] The blueprint spells out a detailed series of measures and a timeline for their implementation, comprising the following: the integration of state quantum online information at a single site; the expansion of teacher externships in quantum; the establishment of quantum professional learning (PL) resources that teachers can use to satisfy their PL requirements; the establishment of a statewide QIST framework; and the leveraging federal career and technical education (CTE) funds by integrating QIST concepts into existing CTE pathways.[115]

FRONT RANGE COMMUNITY COLLEGE (FRCC)

Colorado's FRCC, the largest community college in Colorado, is the only community college in the state to offer an optics and photonics program that directly supports the state's quantum workforce. FRCC estimates that technician roles in the quantum industry will double in five years,

demanding soldering technicians, machinists, welders, and various other roles. The school's optics and photonics program trains laser, optics, and photonics technicians who will have key roles in the state's quantum industry.[116] Supportive investments will be necessary to reinforce and grow this asset.

Conclusion

Robust regional technology ecosystems are the foundation of continued U.S. leadership in science, manufacturing, and innovation. Growing these clusters requires long-term institutional support and funding to connect national laboratories, educational institutions, workers, investors, quantum firms, and state and federal government programs.

Fortunately, the nation already possesses a unique and highly concentrated cluster of interconnected stakeholders in Colorado and the broader Mountain West region. This ecosystem brings together world-class talent, including Nobel laureates in quantum physics, with advanced research infrastructure and deep institutional expertise in the NIST laboratories and their cooperative programs with the University of Colorado Boulder and the JILA facility. Together, these groups form a dynamic environment that enables innovation and increasingly fosters commercialization.

Robust regional technology ecosystems are the foundation of continued U.S. leadership in science, manufacturing, and innovation. Growing these clusters requires long-term institutional support and funding.

Colorado's quantum ecosystem is expanding its role from a global hub for fundamental quantum research to a center of the emerging global quantum industry. This innovation ecosystem is a

national asset that contributes significantly to U.S. quantum R&D and provides a firm foundation for attendant job creation, economic growth, and enhanced national capacities. Colorado's quantum hub benefits from unique assets, notably facilities, a supportive state government, and the ability to leverage public investments with private sector partners. With sustained support at scale, the region can help the United States lead the global race in quantum technology.

The Colorado quantum ecosystem is a remarkable national asset, demonstrating how scientific knowledge can be translated into practical applications with enormous economic and strategic potential. It is a model of successful federal-state collaboration and enlightened, bipartisan public policy measures with a hugely positive regional impact. That said, as Colorado's leaders are acutely aware, the commanding position the state has achieved in quantum science could be erased in the not-so-distant future in the absence of a sustained national effort to address the quantum challenge emerging from China. Continued investments across the ecosystem and cooperation at the national and state levels will be essential to the continued growth of the U.S. position in quantum technologies.

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