QUANTUM

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BUILDING A QUANTUM-READY WORKFORCE

A Roadmap for Colorado and the Mountain West Region

Acknowledgments

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Ecosystem Signatories

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Boulder Valley School District
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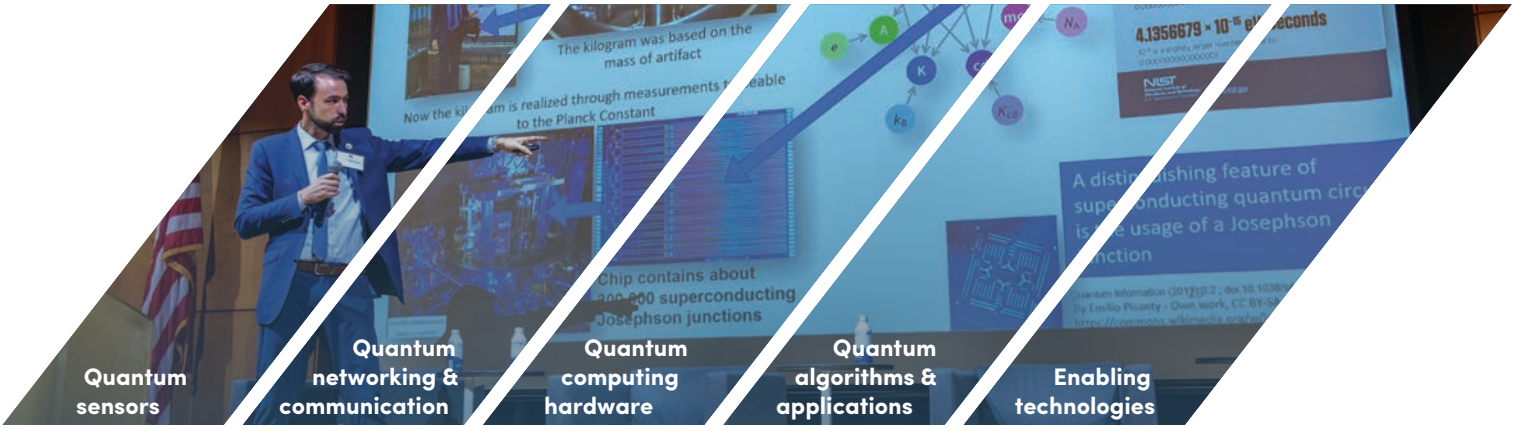
Executive Summary

Recent national efforts established to bolster United States' leadership in Quantum Information, Science, and Technology (QIST) include the National Quantum Initiative Act[1] (NQI), the formation of the Quantum Economic Development Consortium (QED-C), and a multitude of federal funding opportunities. Growing in national prominence, Colorado and the Mountain West region represent a significant area of opportunity for QIST based on the region's vibrant technology ecosystem, research and educational institutions, national labs, industry investments, and progressive workforce development policies and programs.

Colorado's leadership in the quantum industry led to its 2023 designation and 2024 funding for the Elevate Quantum Initiative as an Economic Development Administration Regional Technology and Innovation Hub. The region, including New Mexico and Wyoming partners, will soon have access to over $120 million in federal, state, private sector, and non-profit funding for quantum programs, infrastructure, and capacity building. To further support this opportunity and accelerate its success, the Colorado Office of Economic Development and International Trade generously funded a 2023 effort managed by the University of Colorado's CUbit initiative to convene cross-ecosystem, regional stakeholders to develop a "roadmap" for Colorado and the Mountain West to build a quantum-ready workforce.

The roadmap effort included the (1) recruitment of a cross-ecosystem team to represent the region's industry, government, and skill-building institutions, (2) creation of the 2023 Quantum Workforce Development Forum where over 200 QIST industry, government, and skill building experts convened to educate, align, and provide a common vision to support QIST, (3) development of a vision document including emerging themes to guide a subsequent roadmap, (4) alignment and easily-understood definitions of QIST market segments and skills required, (5) identification of the region's current state workforce development strengths and gaps, and (6) creation of the roadmap with accompanying workforce recommendations for the next 3-5 years.

The QIST market includes five segments, each with its own relative maturity and density in the region:



/ OCTOBER 2023 QUANTUM WORKFORCE DEVELOPMENT CONVENING

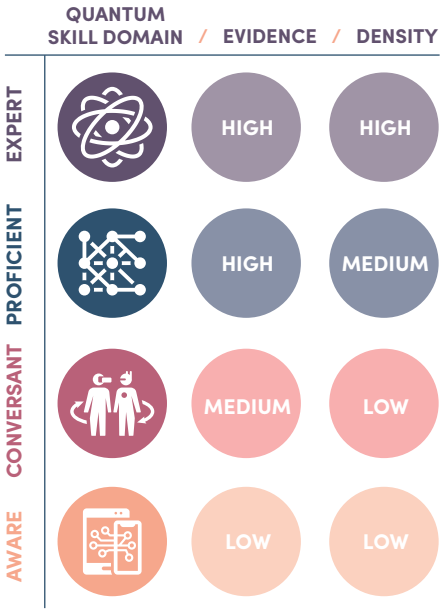
EXECUTIVE SUMMARY

Strengths and Gaps

The Colorado ecosystem has well-established programs for training a quantum-ready workforce at multiple institutions of higher education, and partnerships across the region are riding the tailwinds of the recent Elevate Quantum effort. Despite the recent percolation of programs and increased attention on Colorado's quantum assets, a more comprehensive focus on workforce development is essential, building on and aligning with the strategies proposed by Elevate Quantum. Perhaps one of the most critical opportunities to grow the QIST workforce is by removing barriers in communicating with the broader community about opportunities QIST will offer[2].

The scarcity of U.S. programs with experiential quantum training labs further limits workforce preparation in this rapidly evolving field frequently focused on improving quantum hardware and useful quantum systems.

QIST workforce strengths are highlighted by skill domain area, using a schema that relatively ranks the **evidence** of skill building programs that are unique to the region and not typically represented in other geographies, and the **density** of said programs which represents relative scale and prominence in the region.



The rapid emergence of the quantum industry necessitates the development of a well-prepared workforce to sustain and drive forward innovation in Colorado and the Mountain West region. The recommendations below outline a strategic approach focused on alignment, skill building, and assessment, with the ultimate goal of building a robust, quantum-ready workforce.

Recommendations

Alignment: To build a cohesive regional strategy, it is vital to establish measurable industry and workforce metrics, commission a comprehensive "State of Colorado's Quantum Industry" report, and actively support the Elevate Quantum Workforce Collaborative (EQWC). These steps will ensure alignment across stakeholders and enable effective monitoring of progress, thus providing a data-driven foundation for future initiatives.

Skill Building:

QUANTUM EXPERT: For those who will lead in quantum research and development, it is crucial to regularly convene regional higher education quantum program leaders. These leaders should collaborate to increase awareness of existing programs, share resources, and identify opportunities to bolster partnerships between institutions. Additionally, leveraging institutional strengths to address regional gaps—such as expanding access to specialized lab experiences and offering foundational quantum courses across institutions—will enrich and diversify the quantum talent pool.

QUANTUM PROFICIENT: Building proficiency in quantum technology requires significant investment in industry-informed pathways and experiential training programs. Establishing a statewide quantum sector partnership, aligned with the national Next Generation Sector Partnership Community of Practice, will ensure that training tracks with industry needs. Creating quantum-adjacent pathways, particularly in biotechnology, aerospace, semiconductors, and IT/computer science, will connect existing regional industries to quantum technology. Furthermore, expanding hands-on experiences at two-year and four-year institutions and enhancing quantum internship programs will create a robust pipeline of talent, increasing the likelihood of retaining skilled graduates within the region.

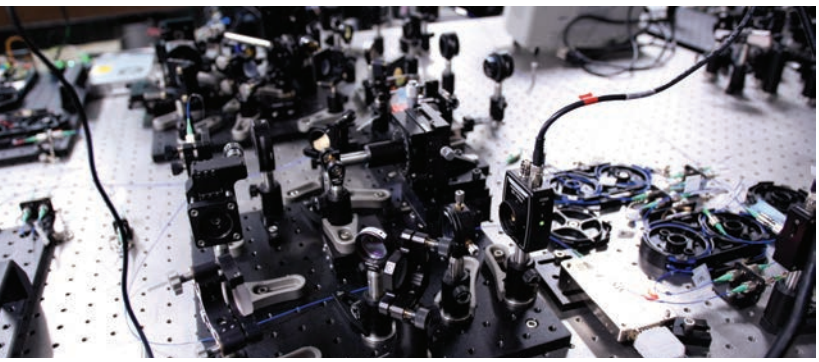
QUANTUM CONVERSANT: For professionals who may not specialize in quantum technology but need to be conversant, integrating quantum-related content into existing statewide platforms and initiatives is essential. Developing a quantum career and technical education pathway under the Colorado Department of Education's standards will promote visibility and accessibility of quantum education. Scaling quantum-specific and adjacent programs through the Colorado Community College System and leveraging apprenticeship intermediaries, such as CareerWise and Apprenticeship Colorado, will expand opportunities further to reach non-traditional learners and industries to engage with quantum technologies.

QUANTUM AWARE: At the most basic level, creating quantum awareness among educators and the general public is critical. Implementing a "Teaching the Teachers" program by deploying resources from national initiatives like the National Q-12 Education Partnership will equip K-12 educators with the tools to introduce quantum concepts. Launching experiential programs to inspire K-12 learners to engage in broader STEM and quantum experiences is essential. Additionally, launching a broad quantum literacy campaign will raise public understanding of quantum technology, ensuring that all community members, including government and business professionals, are informed and able to engage with the quantum economy. This inclusive approach will help to democratize access to quantum education and opportunities.

Assessment:
Given the early stage of quantum industry development, adopting an agile assessment strategy is imperative. This approach should blend quantitative analysis with qualitative insights, drawing from learner experiences and industry feedback to continuously refine workforce development programs. Regular assessment involving all stakeholders, including learners, will ensure that programs remain adaptive and aligned with the rapidly evolving demands of the quantum industry.

> My hesitation to pursue a quantum job is that I think quantum is a very specific field that most people know very well, and that those people have much more education than I do"
>
> / QUANTUM LEARNER PERSPECTIVE

By fostering strategic alignment, investing in targeted skill building, and maintaining rigorous assessment practices, the region can cultivate a diverse and capable quantum workforce that drives future innovation.



/ QUANTUM OFTEN REQUIRES FAMILIARITY WITH OPTICS AND PHOTONICS PRINCIPLES

/ QUANTUM WORK IS A GROUP EFFORT

CONTEXT

Context

NQI, passed in 2018, is a landmark piece of federal legislation aimed at accelerating quantum research and development. It established a coordinated federal effort to advance quantum science and technology; invest in research, education, and workforce development, and bolster collaboration among government, industry, and academia to maintain America's leadership in the emerging field of quantum technology. By fostering innovation and investment in quantum computing, communication, and sensing, the act lays the groundwork for transformative breakthroughs with profound implications for cybersecurity, healthcare, and beyond.

As part of the initial NQI, QED-C was established with support from NIST. Since its inception, QED-C has grown to become the largest quantum industry consortium in the world. In 2022, QED-C surveyed its members to better understand both the demand and the required skills on the Quantum Information, Science, and Technology (QIST) horizon, paying particular attention to the role of the professional technician in the quantum ecosystem[3]. This document leverages those early efforts to inform a Colorado-centric strategy.

/ SIGNING HOUSE BILL 1325 INTO LAW AT JILA

Most recently, Colorado's leadership in the quantum industry led to its designation by the Economic Development Administration as a Regional Technology and Innovation Hub[4]. With federal, state, private sector, and non-profit funding, and a partnership with New Mexico and Wyoming, the region will soon have access to over $120 million for quantum programs, infrastructure, and capacity building. **With such a concerted and collaborative effort, Colorado and the Mountain West aim to launch over 50 new quantum companies, add over 10,000 jobs to the local economy, and attract close to $2 billion in capital investments[5].** With its growing quantum economy, the region has the opportunity to build quantum education and workforce training programs intentionally to create a more skilled and diverse quantum-aware community.

With these efforts as the backdrop, the University of Colorado Boulder and Colorado's Office of Economic Development and International Trade (OEDIT) convened a workshop of higher education, industry, national laboratory, and government stakeholders in October 2023. Building on the work of the QED-C, the gathering emphasized the role of non-PhD quantum workers including professional technicians and focused on connections among K-12, community colleges, smaller four-year universities, and research-intensive universities. **The output of this**

workshop was a vision document entitled "Creating a Colorado Quantum-Ready Workforce in Service of the Nation[6]." This vision document identifies five emerging themes which together show what a successful quantum workforce pipeline could look like:

- Creating cohesiveness and connection
- Industry-driven learning objectives that lead to credentialing equivalents across institutions
- Accessing hands-on laboratory infrastructure
- The criticality of effective training of instructors across Colorado
- How to inspire and raise awareness – the power of the story

These themes were used as a basis for this Roadmap.

Study Scope

This report provides both a snapshot of current resources available for QIST education and workforce training and recommendations for how **Colorado and the Mountain West** can create and deploy additional resources both to support existing workforce demands and to meet growing, future demands. A three- to five-year outlook centers on the Colorado ecosystem with New Mexico and Wyoming included as complementary stakeholders. It is intended to be used by policymakers, industry leaders, educators, and the public.

Gaining the Industry Perspective

Engaging with the quantum industry is essential for gaining a well-rounded perspective on workforce demands and the future of the sector. Industry workshops were a key tool in understanding the specific skills and expertise required by quantum companies, offering direct insights from business leaders. Local quantum companies opened their doors for guided tours, giving core team members a first-hand look at the operational needs of the quantum sector. Additionally, participation in industry panel discussions and regional workforce conferences facilitated deeper discussions about talent gaps and workforce preparation. Collaboration through statewide institutional ideation sessions further helped in brainstorming solutions for building a robust quantum workforce. Lastly these activities were conducted in parallel during the development of the "Elevate Quantum INCLUDE" proposal, aimed at promoting inclusivity in quantum workforce development.

Tapping Surveys and Published Reports

A literature review tapped into a wealth of data from surveys and published reports. The Quantum Economic Development Consortium (QED-C) has been particularly instrumental, offering detailed reports that highlight trends, workforce challenges, and growth potential within the industry. Published academic works provided a broader context on the current state of the quantum sector, discussing technological advancements and commercialization efforts. Where available, regional data on the quantum workforce offered more localized insights, allowing for targeted analysis of regional strengths and areas in need of support.

/ HANDS-ON EXPERIENCE WITH INSTRUMENTATION IS CRITICAL FOR QUANTUM WORKFORCE DEVELOPMENT

OVERVIEW OF COLORADO'S QUANTUM ECOSYSTEM

OVERVIEW OF

Colorado's Quantum Ecosystem

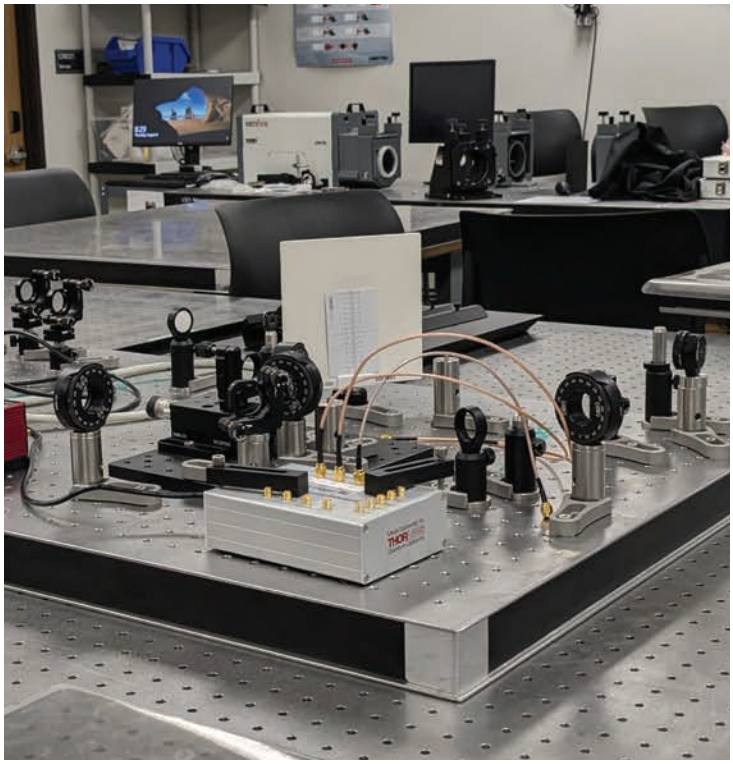
In the rapidly evolving landscape of QIST, Colorado - renowned for its prowess in technology and innovation - now lies at the forefront of this revolution. As the quantum industry surges forward, critical questions arise: What is the current condition of workforce development for the quantum industry in Colorado, and what gaps need to be filled to grow capacity and innovation?

The quantum industry, with its potential to revolutionize computing, communications, navigation, personalized healthcare, and cryptography, demands a workforce equipped with specialized knowledge and skills. Colorado, with its vibrant tech ecosystem and research institutions, has recognized the significance of nurturing a quantum-ready workforce. However, the journey towards achieving this goal is nascent, multifaceted, and dynamic.

At the heart of Colorado's quantum workforce development lies education. Universities across the state have been proactive in establishing programs tailored to quantum science and engineering. Institutions such as the Colorado School of Mines, the University of Colorado campuses, and Colorado State University host academic programs focused on quantum computing, quantum materials, quantum sensing, and quantum communication, as well as strong physics and engineering curricula. These programs not only provide students with theoretical knowledge, but also offer hands-on experiences through laboratory courses, research opportunities, extracurricular engagements, certification and micro-credential opportunities, and internships, preparing them for careers in the quantum industry. Regional community colleges have also begun to offer unique certificate programs including Front Range Community College's Optics & Photonics Program.

The National Institute of Standards and Technology (NIST) has been a world leader in the physical sciences and precision measurement for more than 60 years. NIST Boulder laboratories provide research, measurements, technologies, tools, data, and services that support innovation in QIST.

Connecting higher education and government resources is JILA[Z], a long-standing joint institute between CU Boulder and NIST Boulder. Over its 60-plus -year history, JILA researchers have earned four Nobel Prizes in quantum science, while training hundreds of graduate



/ FRONT RANGE COMMUNITY COLLEGE PHOTONICS TEACHING LAB

COLORADO'S QUANTUM ECOSYSTEM

students and post-doctoral researchers to currently work in and lead the quantum industry worldwide.

For decades, Colorado's public institutions, private enterprises, and academia have led quantum research and commercialization. Further, partnerships span the region ranging from New Mexico, through Colorado, and into Wyoming. Colorado also has a history of bringing the international quantum community together by hosting faculty, students, and researchers from around the world, organizing conferences and symposia, and attracting international companies.

/ JILA

Quantum companies, and other high-tech industries, ranging from startups to large corporations continue to invest in Colorado. The state has been ranked the #1 'State in Private Aerospace Employment Concentration'; #2 'State to Start a Business' and 'State for Technology and Science'; #3 'State for Startup Early Job Creation'; and # 4 'State for Concentration of STEM Workers' [8].

Additionally, Colorado has been recognized for its leadership in innovative workforce development programs including leadership in key policies the state is putting into place to "erase the arbitrary boundaries between high school, college, and the world of work and open the opportunity for all young adults to move along a path toward a postsecondary credential and preparation for a career."[9]

In summary, Colorado's QIST ecosystem has been built on strong academic, government, and corporate commitments. Over time, this has created a strong foundation that has enabled the formation of strategic partnerships, coalition forming, cooperative agreements, and a general collegial spirit to fuel growth. With recent awards providing significant financial and human capital, Colorado and the Mountain West have an opportunity to lead the nation into the next generation of QIST research, education, and application.

COLORADO / RANKINGS

#1 State in Private Aerospace Employment Concentration

#2 State to Start a Business
State for Technology and Science

#3 State for Startup Early Job Creation

#4 State for Concentration of STEM Workers

Market Segmentation for the Quantum Industry

A broad look at the quantum industry reveals the following market segments[10] with illustrative examples of Colorado-based companies:

QUANTUM SENSORS: company that is developing a sensor, such as a clock, magnetometer, gravimeter, or accelerometer, that utilizes quantum mechanical principles to achieve improved precision and accuracy.
Colorado Companies Include: Infleqtion, QuSpin, FieldLine, Vapor Cell Technologies, LongPath Technologies, Mesa Quantum, and Flari Tech, Inc.

QUANTUM NETWORKING AND COMMUNICATION: company that is producing quantum-key distribution technologies or software, or is engaged in the development of hardware technologies to distribute entangled states.
Colorado companies include: Xairos Systems, Icarus Quantum, and Secured Quantum Services.

QUANTUM COMPUTING HARDWARE: company that is building a quantum computer using many different hardware approaches, such as superconducting, trapped-ion, or photonic qubits (including the software development required for the hardware to operate).
Colorado companies include: Quantinuum, Atom Computing, and Infleqtion.

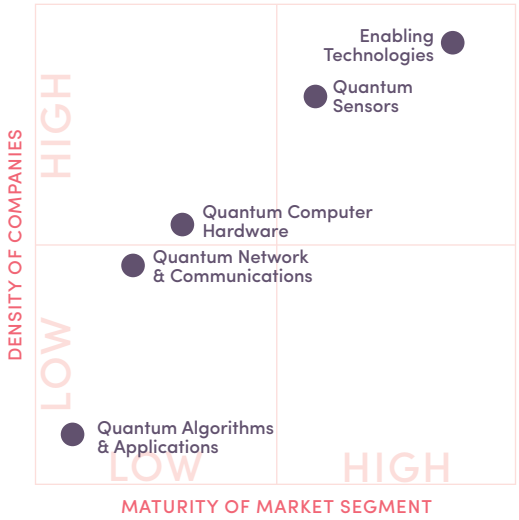
QUANTUM ALGORITHMS AND APPLICATIONS: company that approaches a real-world problem and applies knowledge of quantum computation to solve it or develops platforms designed for quantum solutions.
Colorado companies include: Resilient Entanglement and Quantum Rings, Inc.

ENABLING TECHNOLOGIES: company that builds often customized hardware that is used in either quantum sensors, network and communications, or computing hardware.
Colorado companies include: Maybell Quantum, Vescent Technologies, FormFactor, KMLabs, Danaher Cryogenics, Octave, and Vexlum.

The recent EDA Tech Hub designation awarded to the Mountain West region affirmed that the quantum ecosystem in Colorado is solid and poised for growth. Although still broadly in the nascent stage, the quantum industry is beginning to reach critical mass and is therefore able to be analyzed both subjectively and objectively.

Colorado's current quantum economy can be evaluated by looking at both the relative maturity of the given market segments and the relative density of companies present in the region. Not surprisingly, quantum sensors and quantum

COLORADO'S QUANTUM ECOSYSTEM



/ Relative maturity of Colorado quantum market segments and relative density of companies present in the state compared to market segments across the U.S.

enabling technologies score high on both relative maturity and on density of companies targeting these objectives. This is due, in part, to the long-standing mature markets surrounding the optics and photonics industry in the state.

Quantum computer hardware, and network and communications applications range in the middle, mostly due to the strong research programs in atomic, molecular, and optical physics residing at both NIST Boulder and affiliated university institutes (e.g. JILA). The segment with the lowest density of companies is also the most nascent: the application of quantum computing and/or the creation of computing algorithms needed for application development for sectors including energy, chemistry, pharmaceuticals, aerospace, telecommunications, finance, and logistics. As such, this segment may represent a strong growth opportunity for the region, but will require a unique software skill set separate from hardware-dominated segments.

With such diversity in quantum market segments, universal recommendations for skill development initiatives can be challenging. Additionally, investments from the private sector and incentives from state and federal agencies will inevitably dictate specific workforce development priorities. Therefore, it is most appropriate to look at workforce development not only in the context of market segmentation, but also through the lens of the skills needed for success and advancement in the aggregated quantum industry.

Quantum-Adjacent Industries

Given the emerging state of the quantum industry, it is important to recognize that the existence of mature adjacent industries can complement, and even accelerate, the evolution of a quantum workforce. "Quantum-adjacent" refers to industries that share many commonalities with quantum science, but are not defined as quantum markets per se. These adjacent industries either share employee skill requirements or are markets projected to be impacted by quantum technologies and applications. As Colorado touts many quantum-adjacent industries, the region therefore has an opportunity for employment mobility when considering the needs of developing a quantum workforce.

Quantum-adjacent industries present in the Mountain West include:

- Semiconductor Development and Production
- Advanced Manufacturing
- Aerospace and Avionics
- Biosciences and Pharmaceutical Production
- Information Technology and Cybersecurity
- Telecommunications
- High Performance Computing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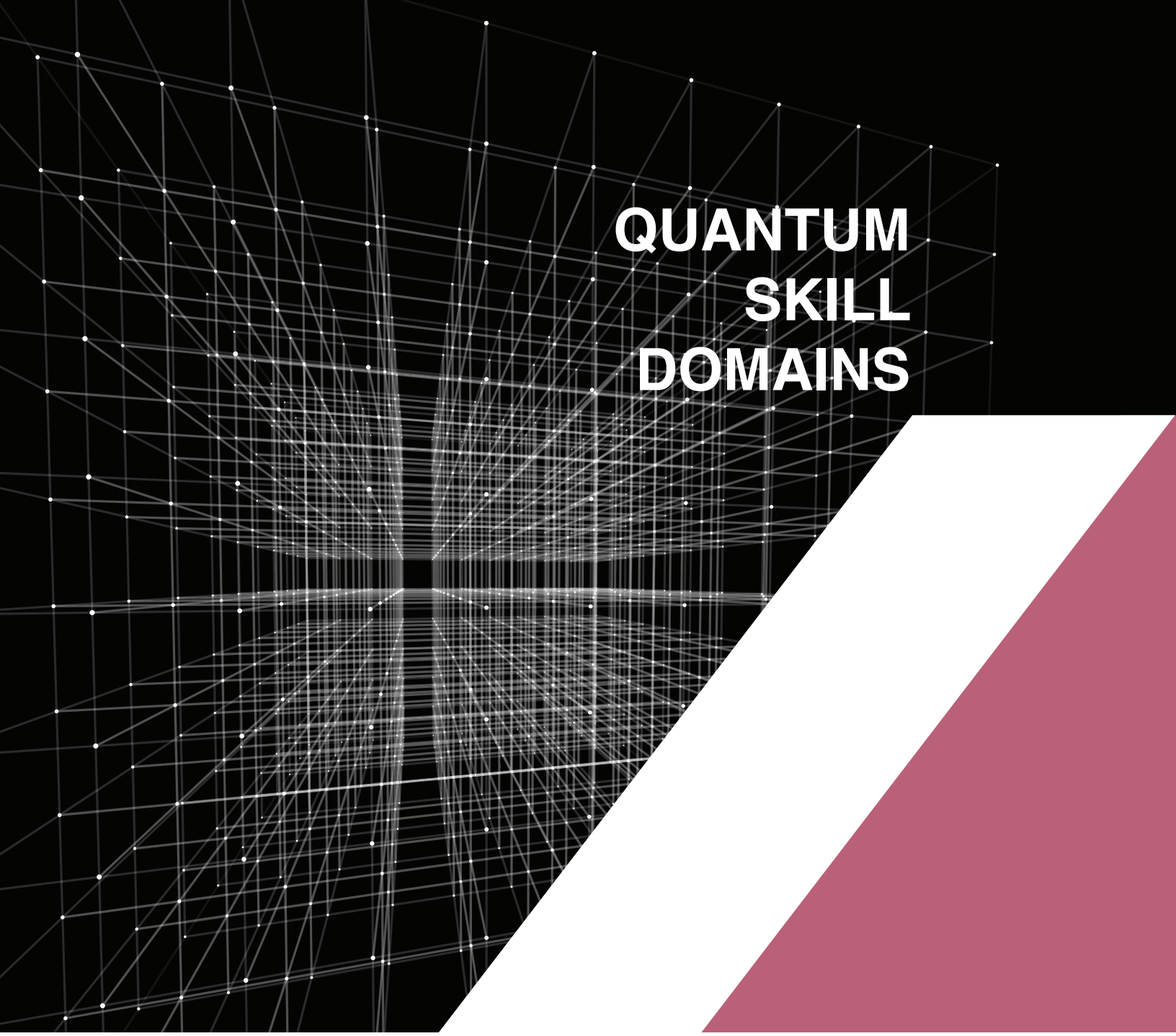
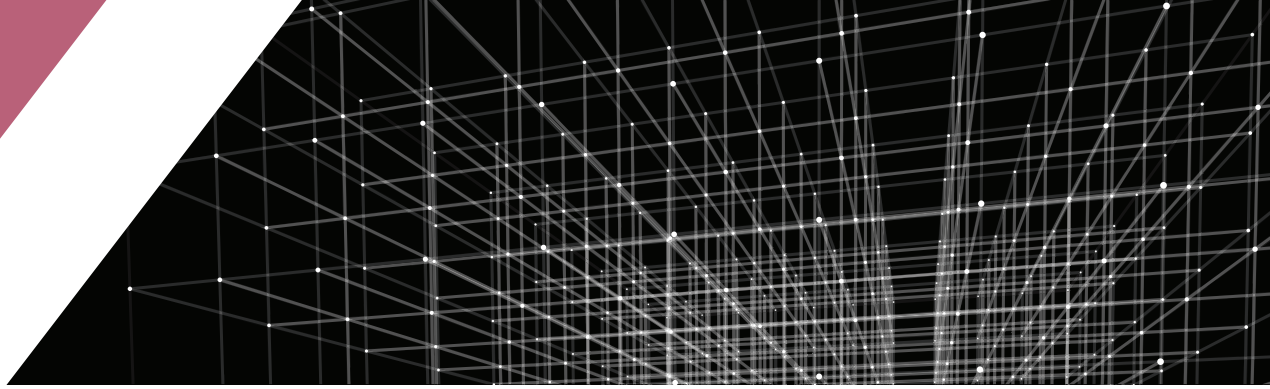


QUANTUM SKILL DOMAINS



Quantum Skill Domains

Defining Quantum Knowledge, Skills, and Abilities

The rapid pace of quantum technology advancements presents the challenge of developing a comprehensive list of mutually-agreed upon KSAs. Various organizations and research efforts have begun to segment the critical skills needed for quantum jobs, often distinguishing between "quantum technician" jobs and "advanced engineering" jobs. The discussion often results in a question of which job segment has the most critical demand.

As mentioned above, it is worth noting the ongoing efforts by the QED-C that have begun to survey quantum industry members to better understand skill needs, in addition to ongoing efforts led by collaborative research teams like the NSF-funded grant, "Education Landscape for Quantum Information Science and Engineering: Guiding Education Innovation to Support Quantum Career Paths."[11] Since each quantum industry segment may have nuanced skill requirements, understanding Colorado's specific quantum skill needs depends on state prioritization.

The skills that will support the quantum industry vary from highly specialized, subject-specific ones to those that are widely trainable and technical in nature. Further, the nascent state of the quantum industry, and the rate of growth at present, suggest that the KSAs needed by a quantum company could change rapidly. Lastly, as the quantum industry is introduced more broadly to government officials, investors, business executives, and the broader public, a cursory understanding of both basic quantum principles and the potential impacts they will have on society is a growing need.

For the purpose of this report, four Quantum skill domains have been created to describe workforce needs and gaps:

- **Quantum Expert**
- **Quantum Proficient**
- **Quantum Conversant**
- **Quantum Aware**

These four categories provide a context for both the identification of the quantum-unique KSAs required and also align with the educational and workforce training institutions best suited to support the industry.

Quantum Expert

Quantum Experts typically hold a PhD in physics, engineering, computer science, or other subjects connected to the basic study of quantum phenomena. They are employed by universities, national laboratories, and both large and small companies focused on quantum-related products. Job titles could include Founder, Vice President of Research & Development, Chief Technical Officer, or Lab Director. Their knowledge and proficiency form the foundation upon which quantum information science is built and therefore they often serve as thought leaders for the industry. Quantum Experts have a deep understanding of topics such as atomic, molecular, and optical physics, superconducting devices, quantum algorithms or quantum theory. Experts can also bring a wide range of knowledge to the development and application of quantum technologies since many disciplines (biology, climate science, aerospace, etc.) are projected to advance with a quantum advantage.

QUANTUM SKILL DOMAINS

Quantum Proficient

Quantum Proficient workers may hold physics or engineering degrees in quantum-specific topics at either the undergraduate or master's degree levels. They are typically employed by both quantum and quantum-adjacent companies and may hold such positions as Project/Program Manager, Design Architect, or Lead Engineer. Further, their backgrounds often contain experiential learning gained from either industry experience or continuing education resources. Quantum Proficient leaders have a working technical understanding of the physical systems that comprise quantum computers, quantum sensor arrays, etc., and often contribute expertise in the areas of micro and macro fabrication, circuit design, opto-mechanical system assembly, and advanced measurement and characterization techniques. These areas of proficiency represent the link between quantum theory and practical application of quantum-based information processing.

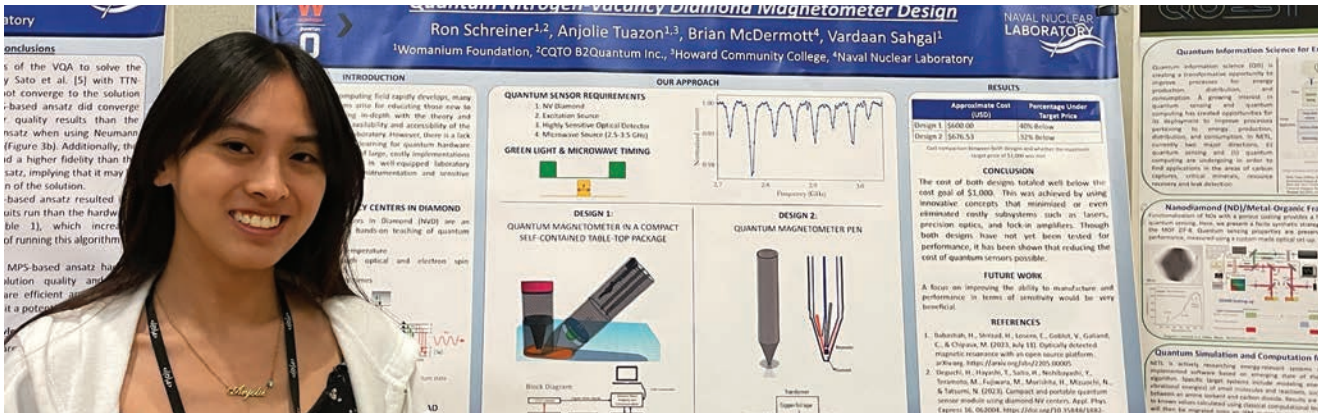
Quantum Conversant

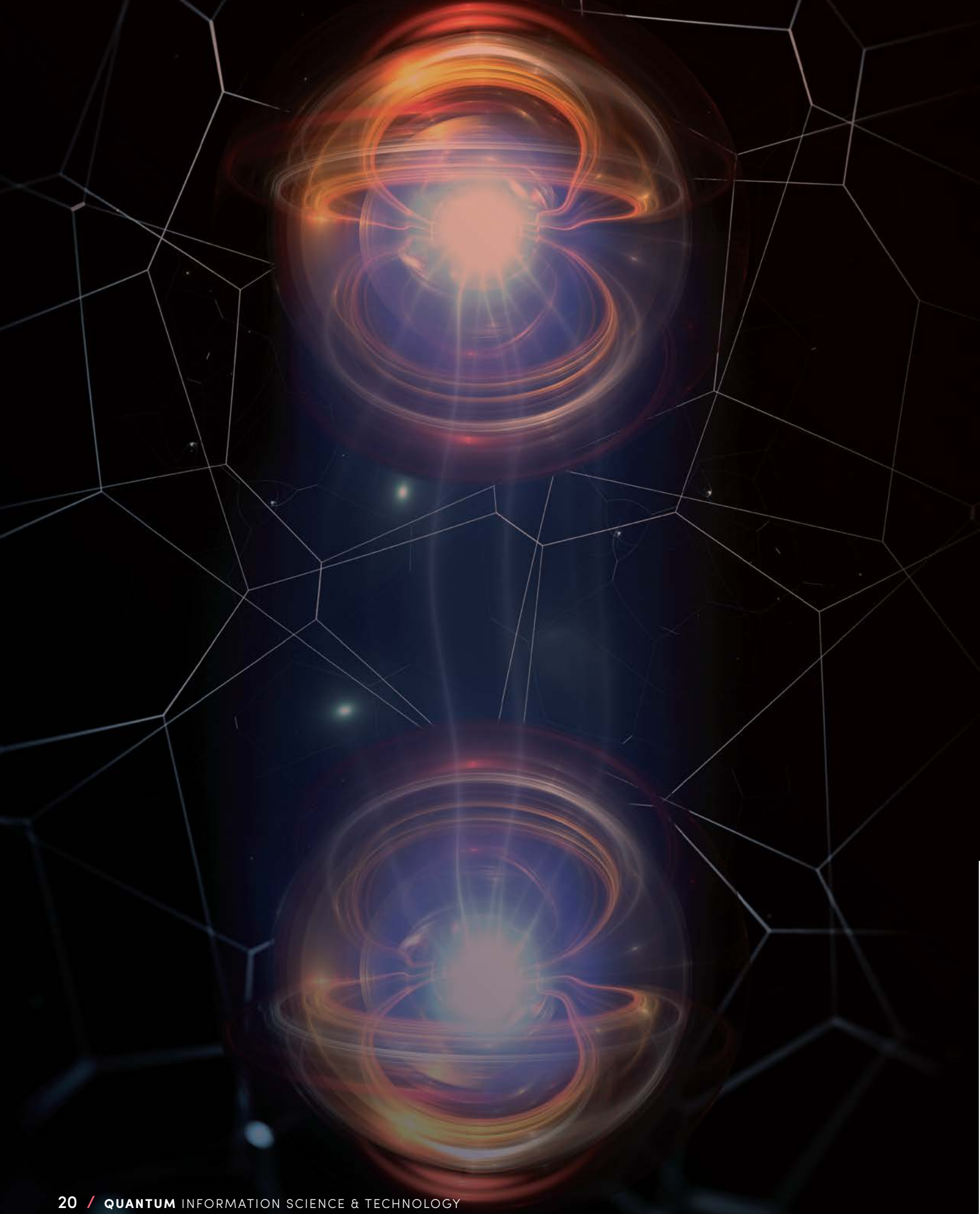
Quantum Conversant employees often work at the technician level for STEM-focused companies or as support staff for government or academic research programs. As such, they may or may not hold a traditional four-year degree. Many Quantum Conversant workers often rely on non-quantum skills developed in K-12 systems, community colleges, or technical institutes. They are essential to the quantum field for successful implementation of the projects conceived of, and designed by, Quantum Experts and Proficient workers. Quantum Conversant workers can hold positions such as Technician, Assembler, Programmer, or Manufacturing Engineer or non-technical positions such as Business Analyst, Marketing Specialist, or Graphic Designer. Their training is supported through a wide variety of pathways and institutions and reflects expertise in such areas as welding, soldering, fabrication, electronics, programming, software development, laser & optics assembly and alignment, and general laboratory and operational processes and procedures.

Quantum Aware

Quantum Aware refers to those who are new to quantum concepts. This may include people exploring a career pathway into the quantum workforce or those holding a position that requires them to be aware of the potential impacts of QIST applications on their business or society, with opportunities for upskilling and reskilling. Those workers may be currently employed in quantum-adjacent industries or may be tracking through the K-12 and two-year college systems.

/ WOMANIUM STUDENT RESEARCH PROJECT





CURRENT STATE OF QUANTUM SKILL BUILDING AND AVAILABILITY

Current State of Quantum Skill Building and Availability

The Colorado ecosystem has well-established programs for training a quantum-ready workforce at multiple institutions of higher education. Partnerships across the state are developing on the tailwinds of the recent Elevate Quantum effort which has seen multiple stakeholders express commitment to building a quantum workforce. Those include the University of New Mexico, Colorado K-12 school districts, apprenticeship programs, and industry players. Through the Elevate Quantum initiative, new ecosystem relationships have been forged and programs are being imagined and launched.

It is estimated that the national quantum industry growth rate outpaces qualified graduate supply, with an 18% annual growth in QIST demand versus a 3% rise in graduates[12]. Despite the recent percolation of programs and increased attention towards Colorado's quantum assets, a more comprehensive focus on workforce development is essential.

The growing divide between the demand for quantum professionals and the supply of trained graduates presents a unique opportunity for forward-looking communities. **With 80% of QIST job postings requiring at least a college degree, and only 16%[13] of universities globally offering advanced programs in QIST** as of December 2023, there is a clear need for more educational institutions to expand and enhance their quantum information and technology programs. With partners across the state serving in complementary roles, there are essential opportunities to expand the community in a way that allows the region's quantum ecosystem to diversify and truly flourish.

Perhaps one of the most critical opportunities to grow the QIST workforce is through increasing the involvement of diverse communities. The racial composition of the quantum workforce is not widely published in a single, comprehensive source, however some insights can be derived from broader STEM fields and specific studies on diversity in QIST. A recent National Science Foundation (NSF) report that collated and analyzed data from multiple sources shows that, in 2021, White individuals comprised 64% of the STEM workforce - a significant majority. When combined, Hispanics, Blacks, and American Indians or Alaska Natives—collectively referred to as underrepresented minorities—made up 31% of the total population and 24% of STEM workers in 2021. In 2021, women made up half (51%) of the total population ages 18 to 74 years and about a third (35%) of those employed in a STEM occupation[14].

These demographic statistics are the product of systemic barriers that prevent the full participation of these groups in STEM education and career pathways. If leveraged properly, the demographic diversity of the Mountain West presents a strategic opportunity to broaden the quantum workforce.

Currently, there are significant barriers in communicating to the broader community about the opportunities that QIST will offer those looking to enter the workforce[15]. To attract greater numbers of diverse participants to the workforce development programs being proposed, relatable ways to talk about the field must be created to provide opportunity for educational on-ramps and off-ramps across the entire educational spectrum. Additionally, methods to blend both traditional and non-traditional learning pathways must be established.

QUANTUM SKILL BUILDING AND AVAILABILITY

/ COLORADO SCHOOL OF MINES QUANTUM LAB

A statewide, partner-focused education and workforce development ecosystem should be equally attentive to the creation of specialists with advanced degrees and to the interests and needs of the Quantum Conversant and Quantum Aware workers described above. Such a focus will ensure the creation of a truly diverse workforce from the start of the quantum revolution—rather than requiring a retroactive fix to some of the entrenched cultural problems that now plague traditional STEM fields like physics, computing, and engineering.

The scarcity of U.S. programs with experiential quantum training labs further limits workforce preparation for this rapidly evolving field that is frequently focused on improving quantum hardware and useful quantum systems. A large sector of the quantum workforce will require training in laboratory or production environments and, presently, providing experiential learning on potentially expensive and technical equipment is a challenge. Currently, only a select few learners can attain highly coveted positions in research labs to gain exposure to these types of technical equipment. Certain Colorado institutions are addressing this challenge through instructional laboratories, with quantum or quantum-adjacent topical experiments.

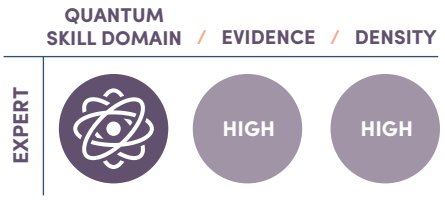
Even in cases where quantum-specific courses are unable to be taught, existing laboratory courses can be slightly modified to place an emphasis on KSAs that relate to broader course learning goals. For example, an electronics lab course can be augmented, at reasonably low cost, to include high-performance analog and RF electronics content, or an optics lab course can include experiments relating interferometers to quantum phenomena. In addition, traditional programming courses can be augmented with the use of quantum libraries to teach quantum concepts to students in the early stages of education.

Although these modifications require reasonably low monetary investment, course transformation can be an intensive activity for faculty members teaching the course, especially in departments with fewer institutional resources. To ensure that quantum workers can be trained at all levels from community college to Research 1 (R1) universities, it is important to consider ways of supporting course transformation across the entire quantum education ecosystem.

Using the skills domain schema introduced in Section 3.0, existing Colorado skill-building programs are highlighted below with a relative ranking of the following:

- **Evidence** of Colorado's unique and distinctive skill building programs: this relative ranking is articulated on a scale of high, medium, and low, and is gauged by the level of quantum skill building programs that are unique to the state and not typically represented in other geographies.
- **Density** of Colorado's existing skill building programs: this relative ranking is also articulated on a scale of high, medium, and low, and is gauged by the existing penetration and density of skill building programs. For example, if a skill-building program such as a quantum undergraduate degree is offered at most four-year universities in the state, its density would be ranked "high."

Current State of Skill Building Programs: QUANTUM EXPERT



Colorado is a demonstrated world leader in training Quantum Experts. With programs and institutions spanning a half-century and more, Colorado's quantum talent pipeline is world-renowned and has resulted in multiple Nobel Prizes. Many generations of graduates from Colorado institutions have gone on either to found leading quantum companies or to hold prestigious positions at universities around the world. Moreover, many currently serve, or have served, on key national and international quantum committees of influence.

Colorado's institutions of higher education offer both physics and engineering undergraduate and graduate degrees across QIST disciplines. All universities house theoretical quantum physicists whose breakthroughs and insights complement the experimental faculty and facilities residing on their respective campuses.

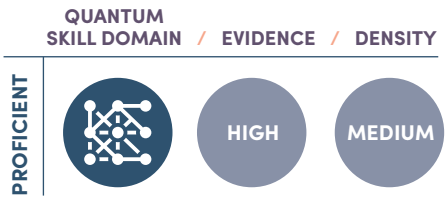
NIST Boulder is located in a research-rich environment near the University of Colorado (CU) Boulder and its researchers collaborate with industrial, academic, and government laboratories throughout the nation and the world. NIST and CU Boulder jointly operate JILA, a world leader in atomic, molecular, and optical physics and precision measurement. **NIST Boulder has more than 350 scientific, technical, and support staff and hosts more than 300 visiting researchers, students, and contractors.** NIST Boulder and NIST/JILA scientists have been awarded the Nobel Prize in Physics four times, a National Medal of Science, and three MacArthur Fellowships, a.k.a. "genius grants."[16]

Importantly, Colorado is also home to researchers focused on the pedagogy of STEM and quantum education practices.

Current Gap(s)

Although Colorado supports an extensive portfolio of educational and research resources, no formal body routinely convenes quantum program managers within the state to identify and discuss complementarity of individual institutional programs and curricula in order to ensure consistent and competitive statewide quantum offerings.

Current State of Skill Building Programs: QUANTUM PROFICIENT



The representation of QIST academic programs and research experiences at Colorado's four-year institutions is especially strong across a few universities. Most of the state's universities have expressed interest in expanding student exposure to quantum programs, with varying considerations about the best strategy and approach to do that.

Further, various efforts are underway by some Colorado universities to expand access to quantum programs for rural communities through engineering partnership programs[17], yet a truly quantum-focused degree is not yet extensible from one university to another. There are considerable assets in place to begin to expand programs between universities, especially those who already have created a strong foundation of working relationships and (often complex and time-consuming) contracts that can be leveraged to launch additional quantum partnership programs.

There is a growing effort to provide hands-on experiences by complementing traditional classroom education with quantum programs. Quantum science relies heavily on complex and sometimes expensive instrumentation. Open access facilities for researchers coupled with industry supported programs, such as CU Boulder's Quantum Forge

course, serve as examples of how exposure to quantum instrumentation can be provided for a growing quantum workforce. These resources and programs also attract some of the best researchers and fastest growing QIST companies to Colorado from around the world.

As the demand for specific Quantum Proficient workers rises, more quantum-specific programs are being created. The University of Colorado Denver offers a focused, four-course Quantum Information Technology certificate program comprising two lecture courses on quantum computing and quantum algorithms and two substantive (3-credit) laboratory courses on quantum computing technology and quantum technology systems. This certificate program is housed under the physics department, but is operated collaboratively between the physics and electrical engineering departments. It places an implementation-agnostic, interdisciplinary emphasis on the content and learning objectives. The courses are cross listed in both departments, at both undergraduate and graduate levels. The program is also partnering with industry to assist in resource and curricular development.

> I thought that my hands-on classes would have been more helpful when I started my quantum job, but I needed more *experiences.*"
>
> / QUANTUM LEARNER PERSPECTIVE

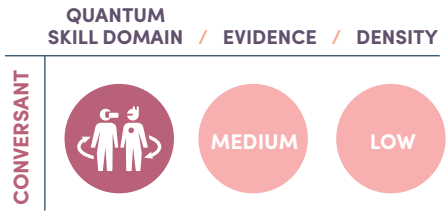
In direct response to the need for Quantum Proficient engineers, the Colorado School of Mines (Mines) has created a Quantum Engineering master's degree. Further, both CU Boulder and Mines have created quantum-specific minors.

Colorado State University (CSU) leads research efforts in quantum metrology, quantum communications, and quantum materials. To complement those research strengths, CSU is focused on creating QIST undergraduate degree concentrations in four departments including physics, chemistry, computer science, and electrical and computer engineering. While these concentrations will be tailored within each department, there will also be in-common courses including introductory courses in QIST (housed in physics) and an "Advanced Quantum Information Science" laboratory course (a collaborative effort among the four departments).

Current Gap(s)

While many institutions have established superior research and curricula , there are no formal quantum career pathway tools available for quantum learners. Additionally, the demand for experiential learning with quantum instrumentation far exceeds the supply of available programs.

Current State of Skill Building Programs: QUANTUM CONVERSANT



Colorado offers a robust supply of two-year community colleges and vocational schools. These colleges and schools are widely represented across urban and rural areas, and many of the community colleges are strengthened by the statewide Colorado Community College System (CCCS), which serves to support the convening, standardization, and optimization of two-year colleges. Most of these programs offer non-specific QIST skill building programs like welding, fabrication, and electrical systems and provide a strong technical foundation for learners.

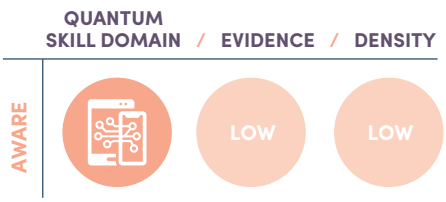
Programs that are uniquely focused on QIST skill building are less dense, but those that exist are highly valued by ecosystem stakeholders. Front Range Community College's Optics Technology Program[18], part of the national AmeriCOM Initiative[19], is often highlighted as a compelling program. Students can obtain either a two-year associate degree or a one-year certificate, complemented by hands-on lab experiences. This program supplies the quantum ecosystem with technicians that service the optics, photonics, laser, and quantum technology needs of the region. Ecosystem stakeholders often point to this program as one that could be scaled up both by expanding to additional regions or expanding the scope beyond optics. Some Community Colleges like the Community College of Aurora and the Community College of Denver also support and participate in experiential programs like the Quantum Research Exchange[20] which connects students with industry partners for internships and other professional development opportunities.

In addition to technical training resources, Colorado also provides a wide range of career assessment and pathway development platforms that could be made available for the identification of quantum skills needs and deployment of training resources. For instance CareerWise Colorado facilitates youth apprenticeship opportunities in various industries. My Colorado Journey is a state funded career pathway platform that connects job seekers and students to careers, education planning, and support resources. Lastly, the Colorado Workforce Development Council supports Sector Partnership programs aimed at addressing the workforce and other competitiveness needs of specific industries.

Current Gap(s)

Currently there is no comprehensive, agreed upon set of KSAs defined for the quantum industry. This significantly impedes adding quantum career pathway models to existing career planning platforms. Further, the lack of such a definitive list impedes two-year community colleges and vocational schools from exploring and creating resources focused on QIST skill building.

Current State of Skill Building Programs: QUANTUM AWARE



Colorado K-12 school districts have expressed high interest in understanding how best to include quantum in their curricula. Most school districts pose the questions: "We've all heard about quantum – but what does it really mean in terms of career possibilities for students? And how can we learn more about quantum so that we can confidently describe it?" Many STEM teachers are beginning to introduce quantum concepts in their classes yet are creatively piloting lesson plans on their own.

This community also includes educators, parents, policy makers, and, more broadly, the public. Moreover, as in many ways this is the beginning of the quantum journey, there is an imperative to build public quantum awareness in an equitable and ubiquitous manner.

To meet the growing demand for Quantum Aware resources, partners in New Mexico have created a training program for high school teachers called QCaMP (Quantum, Computing, Mathematics, & Physics)[21]. At QCaMP, teachers receive a primer on the fundamentals of computing, learn hands-on (the oftentimes perplexing) phenomena of quantum physics, and apply those phenomena to solve computing problems in new ways. Colorado hosted QCaMP in summer 2024 with support from the Colorado Department of Labor and Employment and successful instructor engagement.

QUANTUM SKILL BUILDING AND AVAILABILITY

In addition to QCaMP, other programs help introduce quantum in a non-traditional setting such as Qubit by Qubit[22] and MIT XPro[23], but the target audiences for those programs are students and executives, respectively.

> When I started my first quantum program, some of the terms were intimidating, and I didn't know if I belonged here."
>
> / QUANTUM LEARNER PERSPECTIVE

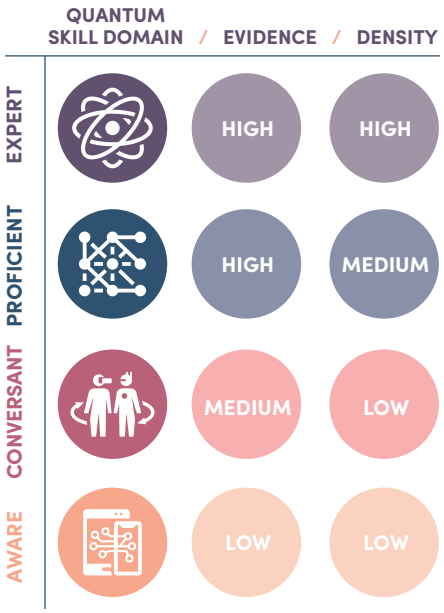
Colorado is also home to initiatives that address underrepresented and rural populations. NCWIT (National Center for Women & IT) and the Womanium Foundation's Global Quantum Program are examples of platforms that have extensive experience and proven results in STEM development. NCWIT's experience with the NSF Broadening Participation in Computing program will greatly contribute to the newly awarded Elevate Quantum effort focused on inclusive workforce development and training.

Lastly, the strong regional presence of organizations such as SPIE (International Society for Optics and Photonics) and Optica, as well as the Colorado Photonics Industry Association, serve as conduits for general educational content, national perspectives, and industrial and economic statistics and trends.

Current Gap(s)

There is currently a notable lack of instructors equipped to provide quantum education outside of university settings, with only a few training programs available across the country helping fill the gap. Teachers and institutions often don't have access to proven teaching models that are easily scaled nor are there resources available for professional development. Further, as QIST is a complicated discipline and is difficult to both explain and understand, there are varied approaches to describing quantum principles in a clear and concise manner.

/ QCAMP QUANTUM TEACHER TRAINING



/ SUMMARY OF SKILL DOMAIN CURRENT STATE ANALYSIS OF EVIDENCE AND DENSITY

/ UNIQUE DESIGN, MANUFACTURING AND TESTING IS REQUIRED FOR ENABLING TECHNOLOGIES SUCH AS DILUTION REFRIGERATORS.

RECOMMENDATIONS

Recommendations

The analysis provided in the previous sections serves as the basis for a set of tangible, actionable recommendations to build a quantum-ready workforce. Those recommendations are broken into three areas: **Alignment, Skill Building, and Assessment.**

ALIGNMENT

The recent EDA Quantum Tech Hub designation, the coalition building leading to the award, and the general excitement around quantum in the Mountain West suggests a need for foundation building and alignment around what is achievable. To create a common baseline, and to monitor effectiveness of programs and initiatives, it is critical to:

Establish a Methodology for Compiling & Reporting Quantum Industry & Workforce Metrics

- Quantum does not currently carry a set of Standard Occupation Codes (SOC) or North American Industry Classification System (NAICS) industry classifications. Accordingly, a set of measurable and trackable metrics needs to be established immediately to evaluate progress.

Commission and Publish a "State of Colorado's Quantum Industry" Report

- To formulate a baseline on where the current regional quantum economy lies, a market-based industry report can serve as a common understanding of the state of quantum business and guide industry-informed workforce initiatives including demographic data to inform diverse participation. That report should incorporate any metrics established via the previous recommendation thus making ongoing periodic reporting possible.

Support the Elevate Quantum Workforce Collaborative (EQWC)

- Regularly convene a group of quantum education and workforce development professionals and stakeholders expressly tasked with addressing statewide quantum workforce initiatives across different communities (education, industry, state government, etc.) and track progress. Immediate tasks for the group should include:
  - Establish a set of community agreements among participating institutions.
  - Compile a thorough inventory of current quantum-specific and quantum-related programs across multiple levels of higher education in CO and Mountain West.
  - Refine KSAs required for various job roles in the quantum workforce with the intention to include them with existing career pathway tools formalized in an open portal with careful attention to inclusivity.
  - Establish a state-wide Quantum Sector Partnership to solicit industry wants and needs.
  - Track other regional or federal programs and larger national research efforts and align where appropriate.

SKILL BUILDING

Each skill domain described previously has its own opportunity to address known gaps and therefore strengthen the availability of QIST workforce development resources. When taken together, the resulting implementation and growth of all skill building programs will increase the regional quantum workforce resources in a strategic and complementary manner. It is worth noting that each domain heavily relies on having a high degree of proficiency with specialized hardware and diagnostic equipment. As such, implementation of work-based learning principles and resources, specifically those supported by Colorado's Work-Based Learning Continuum Framework[24], is encouraged whenever possible.

Quantum Expert

Regularly Convene Regional Higher Education Quantum Program Leaders
Continuing to lead the nation in graduating top quantum talent needs to be a high priority. Increasing collaboration and coordination among regional higher education quantum program leaders can lead to increased awareness of programs and opportunities to share resources and practices. Further, developing an understanding of connections and pathways that exist among institutions of higher education, as well as barriers to those connections, will both enrich and diversify the talent pool of quantum graduates. Regular convenings can be initiated immediately through both formal and informal engagements to communicate this report's findings and recommendations, brainstorm ways to implement quantum or quantum adjacent KSAs into programs, and to form action plans for subsequent university involvement. Regular convenings should also be focused on opportunities to create and solidify transfer articulation agreements among participating institutions.

Identify each higher education institution's strengths and gaps in QIST educational programs and develop a plan to fill the most pressing and critical areas through hub-and-spoke models where strengths can be leveraged.
This could include the expansion of Front Range in-person lab experiences to virtual lab experiences that are more accessible to rural areas; or the expansion of a "Quantum 101"-type course or experimental laboratory course to be delivered from a more developed quantum educational "hub" institution to the "spoke" of a less-developed quantum institution with place-based support from the home school and instructor.

Quantum Proficient

Invest in Industry-Informed Quantum Pathways
Establishment of a statewide quantum sector partnership based on the national Next Generation Sector Partnership Community of Practice[25] will ensure alignment between industry needs and public partners to identify and align industry needs.

Create quantum-adjacent reskill, upskill, and new skill pathways that connect to existing regional industries, initially targeting the biotechnology, aerospace, semiconductor, and IT sectors.

Invest in Experiential Training Programs
Quantum proficiency relies on obtaining hands-on experience with quantum-specific instrumentation and enabling technologies. Increasing tactile quantum experiences at two and four year institutions via capstone-level courses aligned with local companies lengthens the talent pipeline, potentially boosting retention of graduates with quantum know-how within the region. These experiences should be provided via accessible, targeted experiences focused on highly relevant skills.

Investing in the expansion of quantum internship programs will also serve to introduce future workers to both quantum supply chain products and system-level quantum devices. Further, a focus on education and workforce development opportunities within future quantum facilities (incubators, fabs, open access labs, etc.) is an opportunity to further develop quantum-specific skills that can include device design, fabrication, and system test and validation.

Quantum Conversant

Add Quantum to Existing Statewide Platforms and Initiatives

Developing a quantum career & technical education (CTE) pathway under the Colorado Department of Education standard[26] would bring immediate visibility to work-based learning programs designed to help students develop the KSAs, necessary to be postsecondary and workforce ready. Further, this can serve as both promoting and demonstrating the effectiveness of non-traditional experiences and pathways.

Utilizing the Colorado Community College System (CCCS), quantum-specific and quantum-adjacent two-year and certification programs can be scaled up and expanded to additional schools and regions.

Leveraging apprenticeship intermediaries similar to and possibly including CareerWise, and partnering with Apprenticeship Colorado provide a mechanism to fund, deploy, scale, and measure quantum-related apprenticeship programs.

Quantum Aware

Teach the Teachers Quantum

There is significant room for deploying educational resources currently being developed at the national level. Resources such as those created under the National Q-12 Education Partnership[27] and those being developed by QCamp provide both informal and formal learning resources expressly developed to communicate quantum principles at the K-12 levels. Further, establishing a quantum community of practice can help tackle implementation challenges, explore opportunities to encourage and subsidize professional development opportunities, and establish externship opportunities for participants to solidify familiarity with the field.

Launch Experiential Programs to Inspire K-12 Learners to Engage

As referenced in the earlier "'Quantum-Adjacent' Industries" section, it's critical for the region and nation to inspire K-12 learners to further their STEM learning - whether or not that is quantum specific. Launching programs in highly accessible formats, testing efficacy, and expanding to new areas—particularly rural communities—is essential to leveraging and testing new and existing ways to inspire K-12 learners, and especially high school students, to increase their engagement in STEM and quantum learning.

> I believe that if I had engaged in an internship, I would have seen the practical side of quantum computing and understood how quantum could be applied"
>
> / QUANTUM LEARNER PERSPECTIVE

Launch a Quantum Awareness Campaign

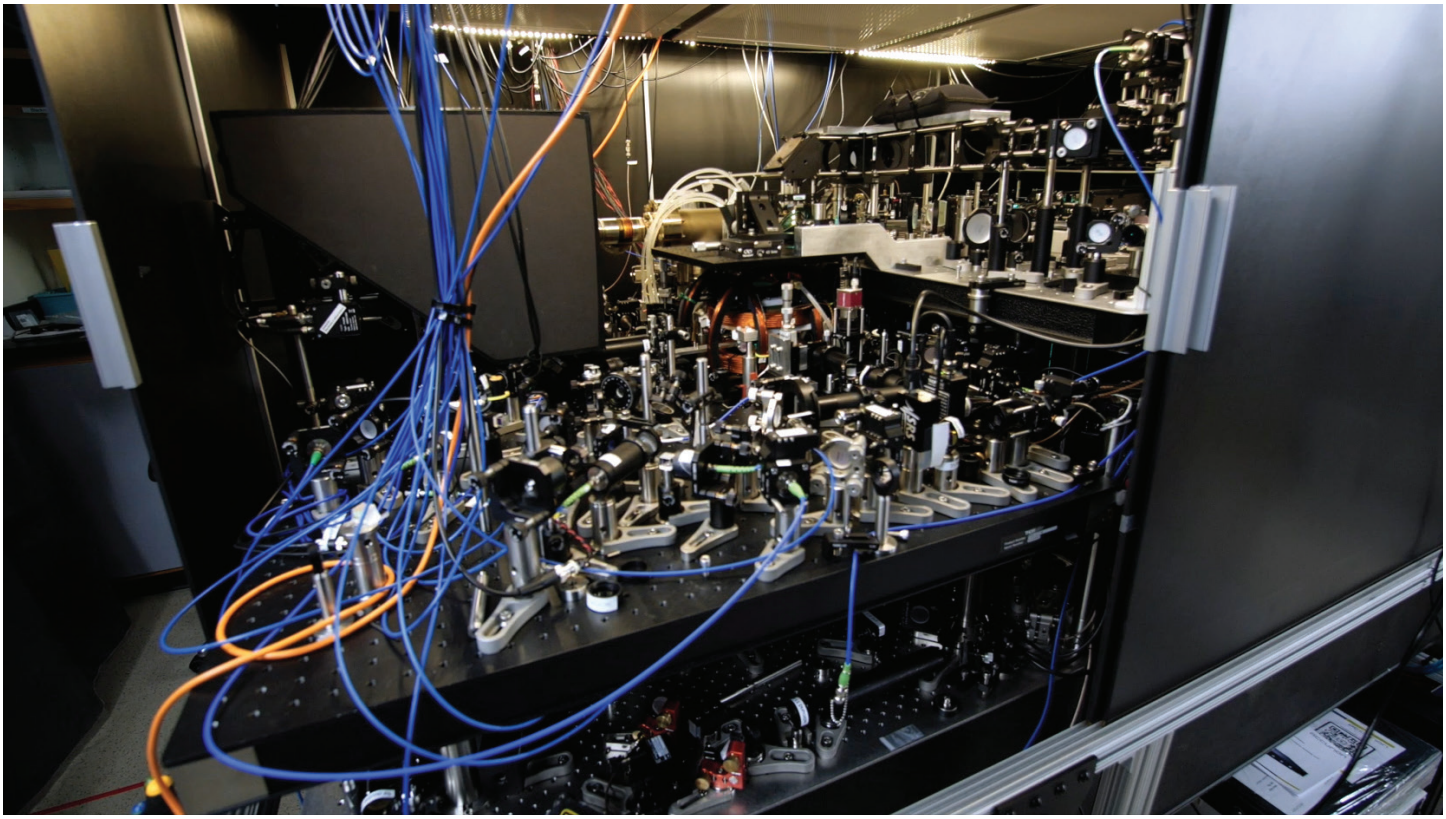
A broad quantum literacy campaign educating the public, and government and business professionals, on what quantum is and inspiring engagement with the subject is imperative for the region. Strong, equity-focused public engagement on quantum topics will ensure that all learners and non-quantum entities have potential opportunities to engage as informed citizens in the future quantum workforce, even if they will not personally become quantum workers.

ASSESSMENT

Adopt an Agile Assessment Attitude

In general, the quantum industry is in an early stage of development. The industry will inevitably see significant changes as new products and applications reach the marketplace. Accordingly, an ongoing assessment process is recommended to improve programs and projects to make them the most effective. Quantitative analysis should be done according to the output recommended in the "Alignment" section. However, qualitative analysis also will be critical in the early stages of quantum market development. Therefore, continual input from both quantum learners' experiences and company interviews and surveys should be included as part of a feedback loop for deployed programs. It is strongly recommended that any assessment process includes representation from all ecosystem stakeholders, including the learners themselves, and is convened on a regular basis.

/ FROM THE QUANTUM LAB BENCH TO PRODUCTS



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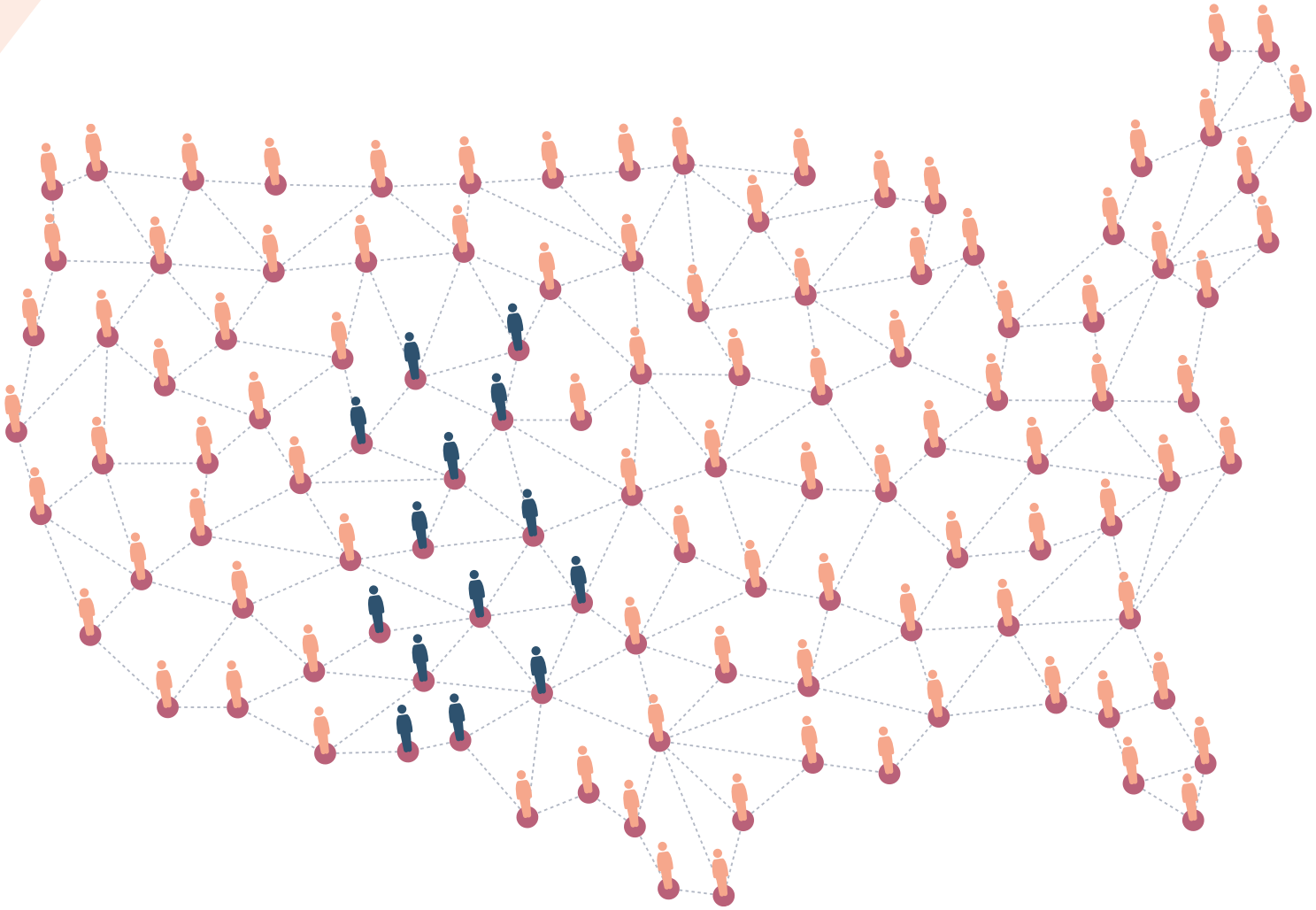

GEOGRAPHICAL SCOPE /
COLORADO AND THE MOUNTAIN WEST

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