Quantum Information Sciences (QIS) in Washington State

A Technology Landscape Report

Prepared for:

Washington Technology Industry Association (WTIA)
Advanced Technology Cluster (ATC)

January 2023

This report was supported by an Economic Development Administration grant administered by the Washington State Department of Commerce.

Our analysis suggests four focus areas to advance Quantum Information Systems (QIS) in the Pacific Northwest.

Focus 1

Cluster Expertise

Washington state has a unique blend of capabilities across the full QIS technology stack. Additionally, its historic expertise in cloud computing, AI, materials, and optics positions the state to lead quantum adoption in these areas. However, industry stakeholders and government need to choose where to focus, e.g., differentiated capabilities such as Quantum Cloud/Quantum-as-a-Service, advanced materials, optics, etc.

Recommendation: Washington state stakeholders should position the state as a national leader in quantum adoption through coordination with other clusters, (1) establishing a forum and cadence, and (2) driving coordination across academia, government, enterprise, and the innovation economy.

Focus 2

Cluster Collaboration

Across North America, Washington is the only quantum center of excellence that is an established innovation hub, has exemplary academic institutions, and is the headquarters of major technology companies investing heavily in QIS. (Chicago has a strong QIS hub, but less startup activity and a smaller tech industry.) Expertise in full-stack, cloud, and applications-focused competencies are a strong platform for a unique, differentiated center of excellence in the U.S. and globally.

Recommendation: Washington should learn and implement lessons from other clusters to position as a geographic center of gravity, establish quantum focus areas as a region, and gather/invite complementary partners through a coalition like Northwest Quantum Nexus from surrounding geographies. Further, the state should support collaboration with complementary international geographies with a focus on connecting full stack tools with applications.

Focus 3

Attract Investment

Washington state has a technology industry that is highly engaged in investing in corporate R&D and commercialization. While it excels at attracting basic research funding, it underperforms in attracting government commercialization funding through the SBIR program and other sources of undilutive investment (capital investment in startups that do not dilute equity, e.g., grants).

Recommendations:

- **Undilutive Investment Attraction:** Programming to help entrepreneurs apply for and win quantum commercialization grants will accelerate this sector; consider models from the SBIR.gov GFAC and SBIR Catalyst programs.
- **Founder Attraction:** The Cluster should support efforts to attract global quantum startups to Washington state.

Focus 4

Retain Talent

Washington produces more talent than is currently employable by local companies. An expanded startup ecosystem would help place this talent. As such, Washington must develop programs to retain and promote diversity in the quantum workforce. 50% of students in quantum programs are foreign nationals and need visa sponsorship to remain in the U.S. after graduation.

Recommendations:

- **Immigration** – Programs to support startups to hire locally educated foreign nationals would help the region retain talent.
- **DE&I mentorship** – Programs that help minorities, women, international students, and mid-career professionals gain access to mentorship that enables them to advance to technology leadership roles can support employers in building a diverse workforce.

This report segments QIS technologies into four categories.

Science

Quantum
Physics / Mechanics / Optics

Principles:

- Wave-particle duality
- Uncertainty Principle
- Entanglement
- Superposition
- Tunnelling

Materials:

- Superconductors
- Graphene
- Topological insulators
- Weyl semimetals
- Spin liquids
- Spin ices

Sectors

Quantum Computing

Quantum Sensing & Metrology

Quantum Information / Communication

Technology

Trapped Ions
Annealing
Superconducting
Photonic qubits
Topological qubits

Software
Google's Cirq, Q-CTRL Python, Quantify, IBM Q's Qiskit, Rigetti Computing's PyQuil

Atomic Clocks
Gravity Sensors
PAR
Magnetic Sensors
Quantum Sensors

Quantum Key Distribution
QRNG
Digital Post-Quantum Signature
Quantum-Safe Cryptography
Post-Quantum Encryption

End-User Application / Industry

Quantum-assisted Optimization, Machine Learning, Simulation, and Data Transfer

Agriculture
Oil and Gas
Space and Defense
Healthcare and Pharmaceuticals

Automotive
Energy and Power
Banking and Finance
Chemicals and New Materials

Washington State has established expertise in Quantum Computing. It has nascent capabilities in other areas, such as Quantum Optics and Devices.

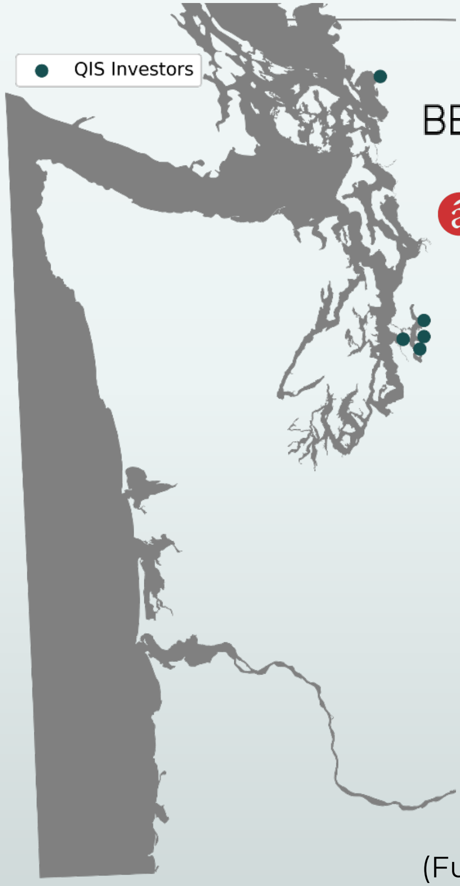
Software and Manufacturing Expertise: Companies focusing on software development and manufacturing of electrical equipment, laser systems, and fiber optic equipment, etc.

Microsoft
IBM
nion
nLIGHT
NLM Photonics
aws
Dotquant

HQ location: WA

(Full sized map on slide 24)

Engaged Investors: Strong VC and angel activity, both already familiar with investment in materials due to Aerospace Technology



BEZOS EXPEDITIONS
acequía capítal
SPIE.
bai bellingham angel investors
Aegis
BILL & MELINDA GATES foundation
Charlie Songhurst
William Gates

(Full sized map on slide 71)

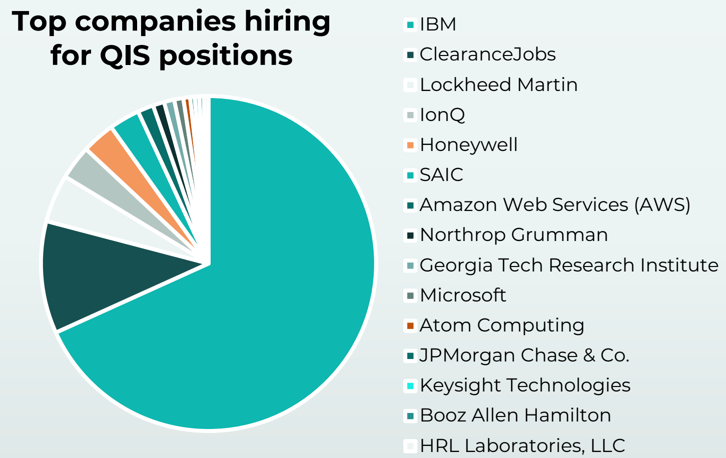
Talent Pool: Increasing STEM degree completion rates and strong quantum programs lead to a well-prepared workforce. Strong QIS R&D departments in academia, capable of acquiring significant financing (over $20B in grants in the last 15 years), and dedicated state facilities contribute to strong QIS development in the region

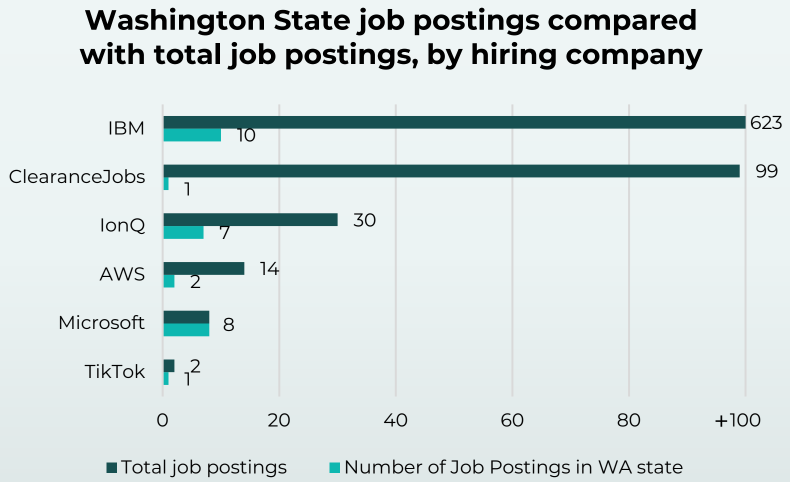
WASHINGTON NANOFABRICATION FACILITY
ELECTRICAL & COMPUTER ENGINEERING UNIVERSITY of WASHINGTON
WASHINGTON STATE UNIVERSITY

(Full sized map on slide 23)

However, Washington is producing more talent than the industry can absorb.

Although important players are present in Washington State, there is not enough start-up or company activity to absorb all QIS professionals produced.





- Lack of Visas for workforce
- No clear path for transitioning from Quantum Materials and Sensors (Washington R&D and industry focus) to Software (Washington overall strength)
- Lack of facility maintenance, resulting in higher costs and inconsistent results

Threats

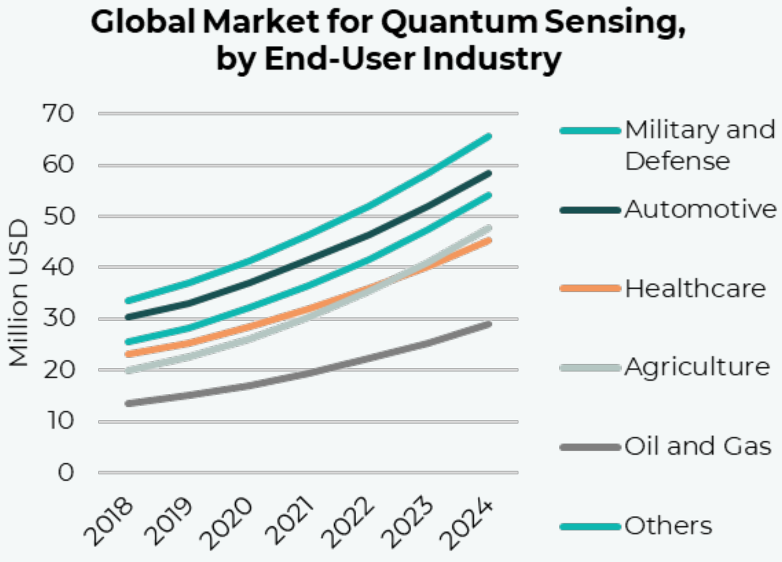
- Brain drain / loss of workforce to other states
- Lack of strategy and inconsistent gains

By focusing on its strengths, Washington can achieve greater gains in Quantum.

Applications

Focus on sectors where Washington State has strengths that also have large potential for Quantum:

- Health Tech
- Agriculture Tech
- Cybersecurity



Collaboration

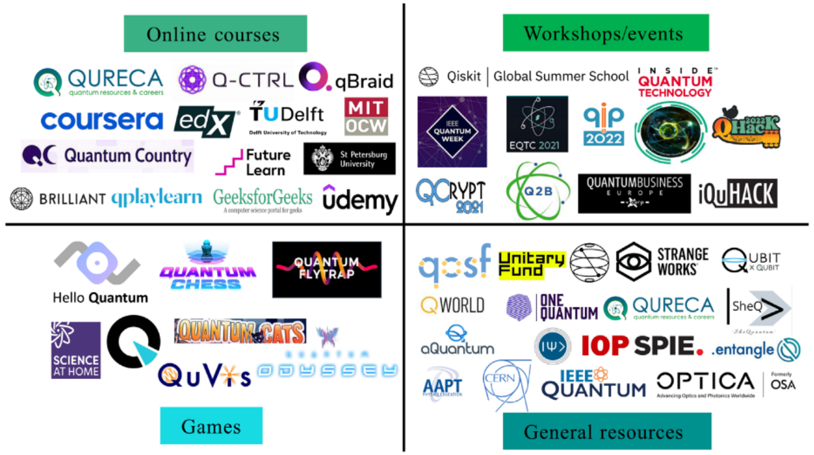
Grow into an industry coordination role:

- Connect with other clusters focusing on optics and devices, e.g. Superconducting Quantum Materials and Systems Center
- Connect with clusters working on QIS application
  - Quantum Consortium (Arlington, VA)
  - Quantum Industry Coalition (U.S.)
  - Quantum Strategy Institute (Toronto, ON)
- Invite collaboration, effort prioritization, and specialization through a flagship industry conference

Workforce

QIS workforce expansion and retention by:

- Supporting strong graduation rates and programs in STEM and QIS
- Support alternative methods to train professionals in quantum areas



Washington State Quantum Information Science (QIS) SWOT Overview

Strengths

Research Environment

- Significant attraction of advanced research funding used to develop differentiated capabilities
- Washington Nanofabrication Facility (WNF) managed by University of Washington (UW) offers shared-use, open-access space for fabrication

Industry

- Presence of important players in the field e.g., Microsoft, AWS, Google, and IonQ
- Ample talent bolstered by strong university programs

Culture

- Collaboration between national lab (PNNL), academia (UW, WSU), and industry focused on quantum technologies
- Experienced angel investor community that understands material science investments

Strategy & Focus: Developing concentration of excellence in quantum optics, devices, and software

Weaknesses

Talent Retention

- Universities are producing more talent than can be employed by the emerging quantum start-up sector. Industry is not absorbing enough of them.
- Poor retention capacity of Washington graduates – many are foreigners that have a lot of trouble getting visas to continue working in the state

Commercialization

- Intellectual property licensing and transfer between universities and academic continue to hinder collaboration.
- With demonstrated excellence in materials and software, there is no clear path for moving innovations in materials to productive use-cases without going out of state.

Opportunities

Collaboration

- Connection with other material clusters around the U.S. and clusters focusing on downstream application that relate to Washington State's economic drivers, e.g., healthcare, cybersecurity, AgTech
- Greater material cooperation between universities and PNNL in the quantum materials area
- Licensing, which circumvents IP law and opens up the research for anyone to use. UW has not historically used Non-Exclusive Royalty-Free (NERF) licensing in QIS, which could help foster better collaboration between academia and industry

Talent

- Legislation and support to help foreign students get work visas
- Support for open-source solutions through NERF licensing collaborations

Threats

Talent Retention

- Loss of workforce to other regions
- Lack of visas for workforce results in exporting our talent

Infrastructure & Strategy

- Investment in infrastructure (e.g., WNF) needs to be obtained. The sector's long-term depends on vital strategy and support for shared resources. Lab resources require maintenance and must be funded accordingly.
- Globally, many regions are proactively developing strategies for their quantum sector. The U.S. economy is challenged to do so. In Washington State specifically, a lack of strategic development in quantum is creating divergent centers of excellence (materials and software).

Report Structure

1

- **Market Assessment**
  - *Government Analysis*
    - USA
    - Washington State
    - Worldwide
  - Market Analysis
    - Quantum Sensing and Quantum Computing
      - Broken down by Technology, Application, End-User, and World Region
  - Worldwide Patent Analysis

2

- **Ecosystem Mapping**
  - QIS Clusters in North America separated by focus: Clusters/Hubs, Industry/Application, Accelerators/Foundries
  - University and federal lab collaborations in QIS
  - QIS Clusters Beyond North America
  - Worldwide QIS Companies Distribution by HQ Location
    - Broken-down by Primary Industry, Business Status, and World Region (NA, EU, and Asia/Pacific)
  - Key players strategic analysis (2019-2021)
  - Worldwide QIS Investors Distribution by HQ Location
    - Broken down by Type of Investment, Preferred Industry, Investment Over Time, and World Region (NA, EU, and Asia/Pacific)

Report Structure

3

- **Diversity and Workforce**
  - Analysis of Quantum job postings requirements
  - Career pathways for academic graduates leading to employment in Quantum Industry
  - Conventional and unconventional ways of overcoming the workforce shortage in Quantum Industry
  - Washington State:
    - STEM background investment
    - Comparison of Quantum Computing hiring with other states

4

- **SWOT Analysis for QIS in Washington State**

5

- **Brief Introduction to Quantum Common Terms and Applications**

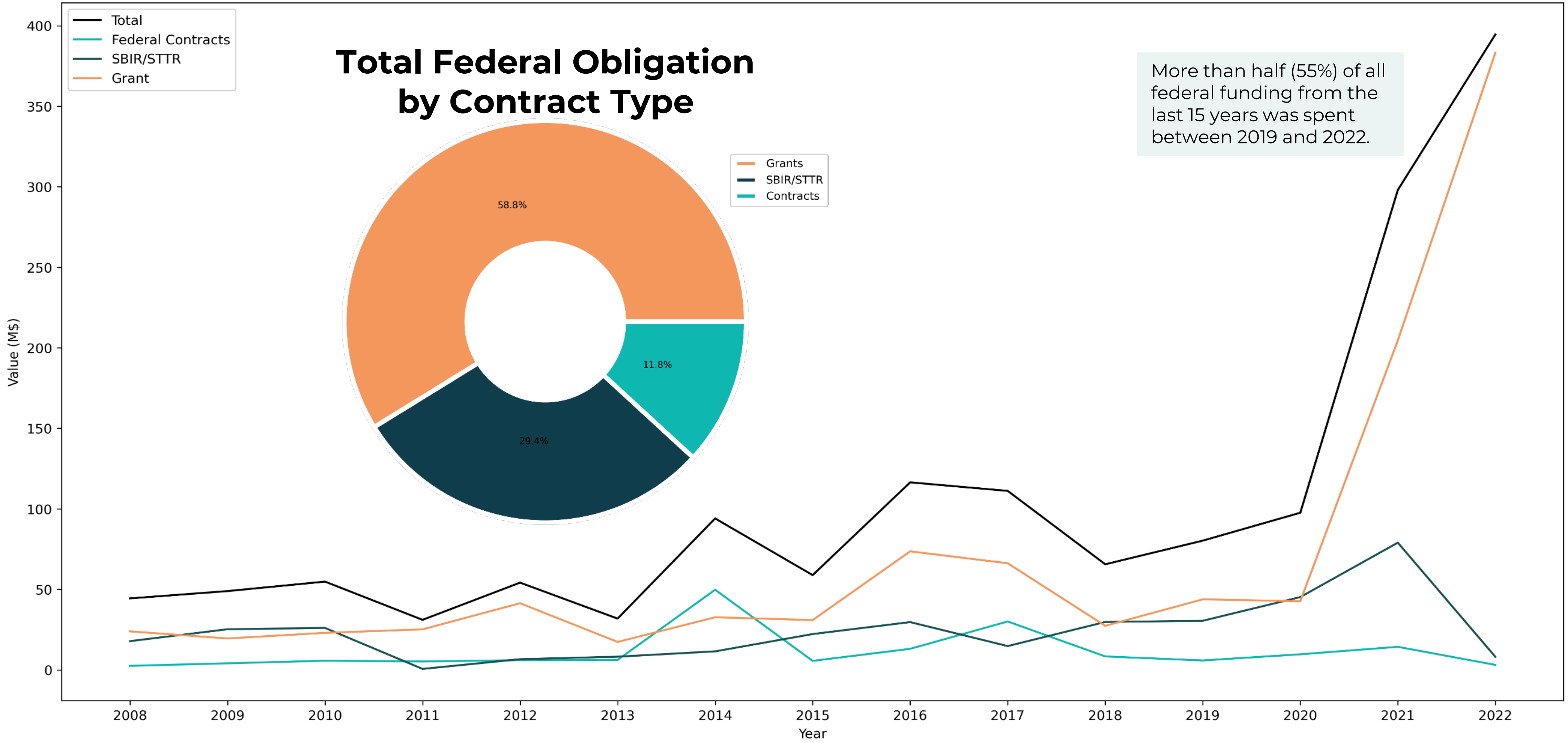
1. Market Assessment

Key Takeaways

- Government Analysis
  - The U.S. government follows global trends.
  - Washington State has succeeded at attracting R&D funding through grants, but it is underperforming on contracts and SBIR/STTRs.

- Market Analysis Breakdown
  - Top end-users for QIS (Computing and Sensors) are: Government, Healthcare, Military, Space, and Defense
  - The U.S. is strong in Quantum Computing, but China has a higher patent submission rate and significant implementation of Quantum Communication.

The U.S. has been actively funding QIS R&D for the past 15 years, with a significant increase since 2019.



Source: **Moonbeam Exchange**
Keyword: **“Quantum Information System”, “Quantum Computing”, “Quantum Communication”, “Quantum Simulation”, “Quantum Control”, “Quantum Networking”, “Quantum Optics”, “Quantum Cryptography”, “Quantum Sensing and Metrology”, “Quantum and Cybersecurity”**
Dates between: **FY 2008 – FY 2022**

The National Quantum Initiative Act (NQIA), investing in five key areas, provides a framework to strengthen and coordinate QIS R&D across federal agencies.

NQI Program Component Areas:

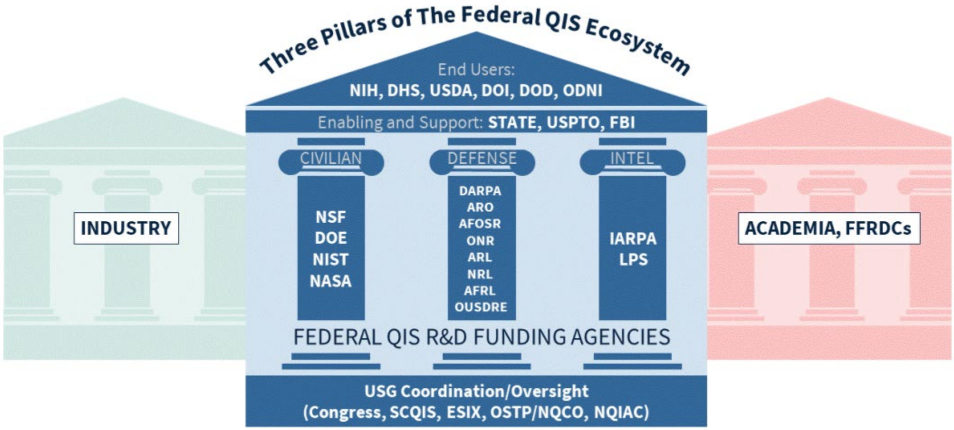
Quantum Sensing and Metrology (QSENS)
Use of quantum mechanics to enhance sensors and measurement science

Quantum Computing (QCOMP)
Development of quantum bits and entangling gates, quantum algorithms and software, digital and analog quantum simulators, quantum computers and prototypes, among others

Quantum Networking (QNET)
Uses entangled quantum states distributed over distances and shared by multiple parties for new information technology applications and fundamental science

QIS for Advancing Fundamental Science (QADV)
Foundational efforts to invoke quantum devices and QIS theory to expand fundamental knowledge in other disciplines like biology and chemistry, among others

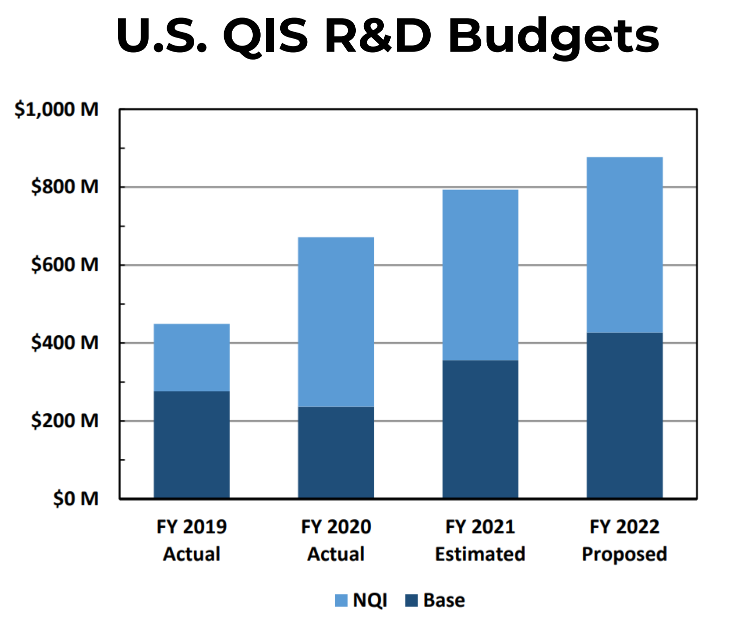
Quantum Technology (QT)
Several topics such as work with end-users to deploy quantum technologies and develop use cases, and basic R&D on supporting technology for QIS and Engineering

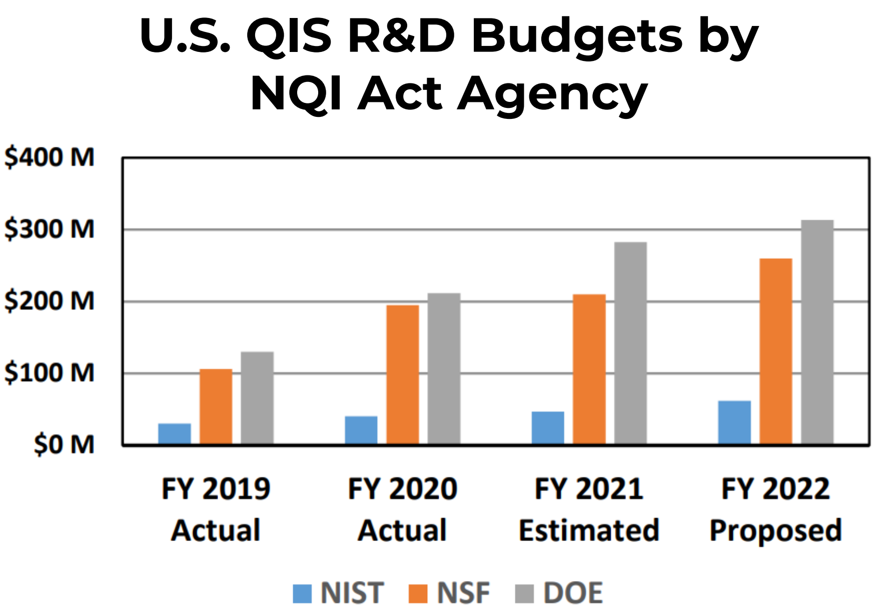


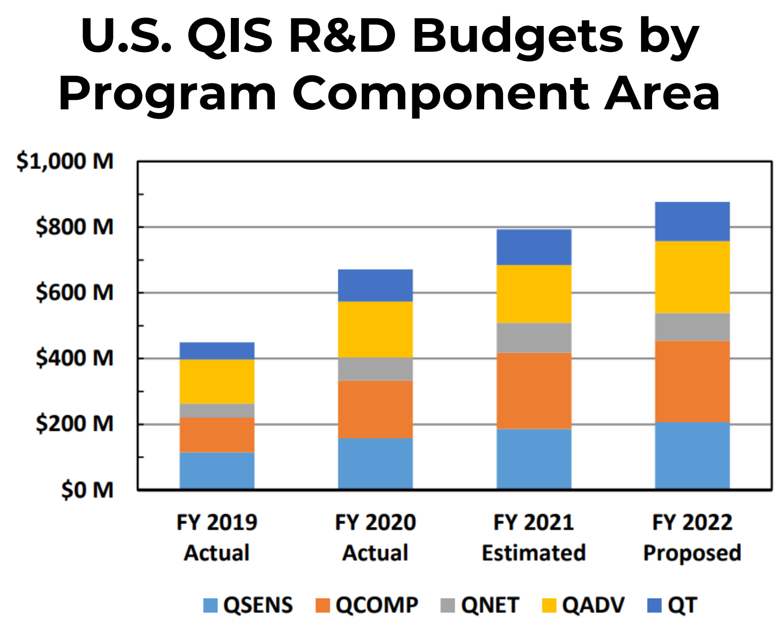
- NQI promotes engagements with the private sector industry, the academic community, National Laboratories, and Federally Funded Research and Development Centers (FFRDCs).
- It aims to reinforce investments in fundamental QIS, basic QIST research, education, training, and workforce development and collectively unite agencies' efforts.
- The resulting ecosystem accelerates America's leadership in QIST by simultaneously promoting discovery, exploration, and efforts to develop the market, supply chain, infrastructure, and capacity to utilize quantum technologies.

Energy (DOE), NSF, and NIST are the 3 most prominent agencies driving the recent increase in QIS R&D funding.

Across the QIS research areas, Quantum Computing (QC) and Advances in Fundamental Science are the most heavily funded research areas.

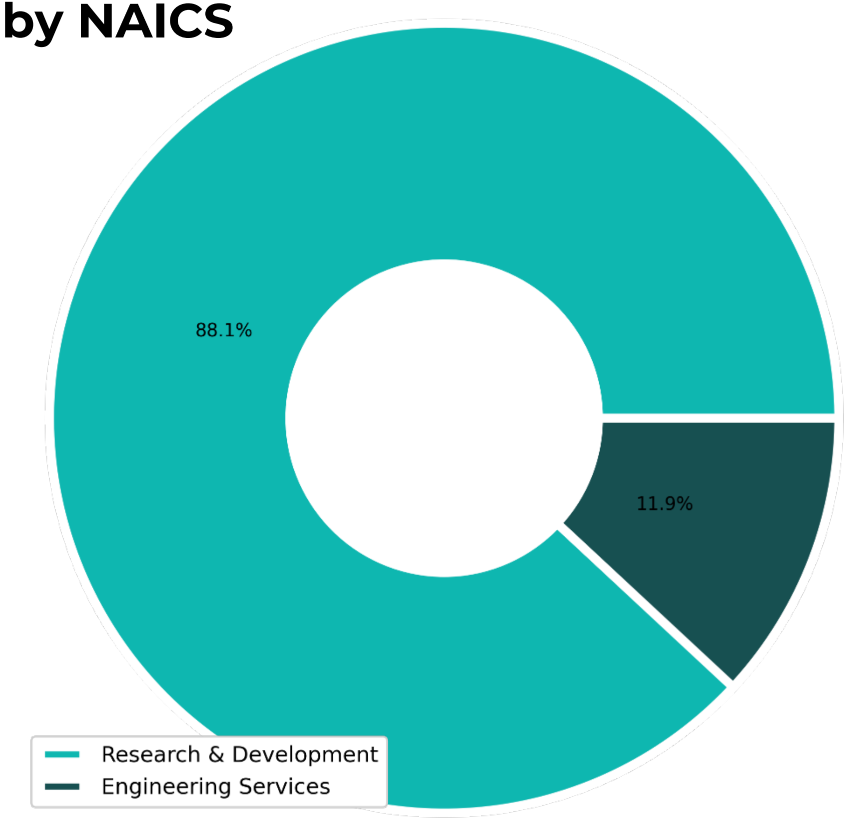






As QIS is still an emerging field, federal funding is focused mainly on R&D and Engineering services that are crucial to advance science.

Total Federal Obligation by NAICS



Broader Category	NAICS	Number of Contracts	Total Federal Obligation
R&D	Research & Development in the Physical, Engineering, and Life Sciences	156	$153M
	Research & Development in Nanotechnology	4	$493,521
	Research & Development in Biotechnology	2	$449,996
Engineering Services	Engineering Services	5	$8.8M
	Other Measuring and Controlling Device Manufacturing	49	$2.7M
	Other Computer-Related Services	16	$1.18M
	Electronic Computer Manufacturing	15	$1.07M
	Analytical Laboratory Instrument Manufacturing	16	$824,205
	Computer Facilities Management Services	2	$775,506
	Computer and Software Stores	7	$640,168

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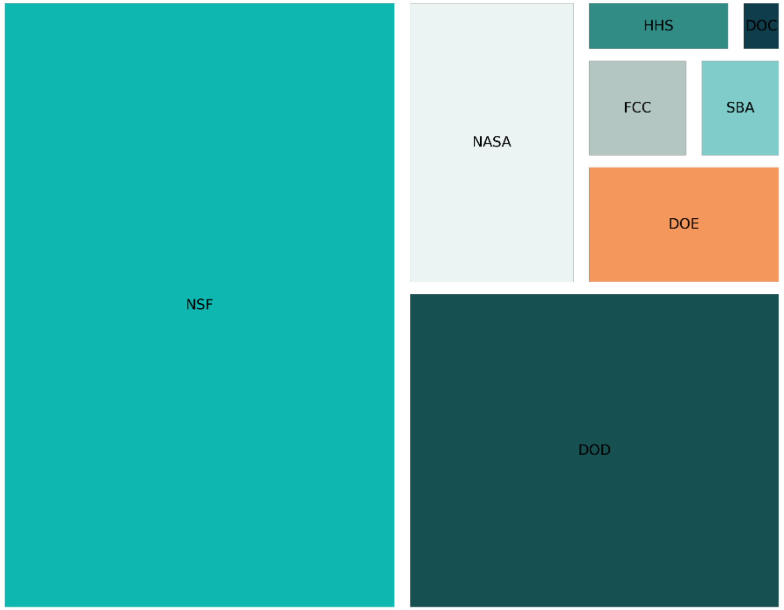
Looking at all federal funding together, NSF, DOD, DOE and NASA are the top departments funding QIS.

Total Federal Action Obligation by Department



Awarding Agency Name	Number of Contracts	Total Federal Action Obligation
Department of Defense (DOD)	1216	$673,305,176
National Science Foundation (NSF)	859	$381,360,724
Department of Energy (DOE)	319	$219,927,448
National Aeronautics and Space Administration (NASA)	305	$110,321,123
Department of Health And Human Services (HHS)	152	$79,663,904
Department of Commerce (DOC)	40	$12,211,669
Department of the Interior (DOI)	9	$769,446
Environmental Protection Agency (EPA)	9	$682,241
Central Intelligence Agency (CIA)	1	$411,731
Department of Homeland Security (DHS)	10	$384,210
Department of Agriculture (USDA)	17	$370,359
General Services Administration (GSA)	8	$256,882

Awarding Agency Name	Awarding Sub Agency Name	Number of Contracts	Total Federal Action Obligation
Department of Commerce (DOC)	National Institute of Standards and Technology	38	$11,976,180
	National Oceanic and Atmospheric Administration	2	$235,492
Department of Defense (DOD)	Department of the Air Force	421	$247,855,600
	Department of the Army	274	$164,581,100
	Department of Defense	107	$85,920,410
	Department of the Navy	242	$72,814,810
	Defense Advanced Research Projects Agency (DARPA)	77	$67,360,330
	Missile Defense Agency (MDA)	43	$11,725,850
	Office for Chemical and Biological Defense	11	$5,257,961
	Defense Threat Reduction Agency	10	$3,448,328
	National Security Agency/Central Security Service	1	$3,238,500
	Special Operations Command	3	$3,058,138
	Office of the Secretary of Defense	4	$2,173,460
	Defense Microelectronics Activity (DMEA)	9	$1,599,159
	Defense Threat Reduction Agency (DTRA)	1	$225,565
	Defense Logistics Agency	2	$199,988
	Immediate Office of the Secretary Of Defense	1	$197,399
	Defense Health Agency	1	$162,000
	Defense Media Activity (DMA)	1	$14,969
	Defense Logistics Agency	4	$11,637
Department of Health and Human Services (HHS)	National Institutes of Health	144	$78,542,550
	Centers for Disease Control and Prevention	5	$869,031
	Food and Drug Administration	1	$13,686
Department of Justice (DOJ)	Federal Bureau of Investigation	1	$24,806
	Federal Prison System	2	$13,182
	U.S. Marshals Service	1	$3,816
Department of Labor (DOL)	Office of Job Corps	3	$114,791
	Bureau of Labor Statistics	1	$1,335
Department of the Interior (DOI)	Geological Survey	4	$168,414
	U.S. Geological Survey	1	$57,441
	U.S. Fish and Wildlife Service	2	$13,723

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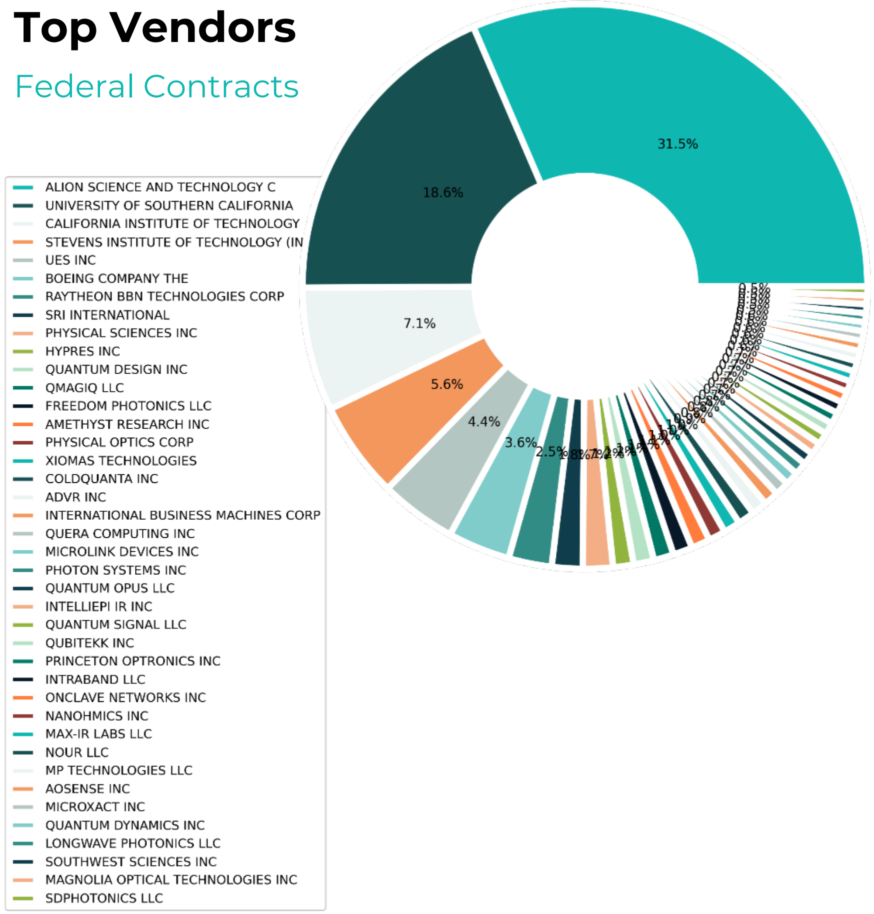
Dates between: **FY 2008 – FY 2022**

Top Vendors for contracts are for consulting services and R&D, while grants are mainly for universities. SBIR/STTRs recipients have strong academic ties.

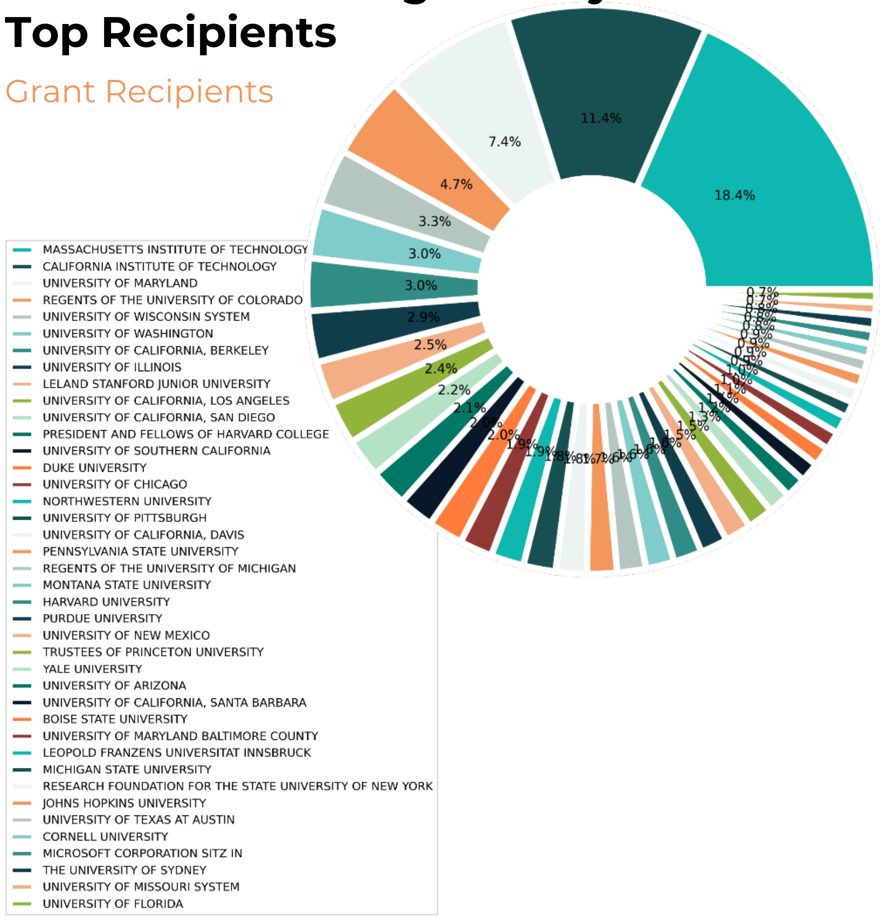
Total Federal Obligation by Top Vendors

Federal Contracts



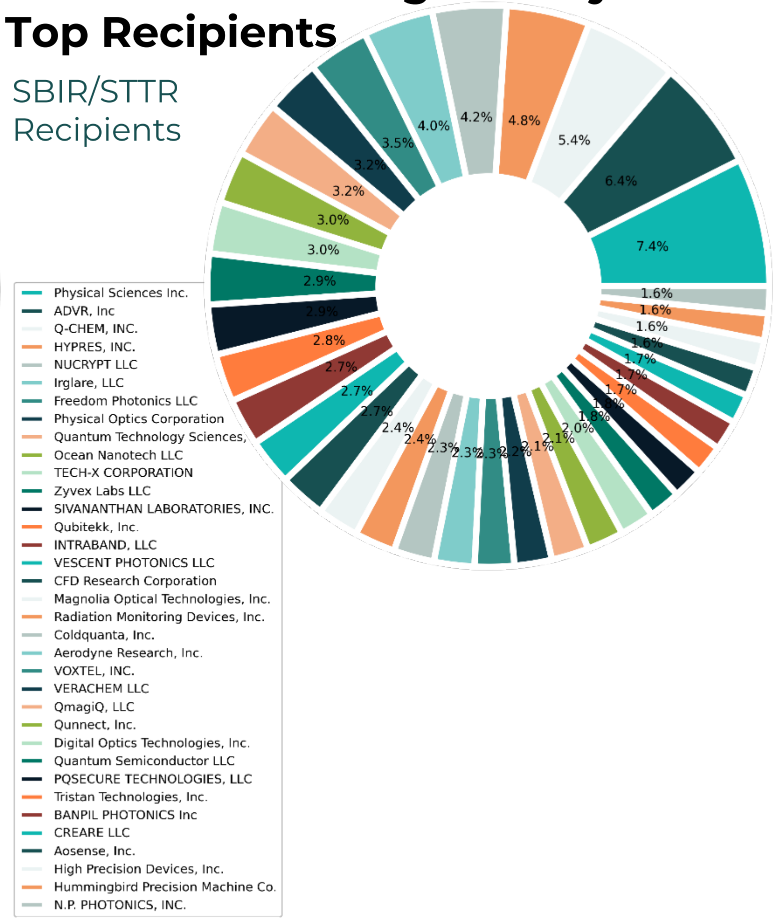
Total Federal Obligation by Top Recipients

Grant Recipients



Total Federal Obligation by Top Recipients

SBIR/STTR Recipients



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Top Vendors with Federal Contracts for QIS

	Alion Science and Technology (now Technical Solutions)	University of Southern California	California Institute of Technology	Stevens Institute of Technology	UES	Boeing Company	Raytheon BBN	SRI International	Physical Sciences	Hypres
Description	Provide mission-critical national security solutions to government and customers worldwide, leveraging unique capabilities across the enterprise to solve the nation's most complex problems. Had one contract with DOD for "Advanced processes for persistent communications within the field of nanotechnology, neuromorphic, and quantum computing."	Developed research through DARPA for a Flux-based Quantum Speedup (FluQS). FluQS seeks to harness quantum effects required to enhance quantum annealing solutions to hard combinatorial optimization problems. (Link)	Caltech and NASA have an agreement that establishes the relationship for the operation of a federally funded R&D Center known as Jet Propulsion Laboratory. They develop critical technologies for high-rate quantum communications, realistic SiGe Quantum Dot Qubit design, high information capacity quantum imaging, quantum experiments in space, two-photon light source for deterministic quantum processing, quantum computing circuit fabrication process development, and new reciprocal quantum logic devices for cold logic programs.	New research task awarded for Quantum Technologies for Armament Systems (Link) and Quantum Photonics (Link).	Develops work in many different technological fields, such as materials and processes, aerospace power, surface engineering, nanoscale technologies, photonic and electronic technologies, among others. Through the NEMO program, UES is developing a quantum semiconductor and magnetic materials and processes (link).	Major aerospace and defense firm that operates in the following segments: commercial airplanes, defense, space and security, and global services. Currently recipient of a contract with the DOD for quantum communication, entanglement, and teleportation R&D and visiting experiments.	Providing advanced technology R&D for several areas, including Quantum Engineering and Computing. One contract with DARPA to perform a "Quantum-Secured Imperceptible and Unexploitable Communication and Sensing Technologies (QUIET)" Study and another with Dept. of Navy to develop communications and networking with quantum operationally-secure technology (CONQUEST).	Independent, nonprofit research institute that conducts contract R&D for government agencies, commercial businesses, foundations, and other organizations. One contract with DARPA to develop a chip-scale Quantum Dot	Provider of contract R&D services intended to translate science into solutions that solve mission-critical needs for the customers. Worked to develop quantum dot and satellite quantum communication	Developer of integrated circuits designed to provide unparalleled performance advantages for government and commercial applications. Developed quantum sensor for direction finding and geolocation
Place of Performance	IL	CA	CA	NJ	OH	NM	MA, CO	NJ	MA	NY
Departments	DOD	DOD	NASA	DOD	DOD	DOD	DOD, DOC	DOD	DOD	DOD, NASA
Number of Contracts and Total Amount	1 contract $46,660,237	1 contract $27,595,000	10 contracts $10,486,716	2 contracts $8,232,060	1 contract $6,499,992	1 contract $5,293,061	4 contracts $3,667,695	1 contract $2,614,784	4 contracts $2,535,428	3 contracts $1,749,577

Source: Moonbeam Exchange and Pitchbook

Top Vendors with Federal Contracts for QIS (cont.)

	Quantum Design	QMagiQ	Freedom Photonics	Amethyst Research	Physical Optics Corporation (Acquired by Mercury)	Xiomas Technologies	Infleqtion	AdvR	IBM
Description	Manufacturing arm of Quantum Design International. The leading commercial source for automated materials characterization systems incorporating superconducting technology. Developer of several products in quantum technologies, cryogenics and optics, among others	Market leader and world's leading supplier of Quantum Well Infrared Photodetector Focal Plane Arrays Technology, quantum mechanical device structures that can detect mid-wavelength and long-wavelength infrared radiation, known for their stability, high pixel-to-pixel uniformity and high-pixel operability. They have contracts with NASA to use their technology to detect, count, and track near-earth asteroids, but also analyse wildfires and burning biomasses.	Manufacturer of unique and innovative photonic components, modules, and subsystems to use in high-power laser pumps, atomic and quantum sensing, AI and deep learning, and quantum and cryogenic communication applications. They have one contract with DOD to develop an integrated photonic quantum frequency processor for high-dimensional quantum information processing.	Provides effective, efficient opto-electric materials, services, and device technology. Goal is to provide cost-effective products and services along with the expertise and collaboration needed to create and commercialize innovative opto-electric products. Developed an ultra-efficient integrated photonic quantum transceiver for high-speed quantum communications	Manufacturer and designer of electronic avionics solution systems designed for commercial and defense applications. Has contracts with NASA to develop high-quantum-efficiency, high-resolution, low-cost photodetectors for the far-UV spectral range with AlGaN nanowire photocathode	Combines high-spatial resolution of framing cameras with the wide field of view typically associated with airborne infrared line scanners. Developed an autonomous airborne imaging system equipped with a QWIP detector to improve information for research and operations personnel for earth science research, disaster response, and fire detection.	Developer of quantum sensing technologies intended to avail the commercial availability of quantum technologies. The company offers to harness quantum mechanics to build and integrate quantum computers, sensors, and networks from fundamental physics to commercial products, enabling users to explore their own quantum matter innovations for sensing and other applications. Working on the development of quantum secure communications systems and developing an atomic system	Specializes in Engineered Nonlinear Optical Technologies, including quantum devices. Contracts with NASA to build single photon sources and detectors through the realization of low-loss high-speed switching for Quantum Information Processing and Communication.	Leader of Quantum Computing, developer of an IBM Quantum Platform and Qiskit Runtime. Has a contract with DOD to develop Quantum Computing algorithms for decision making under uncertainty, and develop R&D to qualitatively change the basic theoretical understanding of the nature of quantum entanglement and quantum information processing at a small scale
Place of Performance	CA, MD, MS, DC, GA	NH	CA	OK	CA	MI	CO	MT	NY
Departments	DOD, DOC	NASA	DOD	NASA	NASA	NASA	NASA, DOD	NASA	DOD
Number of Contracts and Total Amount	17 contracts $1,726,329	4 contracts $1,699,987	1 contract $1,499,991	2 contracts $1,588,318	3 contracts $1,299,974	3 contracts $1,424,974	4 contracts $1,419,770	4 contracts $1,124,753	1 contract $1,250,000

Source: **Moonbeam Exchange and Pitchbook**

Top Grant Recipients for QIS

	Massachusetts Institute of Technology	California Institute of Technology	University of Maryland	Regents of the University of Colorado	University of Wisconsin	University of Washington	University of California - Berkeley	University of Illinois
Topics (not exhaustive)	• **Computing** Properties Of Hadrons, Nuclei and Nuclear Matter from Quantum Chromodynamics • Development of Methods for Continuous Variable Quantum **Computing** with Trapped Ion • **Adiabatic Quantum Computing a**nd Quantum Walks: Algorithms and Architectures • Analog **Quantum Computing** with a Molecular Quantum Gas Microscope • **Quantum Simulation** of Out-of-equilibrium Spin Models • Quantum Secured **Communications** (QUSECCOMM)	• Role of Classical Cryptography in Quantum **Computing** • Scalable Certification of Quantum Computing Devices and Networks • Fundamental Algorithmic Research for Quantum Computing • Silicon-based Quantum **Plasmonics** for Chip-integrated Single and Few Photon Information Systems • Photonic Technologies for Superconducting Quantum **Information** Systems	• Algorithms, Scientific **Computing**, and Numerical Studies in Classical and Quantum General Relativity • Analog and Digital Quantum **Simulations** of Strongly Interacting Theories for Applications in Nuclear Physics • Fundamental Algorithmic Research for Quantum **Computing** • Quantum **Information Systems** using Solid-state Qubits in Photonic Crystals	• Applications to Adaptive Quantum **Control** to Research Questions in Solar Energy Conversion • Bridging the Gap From Few-body to Many-body through Quantum **Control** • Quantum **Control** and Spectroscopy of a Polyatomic Molecular Ion • Advancing Optical Clock Performance with Enhanced Quantum **Control** • Cryogenic Ion Trap System for Precision Measurements and Quantum **Control**	• Solid State Quantum **Computing** Using Spin Qubits in Si/SiGe Quantum Dots • Spectroscopy and Control of Cold Holmium Atoms for Quantum **Information** and Quantum Optics • DURIP: Laser and Optical Systems for Neutral Atom Quantum **Computing** • Statistical Problems in Large Volatility Matrix Estimation and Quantum Annealing Based **Computing**	• Quantum cascade laser spectrometer for investigating non-equilibrium plasma chemistry • Ultrafast control of emerging electronic phenomena in 2D Quantum • Inqubator for Quantum Simulations of Quantum Systems • Robust Quantum Simulation techniques for fault-tolerant quantum computation • Reliable Quantum Communication and Computation in the presence of noise • Chip-scale Integrated Multibeam Steering System for Cold-atom Quantum Computing	• Ultracold Rings of Trapped Ions in Silicon Traps with Novel Applications to Quantum Many-body Physics and Quantum **Computing** • Emergent Order and Quantum **Information** Flow in Non-equilibrium Systems • Analysis and Control of Quantum Coherences • Quantum-controlled Valleytronic Devices in Bilayer Graphene • New Sampling Tools, with Applications to Quantum Monte Carlo and Stochastic Control • Lattice Codes with Built-in Dynamical Protection for Solid-state Quantum **Computation**	• Distributed Quantum **Computing** and Metrology with Alkaline Earth Atom Arrays • QCCM - Optical Quantum **Computing** • High-efficiency Single-photon Detection System for Advanced Optical Quantum **Information** Experiments • Quantum **Simulations f**or Dense Matter • Computational Problems in Tensors and Quantum **Information** Theory • Quantum **Simulations** for Dense Matter • Porting Classical Approaches for Quantum **Simulations** to Quantum Computers
City	Cambridge	Pasadena	College Park	Boulder	Madison, Eau Claire	Seattle	Berkeley	Chicago, Urbana, Champaign
Number of Grants and Total Amount	179 grants $146,995,812	83 grants $90,806,563	30 grants $58,752,828	23 grants $37,714,153	25 grants $26,198,749	29 grants $24,113,904	27 grants $23,820,353	37 grants $23,199,587

Top Grant Recipients for QIS (cont.)

	Topics (not exhaustive)	City	Number of Grants and Total Amount
Leland Stanford Junior University	• Quantum Neuromorphic **Computing** and **Simulation** with Multimode Cavity QED • Controlled Synthesis of Solid-state Quantum Emitter Arrays for Quantum **Computing** And **Simulation** • Strong Field Quantum **Control** • New Directions in Quantum **Control** • Coherent-feedback Quantum **Control** with Cold Atomic Spins • Ultrafast Quantum **Control** in Molecules • Quantum **Simulation** of Frustrated Magnets by Rydberg Dressing • Laser Control of Quantum Evolution in Molecules	Stanford	24 grants $19,555,409
University of California, Los Angeles	• A Software Stack for **Quantum Computing** • A Chip-scale High-dimensional Entanglement and **Quantum Memory** Module for Secure Communications • Spin Biology under Optimal **Quantum Control** • Precision Chemical Dynamics and **Quantum Control** of Ultracold Molecular Ion Reactions • Hybrid Quantum Dot-nanowire Heterostructures for Deterministic Biphoton **Quantum Communications** • A Laser System for **Quantum Control** of Chemical Reactions and Atom-ion Photoassociation	Los Angeles	25 grants $19,354,266
University of California, San Diego	• Harnessing Nitrogen Vacancy Centers for Hybrid **Quantum Information Systems** • **Quantum Materials** for Energy Efficient Neuromorphic Computing (Q-MEEN-C) • Applications of **Quantum Computing** in Aerospace Science and Engineering • Analog and Digital **Quantum Simulations** with Fermionic Strontium • **Quantum Communication** Circuits on a Cmos Chip (QC4) • Microchip Photonic Devices for **Quantum Communication** over Fiber	La Jolla	14 grants $17,866,125
Harvard College	• Synthesizing and Harnessing Ultracold Single Molecules for **Quantum Simulations** • Many-body **Quantum Dynamics** with Microscope Control - A New Research Frontier • **Quantum Control** Techniques for Diamond-based Magnetometers with Applications for Quantum Information Processing • **Quantum Simulation**: from Spin Models to Gauge-gravity Correspondence • Ultrafast Control of Spin Fluctuations in Light-driven **Quantum Materials**	Cambridge	14 grants $17,086,435
University of Southern California	• Geometric **Quantum Information Processing** in Open Systems • Adiabatic **Quantum Computing** in Open Systems: Methodology, Performance, and Error Correction • Stabilizing Adiabatic **Quantum Computing** • **Quantum Computational** Complexity of Classical Statistical Mechanics • Fault-tolerant **Quantum Computation** in Multi-qubit Block Codes • Realistic Models and Simulations of Systems for **Quantum Information Processing** • Control of **Quantum Open Systems**: Theory and Experiment	Los Angeles	24 grants $16,016,155
Duke University	• **Quantum Computing** in Chemical and Material Sciences • Improving **Quantum Computing** and Classical Communication using Discrete Sets of Unitary Matrices • Information on a Photon: Free-space **Quantum Communication** • **Quantum Codes** Optimized for the Dynamics between Encoded Computation and Decoding using Classical Coding Techniques • Scalable Platform for Agile Extended Reach **Quantum Communications** • **Quantum Control** based on Real-time Environment Analysis by Spectator Qubits	Durham	11 grants $15,806,034
University of Chicago	• Coherent Manipulation and Transfer of **Quantum Information** among Single Spin Systems • **Quantum Chemistry** with Mean-field Cost from Semidefinite Programming on **Quantum Computing** Devices • Near-term **Quantum Computing**: Achieving Quantum Advantage, and Next Steps • **Two-dimensional Quantum** Gas with Real-Time Control of Complete Hamiltonian • Quantum Coherence-controlled Chemical Reactions • **Quantum State** Creation and Control in Scalable Two-dimensional Systems for Information Processing and Sensing	Chicago	16 grants $14,997,759

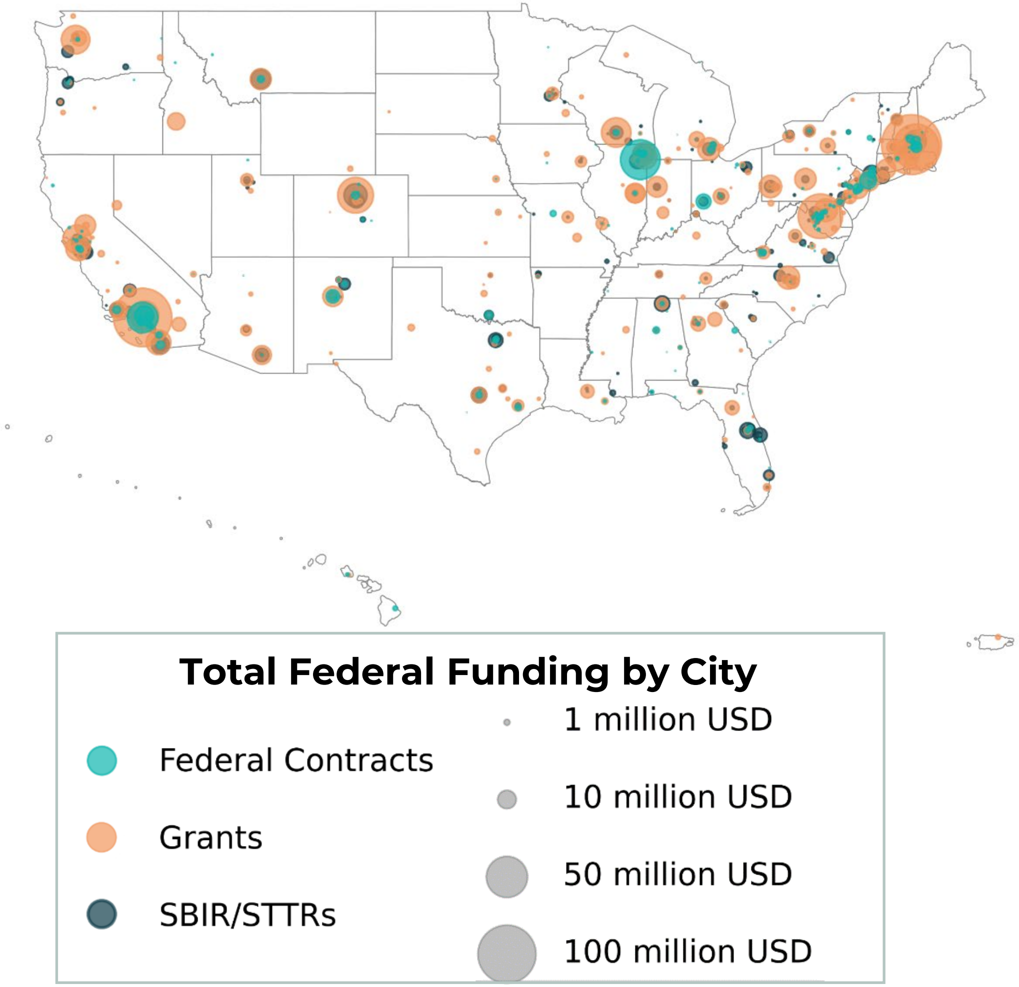
Source: **Moonbeam Exchange**

Top Recipients of SBIR/STTRs for QIS

	Physical Sciences	ADVR	Q-CHEM	Hypres	NuCrypt	Irglare	Freedom Photonics	Physical Optics Corporation (acquired by Mercury)	Quantum Technology Sciences	Ocean Nanotech
Description	Responsible for leading several Quantum-related R&D, including the development of quantum memory that will enable the first quantum networks to link multiple classical computers over fundamentally secure communication lines. They also developed entanglement distributions transceivers for Quantum Information Systems.	Developer of waveguide-based Quantum Devices. They implement different materials to provide miniature, stable, and scalable platforms for developing future light-based quantum technologies, including sensors, secure communications, and information processors.	Developed a comprehensive quantum chemistry software for accurate predictions of molecular structures, reactivities, and vibrational, electronic, and NMR spectra.	Developer of secure, high-performance Superconducting Nanowire Single Photon Detectors (SNSPDs), which are necessary for performance and security of Quantum Networks, Photonic Quantum Computers, and Trapped-Ion Quantum Computers.	Develops inter-disciplinary technologies (photonic, electronic, and Quantum) for emerging applications in communications and metrology. Develops tools that allow a complete characterization of quantum states.	Developed Mid-Wave Infrared Quantum Cascade Lasers (QCLs) and their characterization by the systematic study of QCL optical damage, long-term reliability, and increase in damage threshold for high power QCLs.	Developed a Quantum All-Optical Transponder (QOAT) based on in-band quantum frequency conversion (QFC), which makes it possible to implement any-to-any frequency hopping using low-noise electro-optic techniques, supporting high data rate transparent optical quantum networks.	Developed a new Quantum Information Converter using Modal Coupling Key (QUICK), a new Integrated Quantum Cryptography Receiver (IQCR) based on a chip-integrated CMOS-compatible design, and a new monolithic Silicon/Germanium/ CMOS (SIGNMOS) photoreceiver, among other devices.	Developed a Seismic Acoustic Detection and Ranging (SADAR) system and a Rabidly Deployable Hardened Sensor (RDSH) system with Quantum Sensing Technology.	Develop high-efficiency two-photon lasers based on microbeads doped with colloidal quantum dots for application in coherent-optical coding.
City, State	Andover, MA	Bozeman, MT	Pleasanton, CA Pittsburgh, PA	Elmsford, NY	Evanston, IL	Orlando, FL	Goleta, CA Santa Barbara, CA	Torrance, CA	Cocoa Beach, FL	Springdale, AR San Diego, CA
Department	DOD, NASA, DOE	DOE, DOD, NASA, NSF	HHS, DOD, DOE	DOD, DOE, NASA	DOD, DOE	DOD	DOE, DOD, NASA	DOD, DOE, DHS, NASA	DOD	HHS, NSF, DOD
Total Amount	$13,266,346	$11,407,919	$9,630,371	$8,590,530	$7,601,610	$7,214,551	$6,279,725	$5,707,283	$5,698,400	$5,424,939

Source: **Moonbeam Exchange and Pitchbook**

While performing well on grants, Washington is lagging on SBIRs and contract awards.



Place of Performance (State)	Number of Federal Contracts	Total Federal Obligation	Per Capita
IL	27	$51,193,717	$4.03
NM	4	$6,374,550	$3.04
MA	27	$10,494,116	$1.53
NJ	6	$12,726,835	$1.43
MT	18	$1,430,671	$1.35
NH	4	$1,824,968	$1.35
CA	76	$50,431,182	$1.28
DE	1	$748,612	$0.77
MD	26	$4,198,027	$0.70
HI	3	$881,602	$0.62
WA (25th)	7	$468,286	$0.06

Place of Performance (State)	Number of SBIR/STTRs	Total SBIR/STTR Amount	Per Capita
MT	25	$11,760,891	$11.07
MA	154	$56,676,359	$8.25
NH	22	$7,175,056	$5.30
CO	57	$25,048,038	$4.41
NM	25	$7,271,791	$3.47
DE	8	$2,741,535	$2.83
CA	293	$107,404,240	$2.73
NY	67	$22,677,995	$2.71
IL	73	$27,172,986	$2.14
MD	29	$10,701,690	$1.77
WA (14th)	19	$8,269,697	$1.10

Recipient State	Number of Grants	Total Grant Amount	Per Capita
MA	246	$191,101,887	$27.80
MD	48	$74,768,800	$12.38
MT	4	$12,916,682	$12.16
CO	29	$41,206,698	$7.25
CA	296	$243,802,894	$6.20
NM	29	$12,801,499	$6.10
RI	23	$6,032,915	$5.50
ID	2	$8,749,741	$4.60
IL	81	$54,257,700	$4.27
WA (10th)	37	$31,962,018	$4.25

Differentiation and strategic focus is needed for Washington State to improve its position.

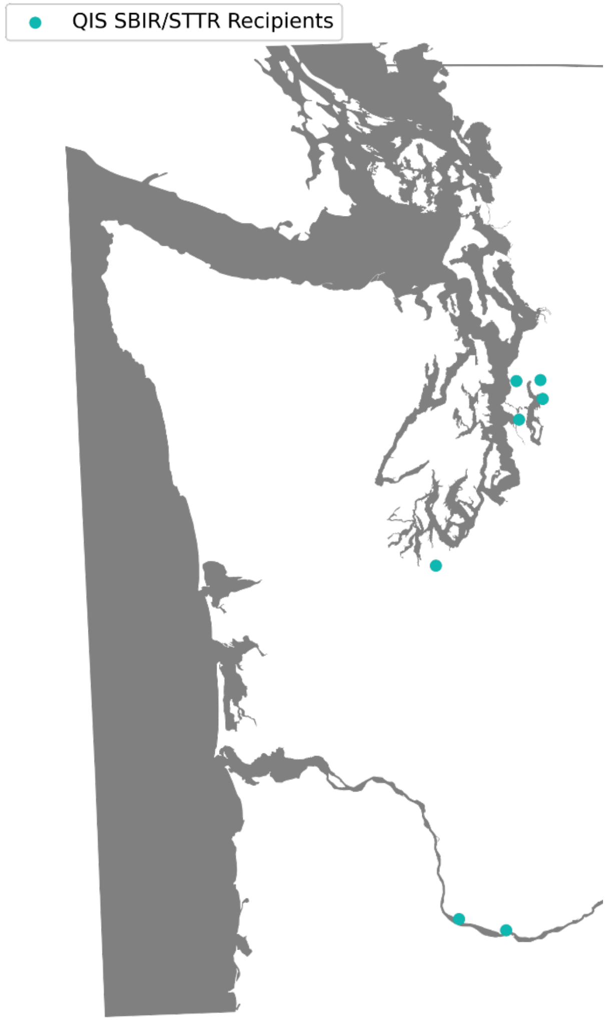
Source: **Moonbeam Exchange**
Keyword: **“Quantum Information System”, “Quantum Computing”, “Quantum Communication”, “Quantum Simulation”, “Quantum Control”, “Quantum Networking”, “Quantum Optics”, “Quantum Cryptography”, “Quantum Sensing and Metrology”, “Quantum and Cybersecurity”**
Dates between: **FY 2008 – FY 2022**

State universities and Microsoft have received funding through grants.

	University of Washington	Microsoft Corporation	Washington State University	Western Washington University
Description	Grant topics • Quantum Simulation • Quantum Dots • Photonic Device to Generate Quantum Entanglement for Quantum Information Processing • Quantum Computing • Quantum Communication	Grant topics • Quantum Computing	Grants • Quantum Simulation • Quantum Computation • Quantum State Engineering	Grants • Quantum Matter and Machines • Quantum Simulation
HQ Location	Seattle	Redmond	Pullman	Bellingham
Departments	NSF, DOD, DOE, DOC, NASA	DOD	NSF, DOD, NASA	NSF
Number of Grants and Total Amount	29 grants $24,113,904	2 grants $6,488,500	4 grants $835,928	2 grants $523,686

Source: **Moonbeam Exchange**
Keyword: **“Quantum Information System”, “Quantum Computing”, “Quantum Communication”, “Quantum Simulation”, “Quantum Control”, “Quantum Networking”, “Quantum Optics”, “Quantum Cryptography”, “Quantum Sensing and Metrology”, “Quantum and Cybersecurity”**
Dates between: **FY 2008 – FY 2022**
Additional Filters: **“HQ Localization – Washington State, US”**

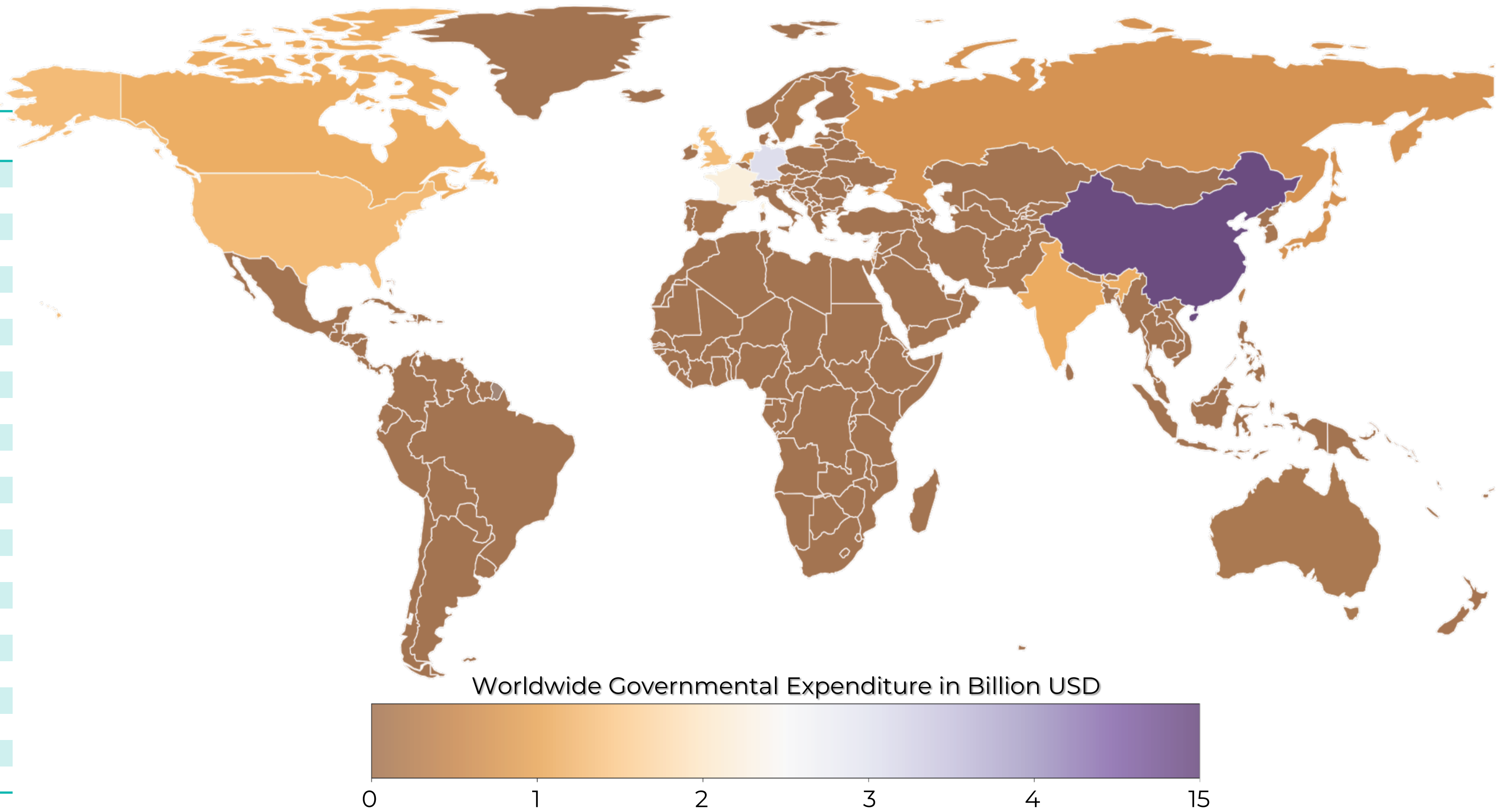
Eight companies based in Washington State have received SBIR/STTR funding.



	Hummingbird Precision Machine	nLight Photonics	Dotquant	Paradigm Optics	NonLinear Materials	Nion	Aculight Corp	Eagle Harbor Technologies
Description	Hummingbird Scientific has successfully developed, prototyped, and tested new, easy-to-use, and highly stable liquid helium-cooled TEM sample holder in order for the fundamental atomic-level physics of quantum systems to be understood and exploited.	Design, grow, fabricate, test, and deliver a 50W (rated, 25°C) compact, conductively-cooled diode laser pump module, coupled to a 200um core, 0.22 NA fiber to “eye-safer” high-power solid state laser for LADAR and directed energy weapons.	Develop a versatile quantum dot (Qdot)-based single-cell molecular profiling technology for in situ multiplexed quantitative molecular characterization of biological specimens with optical imaging resolution.	Develop innovations in the science and application of polymer doping, fiber drawing and bundling technology, by developing new methods of doping polymer with higher concentrations of quantum dots and other nanoparticles. These proposed polymer products will be better replacements for current glass products, not only because of lower fabrication costs, but because of the increased functionality polymers provide.	Producing high-performance hybrid organic electro-optic components capable of direct integration with conventional silicon-based semiconductor technologies to market. These materials demonstrated significant advantages in speed, size, and power consumption compared to existing technologies.	Develop a second generation of a monochromator with improved optics to allow application into the field of quantum materials and other fields of physics and biology. New features will deliver more precise aberration correction, improved stability, and advanced, user-frienly autotuning software.	A high-quantum-efficiency long-lifetime photocathode is a key component for the synchronous photoinjection of GaAs photoemission guns used in modern particle accelerators.	Provides innovative pulsed-power solutions intended to solve challenging problems for commercial and research markets. The company’s precision pulsed-power systems, unique solid-state switching systems and diagnostics are used to advance low-temperature plasmas, fusion energy science, water treatment, combustion, and semiconductor processing, among others. Received a contract with NASA to develop an eddy current NDE tool with high gain integrator sensitivity comparable with superconducting quantum interference devices, without the need for low temperature components.
HQ Location	Lacey	Vancouver	Shoreline	Vancouver	Seattle	Kirkland	Bothell	Seattle
Department	DOE	DOD	HHS	NSF	NSF	DOE	DOE	NASA
Number of SBIR/STTRs and Total Amount	SBIR Phase I & II $2,800,000	SBIR Phase I & II $1,518,444	SBIR Phase I & II $1,427,660	SBIR Phase I & II $599,970	STTR Phase I $256,000	SBIR Phase I $199,798	1 SBIR Phase I $99,998	1 Contract undisclosed

Globally, other governments are investing in QIS, estimated US$30 billion in 2022 – with China accounting for nearly 50%.

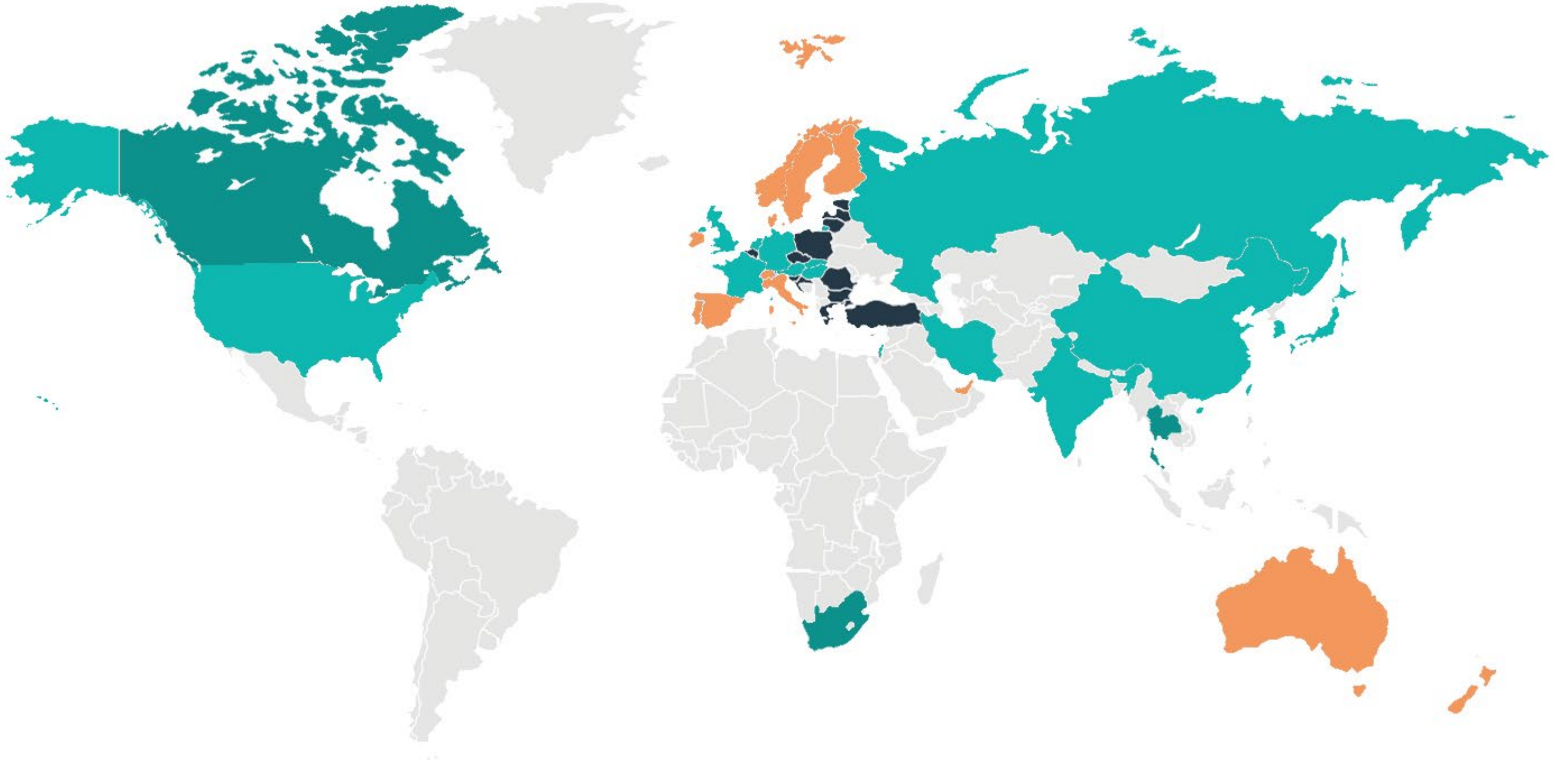
Country	Expenditure (US$ Billions)
China	15.3
Germany	3.1
France	2.2
UK	1.3
US	1.275
Canada	1.1
India	1.08
Netherlands	0.904
Japan	0.7
Russia	0.691
Israel	0.38
Singapore	0.3
Taiwan	0.282
Sweden	0.16
Austria	0.127
Australia	0.1025
Spain	0.067
South Korea	0.04
New Zealand	0.037
Denmark	0.034
Finland	0.027
Hungary	0.011
Qatar	0.01
Thailand	0.006



Source:
IFT149B Quantum Computing: Technologies and Global Markets to 2026 (BCC Research LLC),
A Quantum revolution: Report on global policies for quantum technology (CIFAR, April 2021, link)

(Since 2015 unless otherwise noted; US dollar amount at Jan 2021 conversion rates)

Globally, national approaches to quantum technology R&D can be broadly classified into three categories.



- **National Quantum Strategy** - 37% (17 countries) have a coordinated national quantum strategy and **6.5% (3 countries)** are currently developing that strategy
- **Government-endorsed Initiatives** - 26.1% (12 countries) do not have a national strategy, but have significant government or government-endorsed initiatives
- **International Quantum Partnerships** - 30.4% (14 countries) do not have significant initiatives, but are participating in international quantum partnerships)
    - Mostly throughout Europe. One of the most significant is the €1B EU Quantum Flagship, which brings together stakeholders in government, academia, and industry from 32 countries within and beyond the EU. Other initiatives include QuatERA and OpenQKD.

Source:
Adapted from **A Quantum revolution: Report on global policies for quantum technology (CIFAR, April 2021, link)**

Quantum technology R&D strategies and initiatives in a selection of countries with comprehensive policy measures

	United States	European Union	China	Canada	Germany
National Strategy	National Quantum Initiative	Quantum Technologies Flagship Euro QCI Declaration	Quantum Technology R&D as strategic industry in Five-Year Plans and "Made in China 2025"	N/A (Quantum Canada strategy in development since 2016)	Quantum Technologies – From Basic Research to Market (2018)

Major Quantum R&D initiatives or policy measures	• Up to US$1.275 billion in spending
	• National Quantum Initiative (NQI) with five program component areas: Quantum Sensing and Metrology, Quantum Computing, Quantum Networking, QIS for Advancing Fundamental Science, Quantum Technology
	• National Quantum Coordination Office within White House Office of Science and Technology Policy
	• National Science Foundation: three Quantum Leap Challenges Institutes, Quantum Foundry, Center for Quantum Networks
	• Department of Energy: five Quantum Information Science Centers; blueprint for nationwide quantum internet
	• Quantum Economic Development Consortium (QED-C) of industry, academic, and government stakeholders to build ecosystem and supply chains
	• National Q-12 Education Partnership
		• Quantum Flagship: 10-year, billion-euro (US$1.1 billion) program allocated for 2018-21
		  ◦ 21 technical projects across five areas (7 in basic science, 4 in communications, 4 in computing, 4 in sensing and metrology, and 2 in simulation) plus four horizontal activities (3 in Management and Strategy and 1 in Education) (link)
		  ◦ Quantum Industry Consortium – not-for-profit association established by large enterprises, SMEs, investors, and startups, forming a collaborative hub to build a quantum ecosystem throughout Europe.
		• QuantERA: US$48.8 million coordinated international research funding partnership
		• OpenQKD: Industry-academy consortium for QKD development
		• European Quantum Communication Infrastructure (EuroQCI): working towards a secure Europe-wide Quantum Internet
			• Believed to be one of the leading nations in QIS, began investing in quantum R&D very early on (end of the 90s)
			• By 2030, China aims to have expanded its national quantum communications infrastructure and constructed a practical quantum simulator
			• China Academy of Sciences Center for Excellence in Quantum Information and Quantum Physics
			• Quantum Experimental at Space Scale (QUESS) project (Micius satellite)
			• Beijing-Shanghai Quantum Secure Communication Backbone landline
			• National Laboratory for Quantum Information Sciences in Hefei (US$15.3 billion over five years)
				• Considered one of the world's leading nations in Quantum Research, with a growing private sector, outstanding research expertise, and extensive government commitments to innovation
				• Government funding (US$149.7M) for 4 Quantum Research Centers between 2015 and 2018
				• Canadian Space Agency Quantum Encryption and Science Satellite Mission
				• National Research Council of Canada's Security and Disruptive Technologies Research Centre: Quantum Sensors Challenge Program
				• Natural Sciences and Engineering Research Council / UK Research and Innovation joint call for industry-academia consortia for quantum technology development
				• VC investment in quantum startups
				• 2021 budget proposes US$288M to launch National Quantum Strategy
					• US$2.4 billion to support quantum technology research in COVID recovery
					• Proposed in quantum framework:
					  ◦ Center of Excellence for Quantum Technologies,
					  ◦ Calls for proposals for academic-industry collaborative projects,
					  ◦ "Junior research groups" to train future executives in quantum technology,
					  ◦ Grand Challenge competition in Quantum Communication,
					  ◦ Up to three clusters of Excellence in Quantum Computing
					• Seven current German Research Foundation Clusters of Excellence with a quantum focus; Quantum Alliance of research centers
					• QuNET: central platform for secure quantum communication
					• Fraunhofer-Gesellschaft-IBM collaboration to build Europe's first quantum computer by 2021 (and most powerful in Europe)

Quantum technology R&D strategies and initiatives in a selection of countries with comprehensive policy measures (cont.)

	Australia	Russia	Japan	France	United Kingdom
National Strategy	N/A	Quantum Technologies Roadmap (2019)	Quantum Technology Innovation Strategy (2020)	National Strategy for Quantum Technologies (2021)	National Quantum Technologies Programme (2013)

Major Quantum R&D initiatives or policy measures	• Four Research Council Centers of Excellence focused on Quantum Research (US$98.6M 2017-24)
	• Department of Defense Next Generation Technologies Fund on Quantum Technology (US$4.5M)
	• Federal and state governments part-ownership of Silicon Quantum Computing
	• Sydney Quantum Academy
	• May 2020 CSIRO roadmap "Growing Australia's Quantum Technology Industry"
	• Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS) was set up to conduct world-leading research to exploit the potential of quantum science and develop a range of transformational technologies
		• US$690 million to consolidate ongoing research in 4 sections: quantum computing and simulation, quantum communications, quantum metrology and sensing, and enabling technologies. This will involve over 120 research experts from leading research institutions.	• US$206 million allocated in FY2020 budget
			• Principles and strategies for next 10-20 years: roadmaps for four priority technological areas and three integrated innovation areas (AI, biotechnology, security), 5+ quantum innovation centers, 10+ CV supported via government investments, procurements, etc.
			• Quantum Leap (Q-LEAP) Flagship Program to invest in R&D projects in quantum simulation and computation, quantum sensing, and ultrashort pulse lasers
			• Project for Innovative AI Chip and Next-Generation Computing Technology Development
			• Cross-ministerial Strategic Innovation Promotion Program (Photonics and Quantum Technology stream)
			• Goal 6 of the Moonshot Research and Development Program - practical 100-qubit NISQ computer and effective quantum error correction by 2030; large-scale, fault-tolerant quantum computers by 2050
				• US$2.2 billion plan, including US$1.2 billion from government
				• Key elements of quantum plan:
				  • Call for projects focused on four technological areas
				  • Grand Challenge on first-generation NISQ quantum accelerators
				  • Industrial Development Program to support near-market public-private R&D
				  • Matching fund for startups
				  • Funding for hundreds of new doctoral students, postdocs and young researchers per year
				  • Quantum training for technical diploma, undergraduate and Master's degree students
					• US$540 million for first phase (2014-19), at least US$473 million for second phase
					• Four quantum technology hubs, research programmes comprising academics with industry and government partners, specialized in areas such as imaging, ultra-precise sensors, secure communications and quantum computing
					• National Quantum Computing Centre to develop use cases with industry and promote formation of UK-based quantum supply chain
					• Centres for Doctoral Training, Training, and Skills Hubs in QIS
					• Rigetti Computing-led consortium to build UK's first quantum computer by 2023
					• Industrial Strategy Challenge Fund for projects by academic-industry consortia to bring technology to market
					• Investment in quantum startups

Source:
A Quantum revolution: Report on global policies for quantum technology (CIFAR, April 2021, link)
Qureca - Overview on Quantum Initiatives Worldwide (link)

Note: **(Since 2015 unless otherwise noted; US dollar amount at Jan 2021 conversion rates)**

Quantum Technology R&D strategies and initiatives in a selection of countries with comprehensive policy measures (cont.)

	India	Singapore	South Korea	Israel	Netherlands	Taiwan
National Strategy	National Mission on Quantum Technologies and Applications (2020)	Quantum Engineering Program (2018)	Quantum Computing Technology Development Project (2019)	National Program for Quantum Science and Technology (2019)	National Agenda for Quantum Technology: Quantum Delta NL (2019)	Quantum Computer Project

Major Quantum R&D initiatives or policy measures	• Five-year (2020-24), US$1.08 billion budget with focus on fundamental science, translational research, technology development, and entrepreneurship in four areas: computing, materials, communications, sensing/metrology
	• Establish four research parks and 21 quantum hubs
	• Indian Institute of Science explores many areas such as: superconducting qubit devices, single photon sources and detectors for quantum communications, integrated photonic quantum networks, and quantum sensors
		• US$90.9 million (2018-25) national program to fund research and ecosystem-building
		• Centre for Quantum Technologies (CQT), research center of excellence supported by National Research Foundation (US$74.8 million core funding for 2017-22)
		  ◦ Commercialization collaboration with SGInnovate
		  ◦ QKD technology for Singtel's fiber network
		  ◦ QKD Qubesat (partnership with UK's RAL Space)
		• CQT published around 2,000 scientific papers, participated in projects and established start-up companies
			• US$40.9 million over five years to develop core technology of quantum computing and to expand research base
			• US$11.9 million in next-generation ICT technology
			• Goals include developing core hardware for quantum computers and simulators (practical 5-qubit machine with 90% reliability by 2023, use cases demonstration for quantum simulators), and software for quantum computers
			• Pilot nationwide QKD network in post-COVID "Digital New Deal"
				• US$380 million over six years, including US$58 million in new funding
				• Program recommendations: establish new research labs, build national quantum computing hardware infrastructure, establish applied R&D center, speed up application projects in industry and defense
				• Quantum Technologies Consortium, co-funded by Israel Innovation Authority and Administration for the Development of Weapons and Technological Infrastructure
				• QUEST center (Quantum Entanglement in Science and Technology) was established to advance the application of Quantum Mechanics
				• One of Google's R&D centers in Tel Aviv is actively researching quantum computing
					• US$740 million over seven years (2021-27)
					• Three catalyst programs:
					  ◦ Build the first European Quantum Computing Platform
					  ◦ Create National Quantum Network
					  ◦ Develop Quantum Sensing Applications
					• Five Innovation Hubs; national House of Quantum as meeting place for innovation ecosystem
					• Field labs, expanded national cleanroom facilities, funds for SMEs and startups
					• 2000 researchers and engineers by 2027, expanded educational programs, industry internships, courses for those currently in industry and the public
					• Living Lab Quantum & Society to support research and dialogue on ELSA
						• Launched in 2018 to coordinate quantum technology R&D at a national level
						• Integrates resources of the strong semiconductor industry to develop domestic manufacturing capacity of quantum components
						• Funds individual projects by academia and industry over five years, including support for establishing the Center for Quantum Technology at National Tsing Hua University and the IBM Q Hub at National Taiwan University
						• It will also fund the development of silicon-based quantum computing at the Taiwan Semiconductor Research Institute

Source:
A Quantum revolution: Report on global policies for quantum technology (CIFAR, April 2021, link)
Qureca - Overview on Quantum Initiatives Worldwide (link)

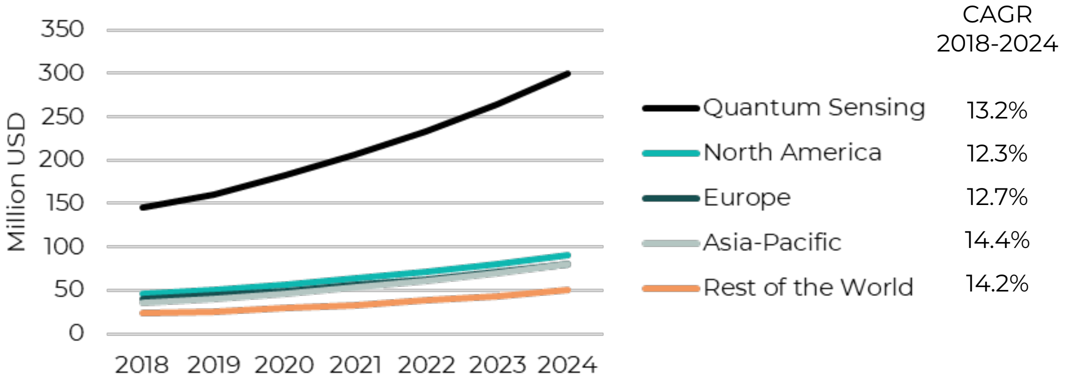
Note: (Since 2015 unless otherwise noted; US dollar amount at Jan 2021 conversion rates)

Quantum Sensing (QS) and Quantum Computing (QC) are both expected to grow in the foreseeable future.

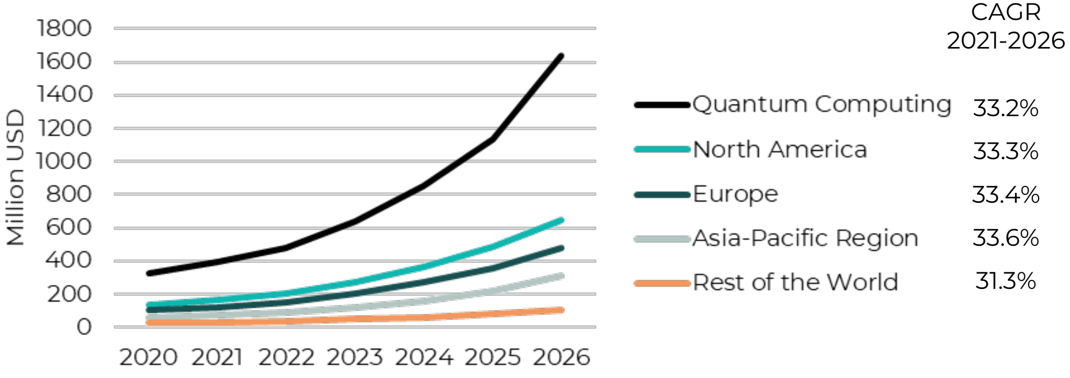
Quantum Information Systems

	Quantum Sensing	Quantum Computing
Types of Technology	Atomic Clocks, Gravity Sensors, PAR Quantum Sensors, Magnetic Sensors	Trapped-ions, Quantum Annealing, Superconducting Qubits, Photonic Qubits, Topological Qubits, Silicon Qubits, Neutral Atoms
Application	Use the sensitive nature of quantum superposition states to accurately measure external effects such as magnetic, electrical and gravitational fields, time, accelerations and rotation.	Can be used to expand simulation capacity, process optimization, complex Machine Learning Computation and problem solving, and develop the fields of Cryptography and Cybersecurity.
End-User Industry	Automotive, Space, Healthcare, and Military & Defense	Government, Healthcare and Life Sciences, Academia, Space and Defense, Energy and Power, among others
Drivers for Growth	Integration of quantum sensors into commercial chip packages (helps transform quantum sensing technology into a versatile range of sensor products)	Early adoption of quantum computers by banking, financial institutions, and the healthcare sector, rise in investments dedicated to quantum computing technology, and surge in number of strategic partnerships and collaborations
Restraints to Growth	High cost of R&D, high implementation and maintenance costs	Technological hurdles in implementation and quantum skills shortage
CAGR	13.2% from 2018-2024, from US$145.8 million to US$299.9 million	33.2% from 2020-2026, from US$390.7 million to US$1638.1 million
Market Details	Fastest Growing Market: Asia-Pacific Largest Market: North America	Fastest Growing Market: Asia-Pacific Largest Market: North America

Quantum Sensing expected growth from 2018 to 2024, broken down by World Region



Quantum Computing expected growth from 2021 to 2026, broken down by World Region

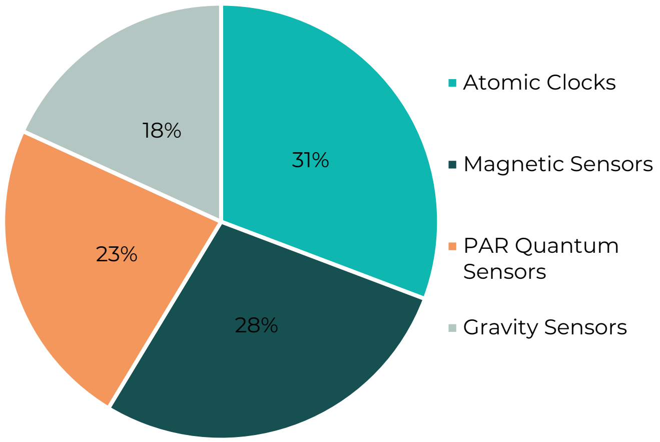


Source:
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing
Quantum Sensors: Quantum Entanglement for Communications and Beyond (Published September 2019) by BCC Publishing

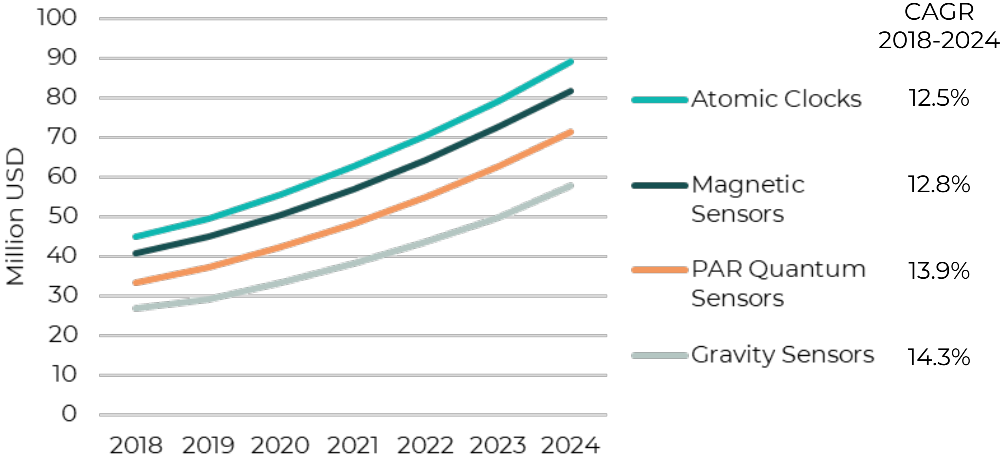
Market share is well distributed along the four main technologies in QS; all with CAGR > 12%.

Technology	Main Companies
Atomic Clocks	• M Squared Lasers • Infleqtion • Thales • Vector Atomic • Teledyne e2v
Magnetic Sensors	• Bosch • Oxford Instruments • SBQuantum • Honeywell
PAR Quantum Sensors	• Sea-Bird Scientific • Apogee Instruments • LI-COR • Campbell Scientific • NuCrypt
Gravity Sensors	• Atomionics • NOMAD Atomics • µquans

Global Market Shares of Quantum Sensing by Technology (2019)



Global Market for Quantum Sensing, by Technology

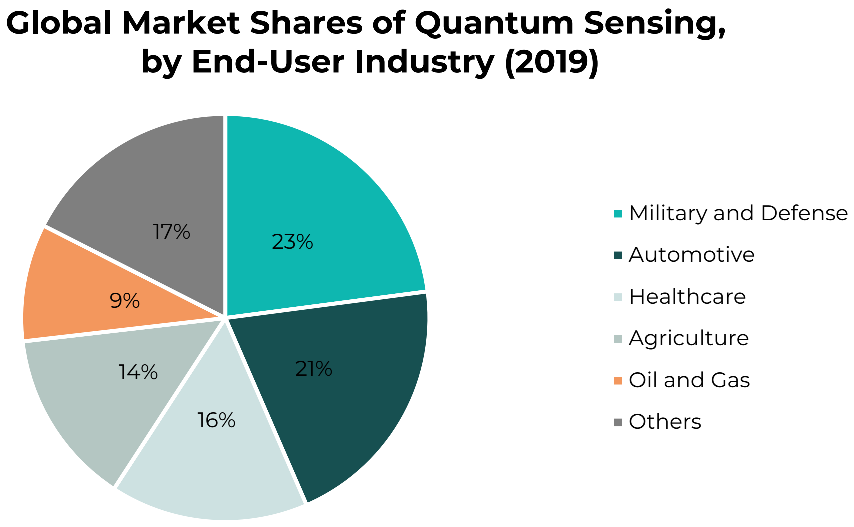


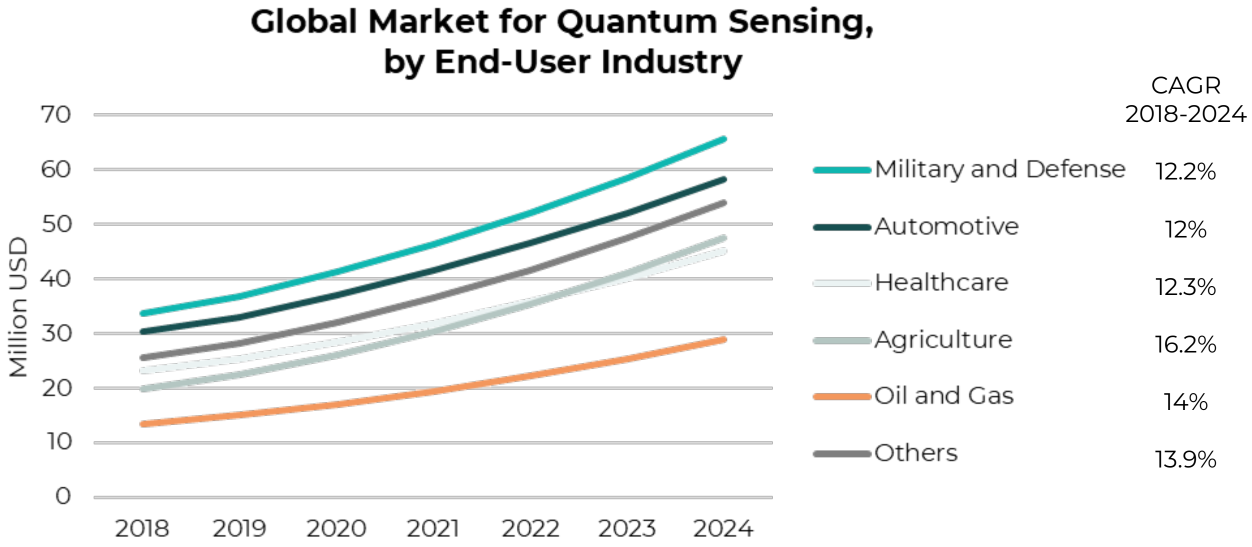
Among all the product types, atomic clocks held the highest share of the market in 2018 and commanded a market share of 31% in the global quantum sensors market. However, the gravity sensors segment is expected to witness the fastest growth rate during the forecast period, growing at a CAGR of 14.3% from 2019 through 2024. This is mainly because of its potential as a tool for subterranean surveying (e.g., detecting groundwater reserves and deposits of minerals, oil, or gas, among others).

Quantum Sensing

Source:
Quantum Sensors: Quantum Entanglement for Communications and Beyond (Published September 2019) by BCC Publishing
14 Companies Focused on Quantum Sensing and Manufacturing Superior Instrumentation to Revolutionize the Industry – The Quantum Insider (link)

Research on QS reveals numerous applications; reducing manufacturing costs is critical.





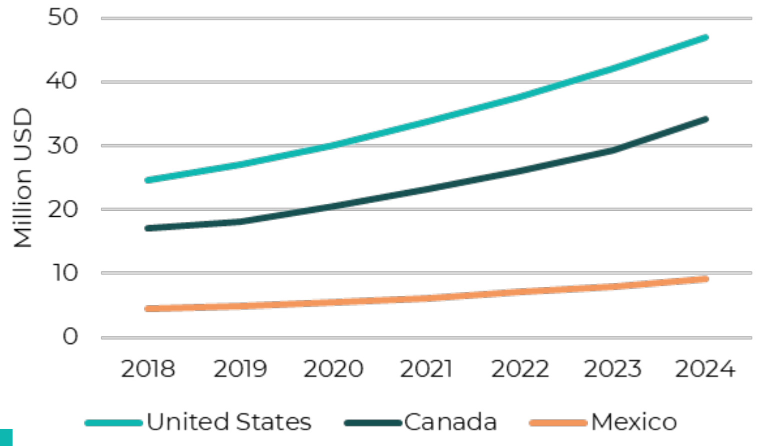
Quantum sensors show high promise for the Military & Defense industry by helping in the detection of radar signals that cannot be detected with stealth technology. The Automotive industry is also a sizable potential end user due to the interest in self-driving vehicles. Combined, these two industries account for close to 45% of the global market share.

PAR Sensors are ideal devices the photosynthesis process, which is essential for food production. As such, they have the potential to increase agriculture productivity. Therefore, it is believed that the Agriculture industry will show the strongest growth (CAGR 16.2%).

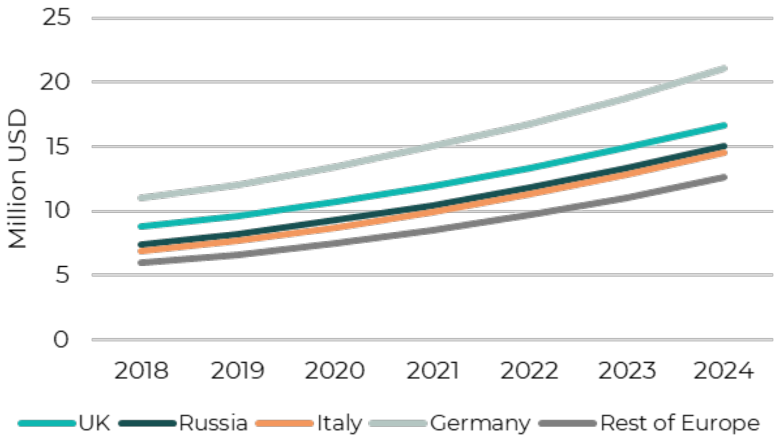
Quantum Sensing

QS is expected to grow globally, with most countries investing in defense and agriculture use cases.

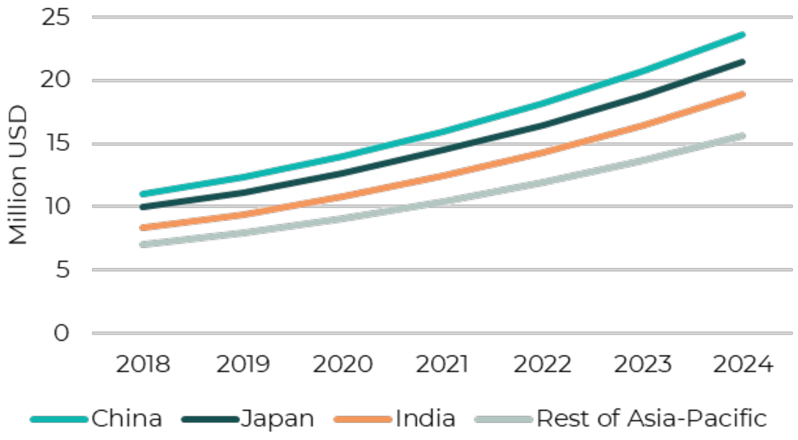
North American Market for Quantum Sensing, by Country



European Market for Quantum Sensing, by Country



Asia-Pacific Market for Quantum Sensing, by Country



Quantum Sensing

- In North America, QS growth will be driven by construction, strong investment in the defense sector, and agriculture.
- Europe has several ambitious initiatives in quantum technology R&D, with almost half of the research being carried out in Germany, France, and United Kingdom. Key research areas for photonic technology are laser technology, photonics design research, nanophotonics, and thin films.
- The Asia-Pacific region is expected to have the fastest growth rate, as quantum technology is swiftly penetrating large-scale industrial verticals and replacing the traditional systems. China is leading the market for quantum sensing in the region, having launched the world's first quantum satellite in 2016 and advancing with a radar prototype that it claims could detect stealth aircraft in flight in 2018.

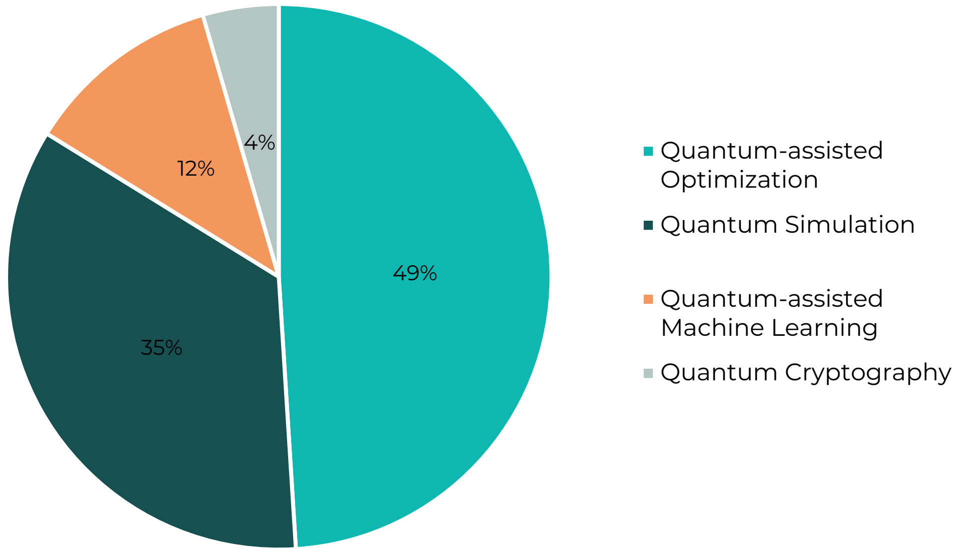
QS value chain analysis helps business entities reduce costs of production and increase performance levels by focusing on their core capacities

Quantum Sensor Components	Sensor Design and Manufacture	Assemblers and Fabricators	Application	Distributors	End Users
Quantum sensors work in accordance with quantum physics principles. The components that comprise a quantum sensor are *optical filters, diffusers*, and *photodetectors*, and all determine the performance of a quantum sensor.	Design of a sensor determines the initial cost of production, i.e., the manufacture *cost strictly depends upon the design and purpose of the sensor*. In addition, quantum sensor design requires detailed *study and research*. Manufacturing companies: Boston Electronics, Albis Optoelectronics AG, and Hamamatsu.	Fabricators and assemblers put together all the parts and components of the final sensor. They might use several tools, machines and engines for fabrication. There is a *high level of integration* between final equipment integrators and product fabricators and assemblers. Major companies: IMRA America, Hamatsu Photonics, and EKSPLA	Most companies that supply quantum sensors offer them to a wide range of applications in various fields, which adds value to the market. Some of these companies are: AO Sense, GWR Instruments, Spectrum Technologies, Apogee Instruments, and Biospherical Instruments.	Finished products and solutions are available to customers through a number of distribution channels, including *direct sales, indirect sales, retailers, online company stores, e-commerce channels, and engineering application channels*. Electronic manufacturers distribute, test, design, and provide services for electronic components, particularly for original equipment manufacturers (OEMs).	Current application in a vast number of areas like *defense, disaster management, agriculture, geographical monitoring, environmental monitoring and public safety and surveillance sectors*. With the current rate of technological advancement, applications are expected to expand to other areas. Research will help reduce costs, making quantum sensors more affordable and efficient.

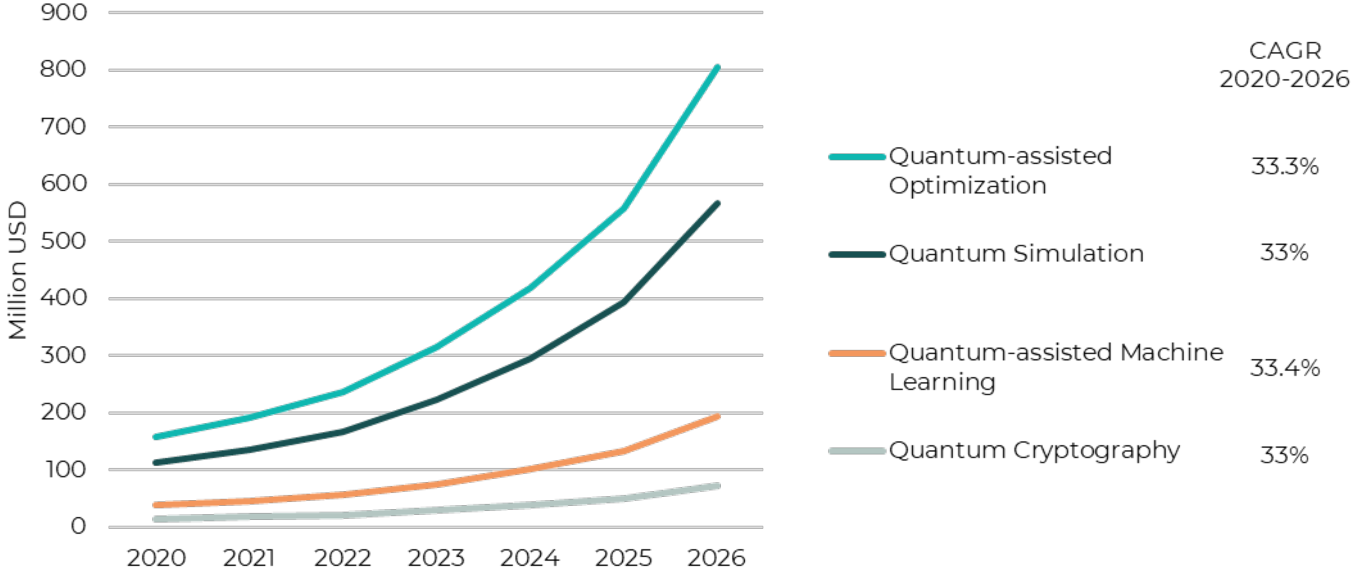
Source:
Quantum Sensors: Quantum Entanglement for Communications and Beyond (Published September 2019) by BCC Publishing

Top applications of QC include optimization and simulation.

Global Market Share of Quantum Computing Technologies, by Application (2020)



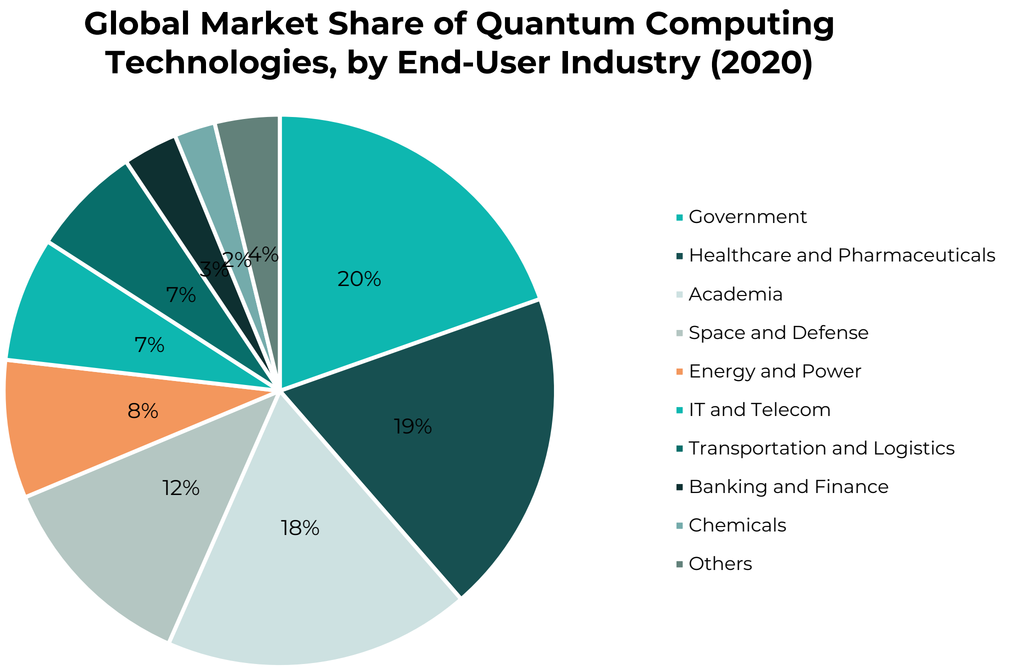
Global Market for Quantum Computing Technologies by Application

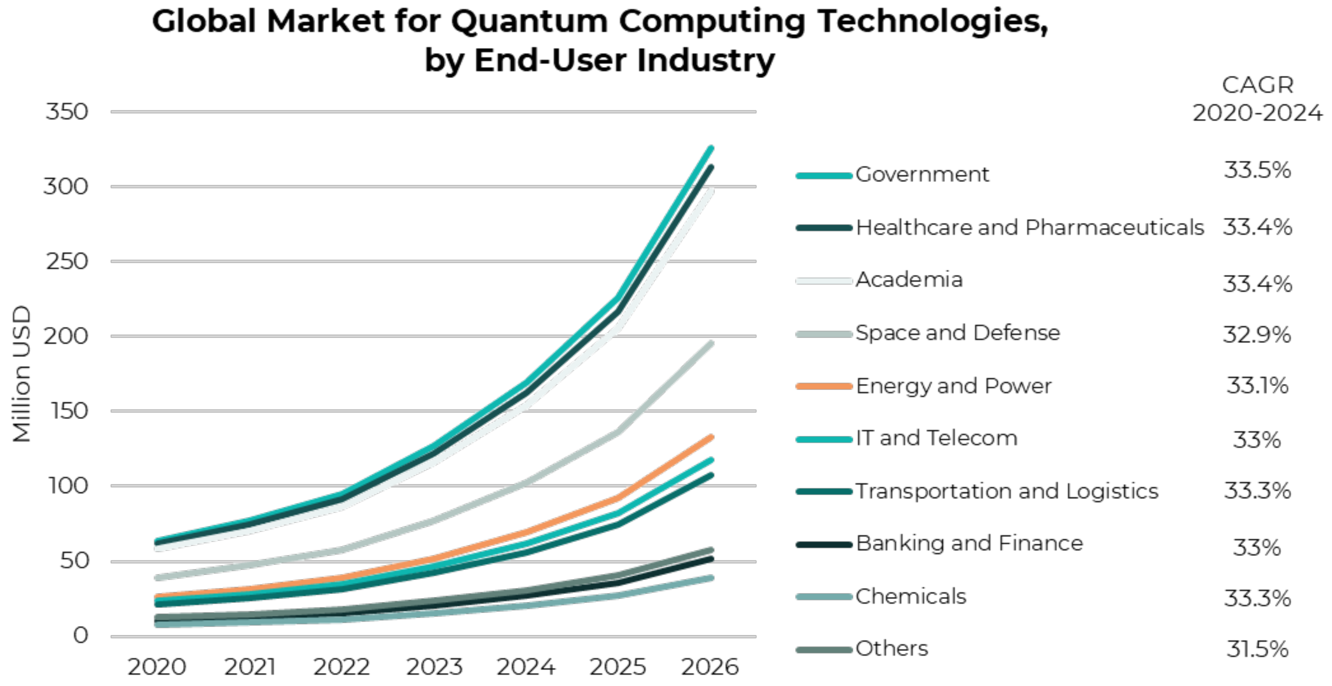


In QC, all potential applications are expected to grow. Quantum-assisted optimization accounts for 49% of market share, followed by Quantum Simulation with 35% of market share. However, Quantum-assisted Machine Learning is the application with the highest CAGR.

Quantum Computing

QC is expected to bring new models of computation to the pharmaceutical, materials sciences, financial, travel/logistics, and government sectors.



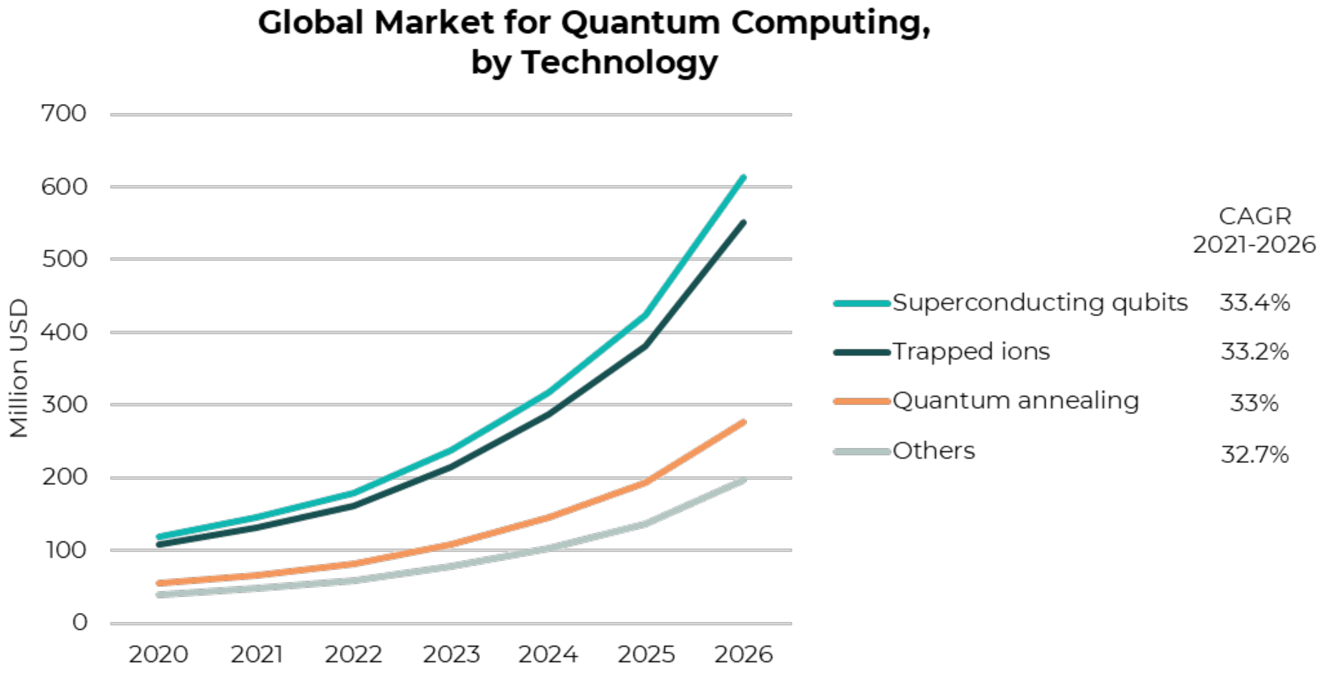


According to McKinsey, over the long term, the highest-value quantum computing use cases will likely be in the life sciences; financial services; and travel, transport, and logistics sectors.

Quantum Computing

There is significant fragmentation in qubit technology, with several experiments in place.

Technology	Main Companies
Trapped ions	• IonQ • Honeywell • Alpine Quantum Technologies
Quantum Annealing	• D-Wave • Qilimanjaro
Superconducting qubits	• IBM • Google • Rigetti Computing • D-Wave • Alibaba • Intel • NEC • Quantum Circuits • Oxford Quantum Circuits
Others: Photonic qubits Topological qubits Silicon qubits Neutral atoms	• PsiQuantum • Xanadu • Microsoft • Intel • Silicon Quantum Computing • Atom Computing • PASQAL • QuEra • Infleqtion



- Although superconductivity is the most common, trap technology is more stable and has higher connectivity with other qubits
- The Superconducting qubits segment had the highest revenue, with US$120 million in 2020, growing at a CAGR of 33.4%

Quantum Computing

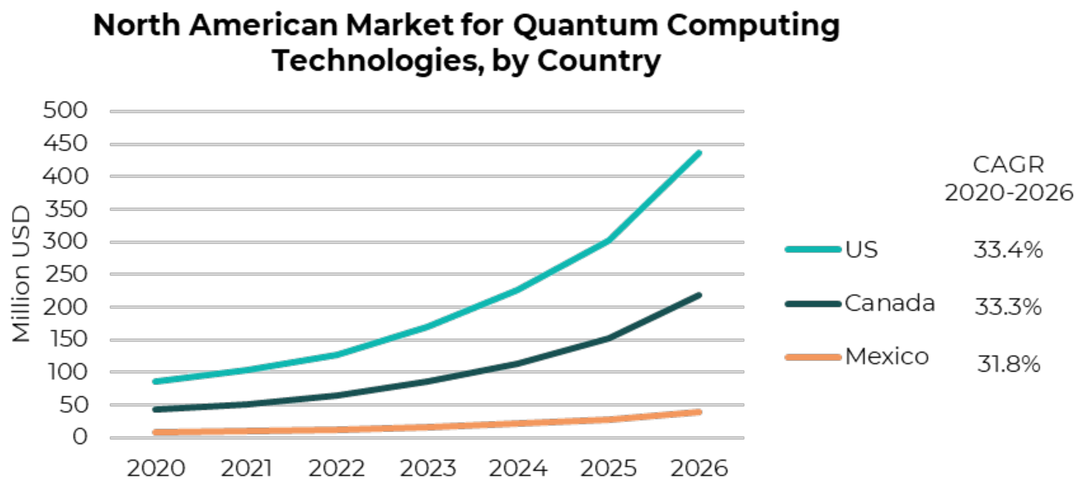
Source:
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing

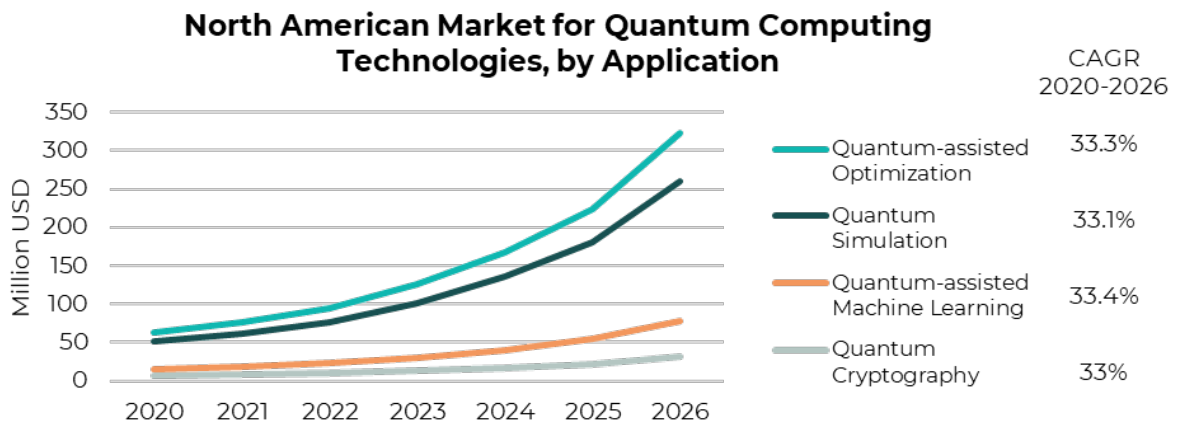
North America is currently the largest QC economy, which is likely to continue.

North America (U.S., Canada, and Mexico)

- The U.S. is the principal contributor to North America's regional market growth, corresponding to 62.5% of the Market Share in Quantum Computing Technologies. It is estimated to register significant growth over the forecast period due to the presence of a strong innovation ecosystem. Moreover, the emergence of technologies such as AI, Big Data, and cloud in virtually every sector is causing huge data generation, which requires faster, more efficient, and cost-effective memory solutions to retrieve or add information.

- North America has always been a leader in the adoption of new technologies, and Quantum Computing is no exception. It is mainly focusing on Quantum-assisted Optimization and Quantum Simulation, corresponding to over 65% of the market share of Quantum Computing Technologies.





Quantum Computing

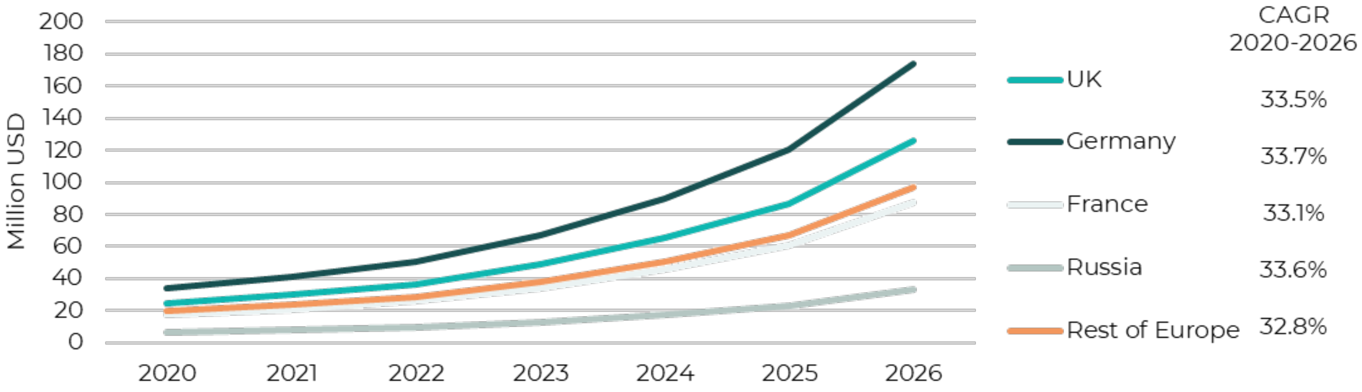
Source:
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing

Europe is the second-largest QC market and is also investing optimization and simulation.

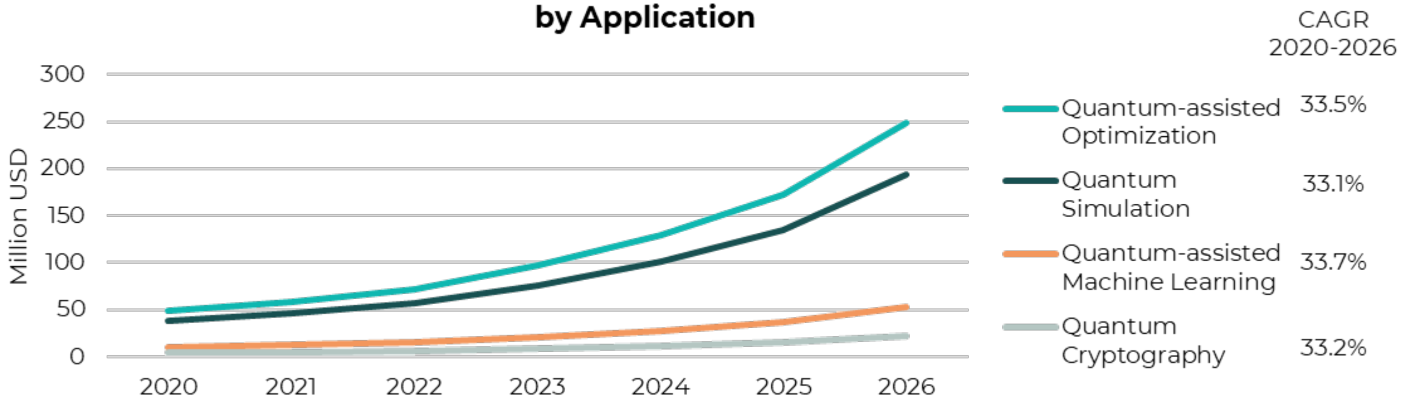
Europe

- Being the second-largest regional market, Europe's strength lies in its scientists' excellence and high level of cooperation throughout the continent, maximizing the benefit of collaborative science in a highly interdisciplinary field.
- Similar to North America, Europe is heavily investing in Quantum-assisted Optimization and Quantum Simulation, corresponding to over 80% of market share.
- Europe is mainly investing in superconducting qubits (39.2% market shares) and trapped ions (32.8%).

European Market for Quantum Computing Technologies, by Country



European Market for Quantum Computing Technologies, by Application

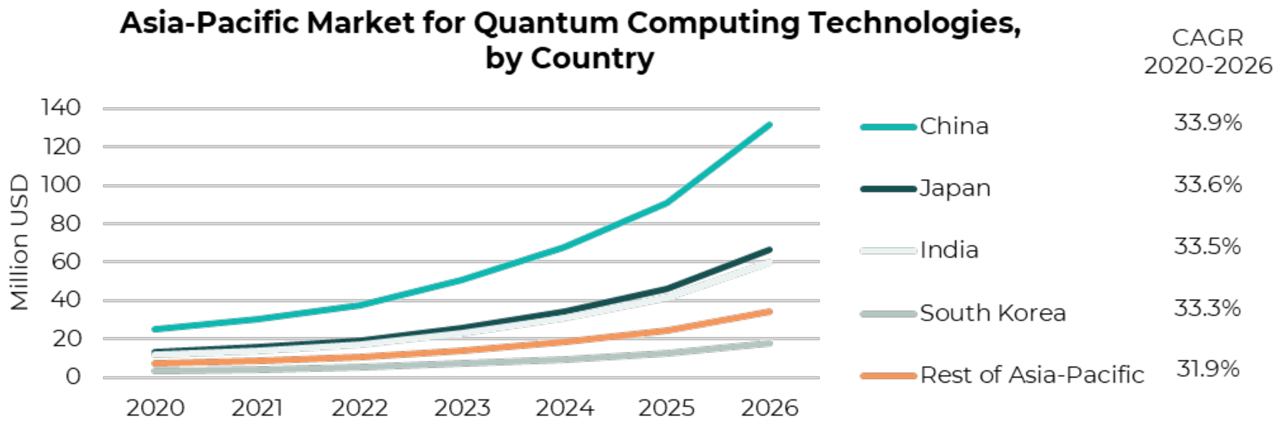


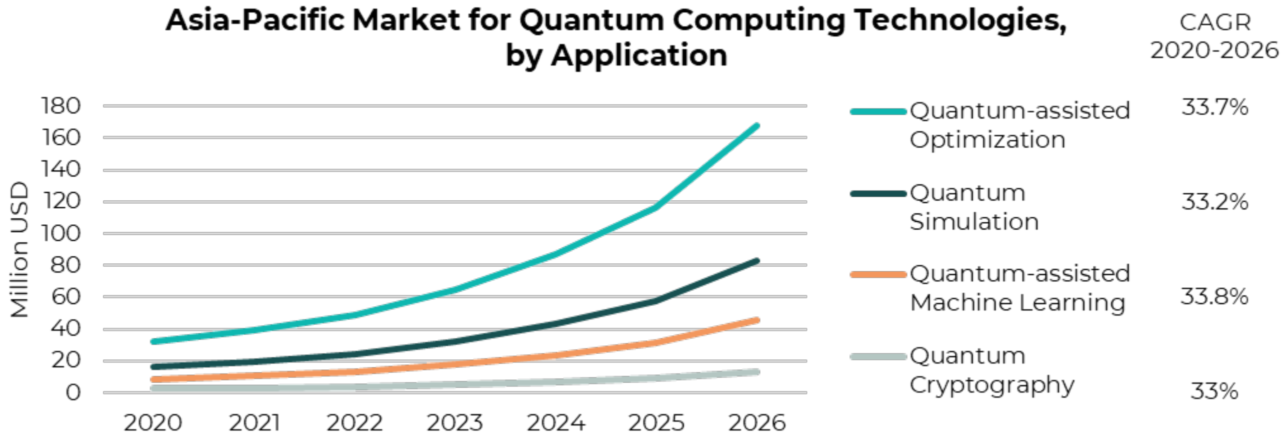
Asia-Pacific nations are actively investing in R&D, with over 70% of market share belonging to technologies like superconducting qubits and trapped ions.

Quantum Computing

Asia-Pacific

- Most of the region's revenues come from Japan and China, two countries expected to track closely in revenues throughout the forecast period.
- Investment and funding for R&D and strategic partnership reflects the market's growth. In fact, it is projected to be the most promising region for quantum in the coming year.
- Over 50% of the region's market share in Quantum Computing Technologies is dedicated to Quantum-assisted Optimization. Quantum Simulation is second with 27% of market share.

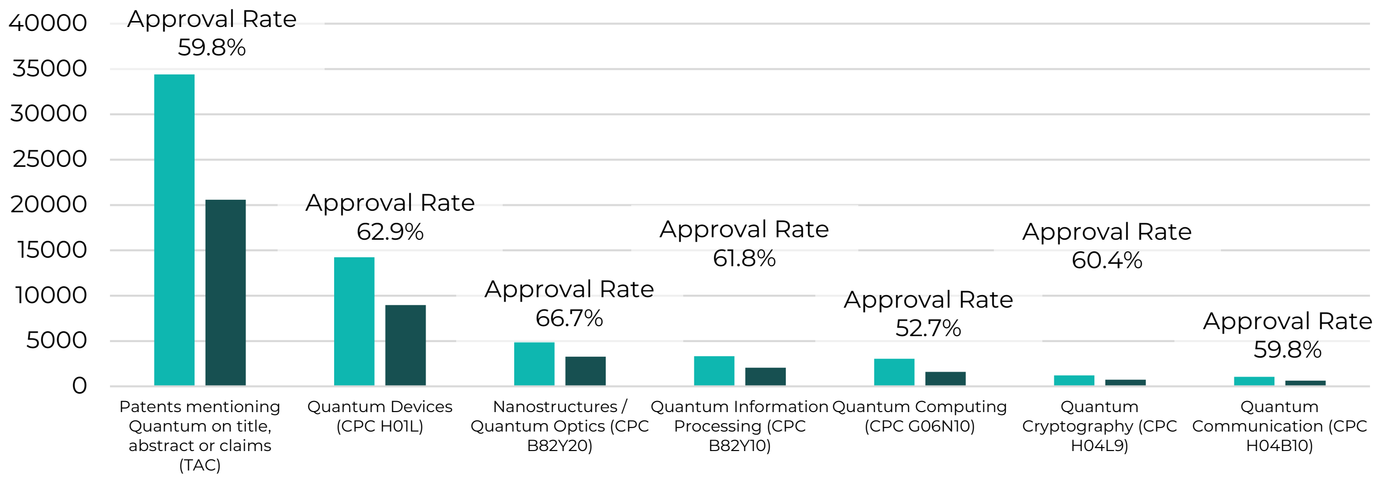




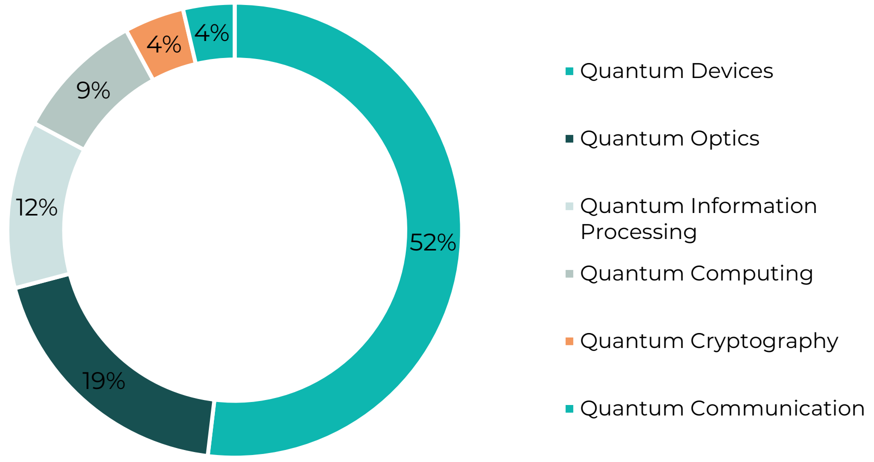
Over the last 20 years, +20k QIS patents were granted – mostly in communications and optics.

We define QIS patents as patents where "quantum" is a core concept present in the title, abstract, or claims.

Quantum Technologies patented in the US (USPTO) and Europe (EPO)



Granted Patents by quantum area of R&D



CPC (Cooperative Patent Classification)	Description	Number of Granted Patents
H01L*	Semiconductor Devices	8965
B82Y20/00	Quantum Optics	3282
B82Y10/00	Quantum Information Processing	2057
G06N10/00	Quantum Computing	1063
H04L9/0852	Quantum Cryptography	736
H04B10	Quantum Communication	632

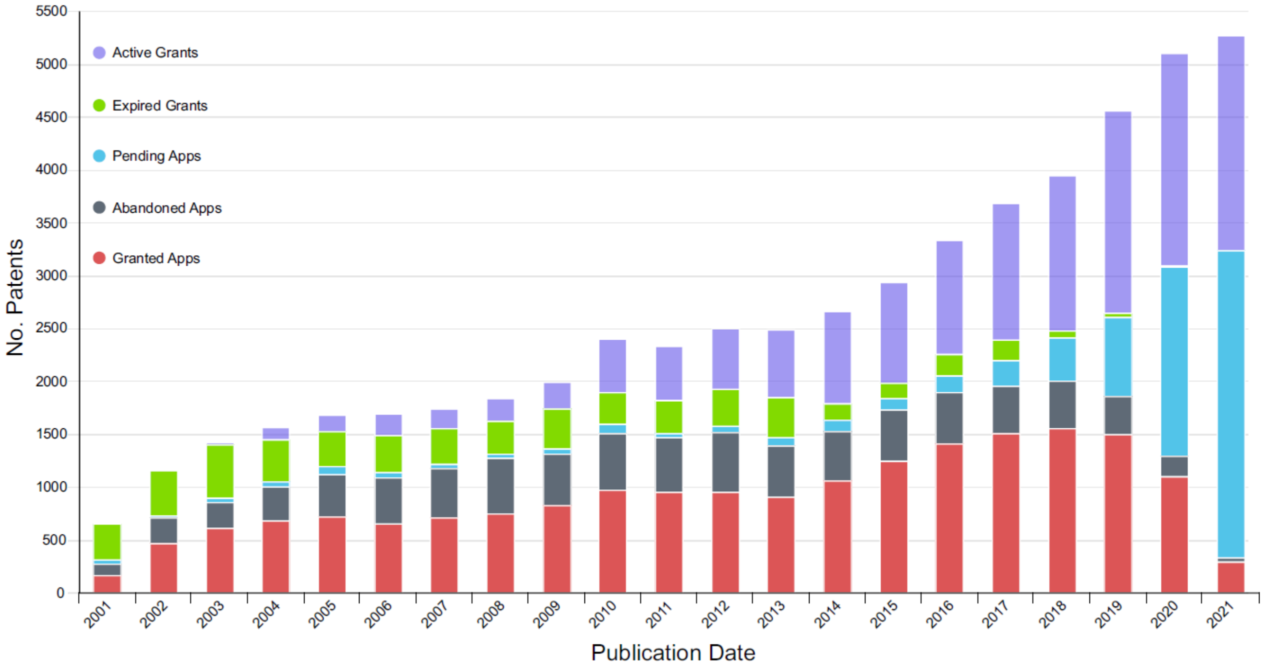
Investigating deeper into the type of research being developed in each patent, there are six main areas defined by different CPCs (Cooperative Patent Classifications). Of these, patents related to Quantum Devices were the most prominent (over 50%). Quantum Computing was fourth, with 9% of related patents.

Approval rates are high in all quantum fields (above 50%).

Source:
Aboy et al., 2022. Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy Implications. ICC 53, 853-882 (link)

Quantum patent grants have increased nearly 10x over the last 20 years.

Annual patenting activity for quantum technologies at the USPTO and EPO and legal status by publication date of the patent document



Only 161 patents were granted in 2001. In 2018, 1,555 patents were granted by USPTO and EPO, corresponding to an overall CAGR of 15.23%. Most of the growth took place between 2001-2003 and 2014-2021.

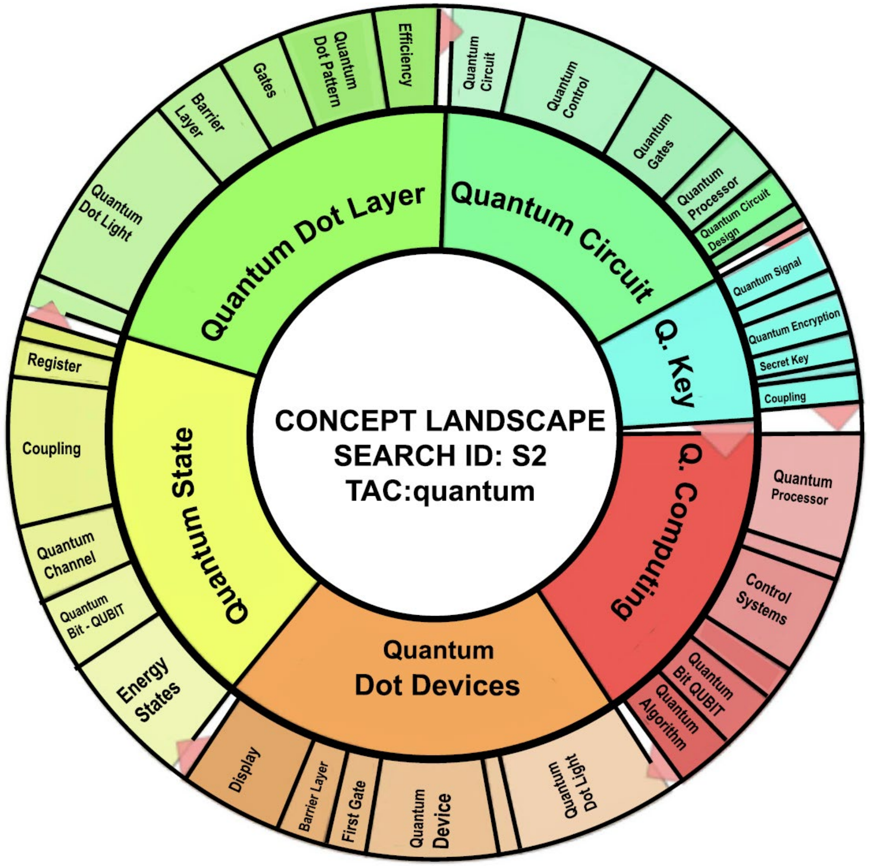
Overall, 56.89% of the applications filed in the last 20 years have been granted (n = 19,571 patents) and 43.11% (n = 14,830) were rejected/abandoned. Additionally, 22% (n = 4534) of the granted patents during this period have expired. Thus, approximately 50% (n = 19,364) of all the patent disclosures in the last 20 years are now in the public domain.

USPTO has been the patent office of choice for the last 20 years. In 2001, 63.2% of the quantum technology patents were published by the USPTO. By 2021, that figure increased to 78.8%. Overall, the EPO is the priority office for 22.04% of quantum technology patents, while the USPTO accounts for 77.96%.

Source:
Aboy et al., 2022. Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy Implications. ICC 53, 853-882 (link)

These patents can be clustered into six main areas.

Concept landscape for quantum technology patents



Automatic text analysis of the abstract, title, and claims is clustered into six areas:

- quantum circuits
- quantum dot devices
- quantum computing
- quantum dot layers
- quantum states and
- quantum keys.

- There is a second layer that includes additional details regarding the terms used to describe and claim the respective inventive concepts. Some of these overlap across the primary groups. For instance, "quantum bits" (qubits) are both in patents related to "quantum states" and "quantum computing." Similarly, the terms "quantum processor" and "quantum control" are part of the "quantum circuits" and "quantum computing" clusters.

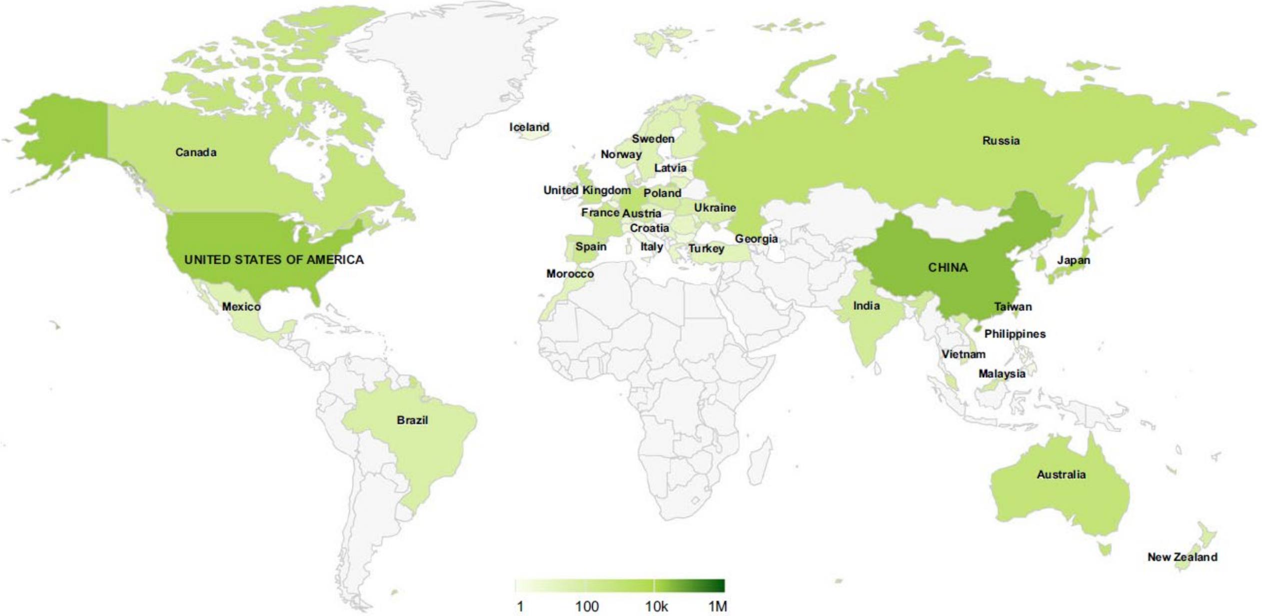
Review of patent grants in quantum computing reveals that patent claims are directed to:

- physical realizations of building blocks for quantum computers (e.g., quantum processors and components for manipulating qubits such as qubit control);
- quantum error correction (e.g. detection and prevention of errors using surface codes, magic state distillation, etc);
- models of quantum circuits and universal quantum computers;
- applications of quantum algorithms (e.g., quantum optimization, applied quantum Fourier or Hadamard transforms, etc);
- And platforms for accessing, simulating, and programming quantum computers (e.g., cloud-based computing, platforms for simulating quantum systems, and quantum programming interfaces).

Source:
Aboy et al., 2022. Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy Implications. ICC 53, 853-882 (link)

Through U.S. and China grantors, most patents are filed by companies in China and Japan.

Top patenting countries of issuance for quantum technology patents



Share of quantum patents by company headquarters, 2000-2021[1] (%)

		Quantum computing	Quantum communications	Quantum sensors
China	53.8	54.1	46.2	59.7
Japan	15.2	15.4	18.4	14.8
European Union	11.2	11.5	10.0	14.8
United States	10.0	9.6	6.5	4.5
South Korea	4.0	3.9	6.2	3.4
Taiwan	1.8	1.8	4.5	2.3
United Kingdom	1.2	1.0	3.4	0
Canada	0.8	0.6	1.6	0
Switzerland	0.6	0.6	1.0	0
Russia	0.6	0.6	0.6	0

[1]Only 50% of headquarters for patent applications are disclosed.
Source: Expert interviews; Innography; McKinsey analysis

While the U.S. continues to lead the field of quantum computing, China is arguably becoming the leader in quantum communications, which has seen most of the growth in secure quantum communications in the last five years. It is expected that Chinese quantum networking and communications devices will soon be available in global markets.

According to McKinsey, and looking at quantum patents by company headquarters, China seems to hold the largest share of patents in all major types of quantum technology.

The top patent owners in QC are less concentrated than in the classical computing and IT markets.

Top 10 QC patent owners are composed of:

- U.S. global companies focused on hardware and software platforms (IBM, Microsoft, Google, Intel),
- U.S. defense technology company (Northrop Grumman),
- A California-based, venture-backed ($200M) company founded in 2013 to provide scalable quantum processor technology based on superconducting chips (Rigetti Computing),
- Honeywell International,
- The U.S. government,
- Non-U.S. companies: D-Wave Systems (Canada) focusing on specialized quantum annealing computers and Toshiba (Japan).

In addition to well-known and well-capitalized companies, data shows that universities, public entities, and new ventures are featured among the top assignees. Strong patent protection is more critical for new entrants and quantum specialized SMEs (e.g., Rigetti Computing, 1QB, D-Wave, MagicQ) than for large-cap IT companies (e.g., IBM, Google, Microsoft, HP), semiconductor electronics and telecom companies (e.g., Intel, Toshiba, Hitachi, NEC, ST) or defense and security firms (e.g., Northrop Grumman, Raytheon).

Incumbent well-capitalised companies such as IBM, Google, Microsoft, and Intel can fund their quantum computing R&D from their internal resources (e.g., strong balance sheets and extensive R&D budgets), but the new entrants must fundraise from external investors largely based on the strength of their intellectual property (given the deeply technical nature of the field and limited prospects of short-term revenues or profits).

Assignee	Patents	Assignee	Patents
IBM	254	HARVARD COLLEGE	8
D WAVE SYSTEMS	183	MAGIQ TECH INC	8
NORTHROP GRUMMAN	120	CALIFORNIA INST OF TECH	7
MICROSOFT CORP	111	HP INC	7
ALPHABET INC	59	NEC CORP	7
RIGETTI & CO INC	53	STANFORD UNIV	7
TOSHIBA CORP	37	UNIV SYS OF MARYLAND	7
INTEL CORP	32	UNIV WISCONSIN WARF	7
HONEYWELL INT INC	26	KYNDRYL INC	6
US GOVERNMENT	26	MITRE CORP	6
HP ENTERPRISE	23	PARALLEL INVESTMENT	6
NEWSOUTH INNOVATIONS	22	QC WARE CORP	6
MASS INST OF TECH MIT	20	SEOUL SILIP UNIV	6
EQUAL1LABS INC	16	TECHNISCHE UNIV DELFT	6
HITACHI LTD	15	UNIV JOHNS HOPKINS	6
JAPAN SCIENCE & TECH AG	15	UNIVERSAL RES KK	6
QUANTUM MACHINES	15	WELLS FARGO BANK	6
1QB INFORMATION TECH	14	CORNING CORP	5
ACCENTURE PUBLIC LTD	12	DARTMOUTH COLLEGE	5
IONQ INC	12	LOCKHEED MARTIN CORP	5
NOKIA CORP	12	PHOENIX CO OF CHICAGO	5
BANK OF AMERICA	11	QUANTUM VALLEY INVEST	5
ELEMENT SIX SA	11	SAMSUNG ELECTRONICS	5
GOV. OF ABU DHABI	11	UNIV CALIFORNIA	5
UNIV OXFORD	11	BULL SA	4
YALE UNIV	10	DWSI HOLDINGS INC	4
COMMISSARIAT ATOMIQUE	9	IMEC	4
RAYTHEON TECH CORP	9	KOREA ELECT. RES INST	4
SEEQC INC	9	QUINTESSENCELABS PTY	4
STMICROELECTRONICS	9	SOCIETE DE COMMERCIAL ISATION DES PRODUITS DE LA RE	4

Source:
Aboy et al., 2022. Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy Implications. ICC 53, 853-882 (link)

2. Ecosystem Mapping

Key Takeaways

- North America is more open to risk as indicated by its investment in diverse applications (B2B and B2C), whereas the EU and Asia seem focused on more proven applications.
- Washington State is emerging as a notable center of excellence, but spread across several areas.
- Clusters to watch: Chicago, D.C./Maryland/Virginia, London, Paris, Tokyo, Beijing, Seoul
- **There is an opportunity to connect the North American ecosystem by connecting clusters through a flagship industry conference.**

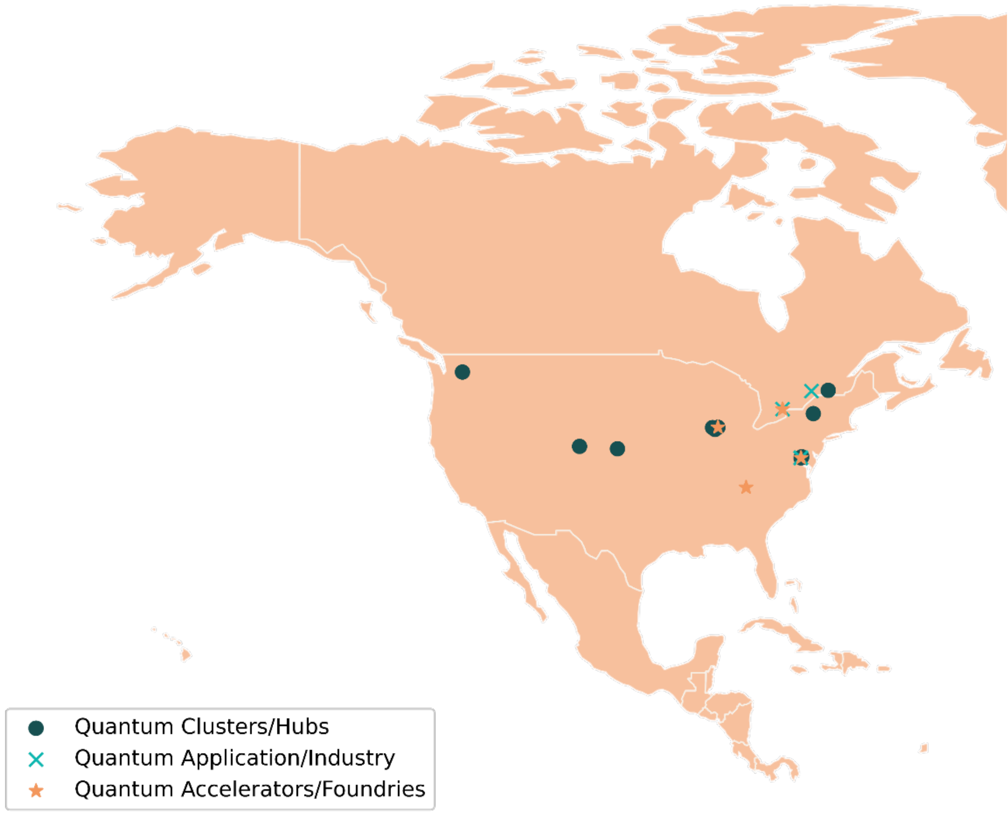
Washington State can benefit from working with and coordinating collaboration with complementary clusters.

Washington State has a unique blend of capabilities across the full technology stack to act as a national leader in quantum adoption through coordination with other clusters.

Washington is emerging as a leader in:

- Quantum Optics
  - Several companies manufacturing devices
  - Strong R&D from academia
- Quantum Computing
  - Big players with a presence in the state
  - Strong R&D from academia
- Potential quantum applications in areas that are already strong in Washington, such as:
  - Healthcare Tech
  - Cryptography / Cybersecurity
  - Agriculture Tech

QIS Clusters (anchored by hubs, accelerators, foundries) are located throughout the U.S. and Canada.



Focus	Name	Location
Quantum Clusters / Hubs	Chicago Quantum Exchange	Chicago, IL
	Potomac Quantum Innovation Center	Washington, D.C.
	Northwest Quantum Nexus	WA, USA
	Midwest Quantum Collaboratory	MI, USA
	Mid-Atlantic Quantum Alliance	College Park, MD
	Superconducting Quantum Materials and Systems Center	Batavia, IL
	Cubit Quantum Initiative	Boulder, CO
	QIR Alliance	USA
	IntriQ	Montréal, Canada
	Air Force Research Laboratory Quantum Group	Rome, NY
	Q-NEXT	Lemont, IL
Quantum Application / Industry	QED-C	Arlington, VA
	Quantum Industry Coalition	USA
	Quantum Strategy Institute	Toronto, Canada
	Quantum Industry Canada	Canada
Accelerators / Foundries	Duality	Chicago, IL
	Quantum Startup Foundry	Washington, D.C.
	Techstars	Oak Ridge-Knoxville, TN
	Creative Destruction Lab	Toronto, Canada
	IBM Quantum Network	Worldwide

Source: **Cluster websites**

North America has several clusters and hubs dedicated to QIS R&D, bringing together academia, industry partners, and national laboratories.

Focus	Name	Location	Description	Partners
Quantum Clusters / Hubs Quantum R&D	Chicago Quantum Exchange	Chicago, IL	A growing intellectual hub for the science and engineering of quantum information. It convenes leading academic researchers, top scientific facilities, and innovative industry partners to advance the science and engineering of quantum information and train the next generation.	Argonne National Laboratory, Fermilab, Northwestern University, University of Chicago, University of Illinois Urbana-Champaign, University of Wisconsin-Madison. Business partners include: Boeing, IBM, Applied Materials, Classiq, Infleqtion, Hamamatsu, Intel, JPMorgan Chase, Microsoft, Oxford Instruments, PsiQuantum, qBraid, Quantinuum, QuEra, Rigetti Computing, among others.
	Potomac Quantum Innovation Center	Washington, D.C.	Non-for-profit with the mission of preparing for the future by bringing together greater Washington, D.C.'s quantum stakeholders across borders and sectors to drive innovation, talent development, economic growth, and positive social impact.	BioHealth Innovation, George Mason University, The George Washington University, IBM, Maryland Tech Council, Mid-Atlantic Alliance, QED-C, Northrop Gruman, Quantum, Startup Foundry, QiC Mitre, among others.
	Northwest Quantum Nexus (NQN)	Washington and Oregon states	The Northwest Quantum Nexus (NQN) is a coalition of research and industrial organizations in the Pacific Northwest and neighbouring regions with the goal of advancing Quantum Information Sciences (QIS) research and developing a QIS-trained workforce. It focuses on clean energy, devices, materials, and testbeds.	Microsoft, Pacific Northwest National Laboratory, University of Washington, IonQ, University of Oregon, Washington State University.
	Midwest Quantum Collaboratory (MQC)	Michigan state	The Midwest Quantum Collaboratory is a consortium between Michigan State University, Purdue University, and the University of Michigan to form a Midwest-based alliance. It focuses on energy, sensing, research, training, and education.	Partners in academia (Michigan State University, Purdue University, and the University of Michigan), private sector and U.S. national labs.
	Mid-Atlantic Quantum Alliance	College Park, MD	Accelerates moving quantum science and engineering to further enhance the region's primacy in the field. This alliance brings together world-leading quantum expertise from academia, industry, government agencies, laboratories, and research centers.	Several academic institutes, including the University of Maryland; several Governmental R&D labs such as NIST, Johns Hopkins Applied Physics Laboratory; and several companies, including Lockheed Martin, IBM, Booz Allen Hamilton, AWS, IonQ and Quantinuum.

Source: **Cluster websites**

North America has several clusters and hubs dedicated to QIS R&D, bringing together academia, industry partners, and national laboratories. (cont.)

Focus	Name	Location	Description	Partners
Quantum Clusters / Hubs Quantum R&D	Superconducting Quantum Materials and Systems Center	Batavia, IL	A national center for advancing quantum science and technology, focusing on superconducting resonators, qubits, and material science, among other topics.	Fermilab, Rigetti Computing, Northwestern University, Ames Research Center, Ames Laboratory, University of Colorado Boulder, University of Illinois Urbana-Champaign, Stanford University, University of Arizona, Johns Hopkins University, Janis, Lockheed Martin, Illinois Institute of Technology, among others.
	CUbit Quantum Initiative	Boulder, CO	Interdisciplinary hub that reinforces Colorado's prominence in quantum information science and technology; partners with regional universities and laboratories that contribute complementary strengths and close ties to quantum-intensive companies. It serves a spectrum of local, regional, and national interests, including workforce development.	Atom Computing, Infleqtion, SPIE, Meadowlark Optics, Lockheed Martin, Honeywell, and University of Colorado Boulder.
	QIR Alliance	U.S.	Joint effort to develop a forward-looking quantum intermediate representation with the goal to enable full interoperability within the quantum.	The steering committee includes Microsoft, NVIDIA, Oak Ridge National Laboratory, Quantinuum, Quantum Circuits, and Rigetti Computing
	IntriQ	Montréal, Canada	Group of university researchers divided between nine departments of four universities in Quebec. Among them are computer scientists, theoretical physicists, experimental physicists and engineers.	Université de Sherbrooke, de Montréal; McGill; and Polytechnique Montréal. Other collaborators include Institut Quantique, University of Chicago, uOttawa, Thales.
	Air Force Research Laboratory Quantum Group	Rome, NY	The Air Force Research Laboratory is breaking new ground in its efforts to partner with industry, academia, and the Department of Defense to apply quantum information science to Air Force concerns and ensure it remains the most advanced and capable force in the world.	Air Force Bases in CA, NM, TX, FL, TN, OH, VA, HI, and NY. Collaborations with University of Washington.
	Q-NEXT	Lemont, IL	A collaboration involving the world's leading minds from the Argonne National Laboratory, universities and companies. It establishes partnerships to create an innovation ecosystem that enables the translation of discovery science into technologies for science and society.	National laboratories: Argonne, SLAC, and PNNL. Academia: Caltech, Cornell University, MIT, PennState, Northwestern University, among others. Industry: AWS, Applied Materials, Boeing, Microsoft, IBM, HRL, Infleqtion, Quantum Opus, and others.

Source: Cluster websites

Some of these organizations are dedicated to the transition from R&D to applicable solutions.

Focus	Name	Location	Description	Partners
Quantum Applications / Industry	Quantum Consortium QED-C	Arlington, VA	QED-C's mission is to enable and grow a robust commercial quantum-based industry and associated supply chain in the United States. It also aims to provide a collective industry voice to inform and guide Federal R&D investment priorities, standards and regulations, and quantum workforce education and development. It fosters sharing of intellectual property, efficient supply chains, technology forecasting, and quantum literacy.	Several companies, including IBM and Microsoft. Several academic institutes, including the University of Washington. Several Federally Funded R&D Centers Governmental Partners.
	Quantum Industry Coalition	U.S.	The Quantum Industry Coalition is a lobbying group of several leading quantum-industry businesses in the U.S. It primary objective is shaping U.S. quantum policy and the implementation of the National Quantum Initiative to promote real-world applications, commercial success, and international competitiveness.	Leading businesses such as IonQ, Infleqtion, D-Wave, AWS, Rigetti Computing, Zapata Computing, IBM, Quantinuum, SandboxAQ, among others.
	Quantum Strategy Institute	Toronto, Canada	Quantum Strategy Institute is an international non-profit organization that consists of a network of cross-domain experts with rich and varied expertise who share a passion for quantum technologies. Its objective is aligning quantum technologies' potential with the reality of business demands through the insights and expertise of a global network of quantum and business experts, researchers, and enthusiasts.	Unknown
	Quantum Industry Canada	Toronto, Canada	A non-profit organization whose mission is to ensure that Canadian quantum innovation and talent is translated into business success and economic prosperity in the country. It consists of a consortium of Canadian quantum technology companies that include developers of technologies for all areas of QIS.	Several companies such as 1QBit, AFT, evolutionQ, Ki3Photonics, Zapata, Qeynet, NXM, Isara, D-Wave, ProteinQure, Quantum Benchmark, Zero Point Cryogenics, and others.

Source: **Cluster websites**

There are specific programs dedicated to help QIS start-ups with resources, information and connections.

Focus	Name	Location	Description	Partners
Accelerators / Foundries	Duality	Chicago, IL	First accelerator program in the U.S. exclusively focused on supporting early-stage quantum companies. It offers a 12-month program providing innovative quantum startups the critical resources they need to develop and scale their businesses.	Polsky, Chicago Quantum Exchange, University of Chicago, University of Illinois Urbana-Champaign, Argonne National Lab, P33.
	Quantum Startup Foundry	Washington, D.C.	Brings together the physical and virtual resources to support entrepreneurs and startups in accelerating quantum technologies' time to market. The TraQtion Program is a market accelerator program that leverages partnerships to connect companies with large government contractors for technology validation and potential customers looking for quantum and quantum-enabling technologies	University of Maryland, Mid-Atlantic Quantum Alliance (MQA), Quantum Technology Center, Potomac Quantum Innovation Center, DC I-Corps, and IonQ.
	Techstars	Oak Ridge-Knoxville, TN	A program committed to supporting and advancing world-class startups focused on emerging technologies across industries including artificial intelligence, advanced manufacturing, QIS, 5G/advanced wireless technology, biotechnology, and clean energy technology.	Jetro, United Healthcare, COX Enterprises, NCAA, ABN AMRO, Ecolab, Equinor, Sony.
	Creative Destruction Lab	Toronto, Canada	Non-profit organization that delivers an objectives-based program for massively scalable, seed-state, science- and technology-based companies. Quantum Stream brings together entrepreneurs, investors, scientists in quantum technologies, and quantum technology partners to build ventures in the emerging domain of quantum computing, optimization, sensing, and other applications of quantum technologies. Accepts applications from international candidates.	IBM, Xanadu, Zapata Computing.
	IBM Quantum Network	Worldwide	Network of several important partners in the quantum field that help develop the quantum workforce. It also hosts a monthly IBM Quantum Network Colloquium and an annual IBM Quantum Summit to showcase the forefront of quantum development. It also has a Premium Plan for clients to access their powerful systems, hands-on support, and training.	Goldman Sachs, QCWare, University of Tokyo, Fraunhofer, Cicago Quantum Exchange, Capgemini, Cleveland Clinic, Oak Ridge.

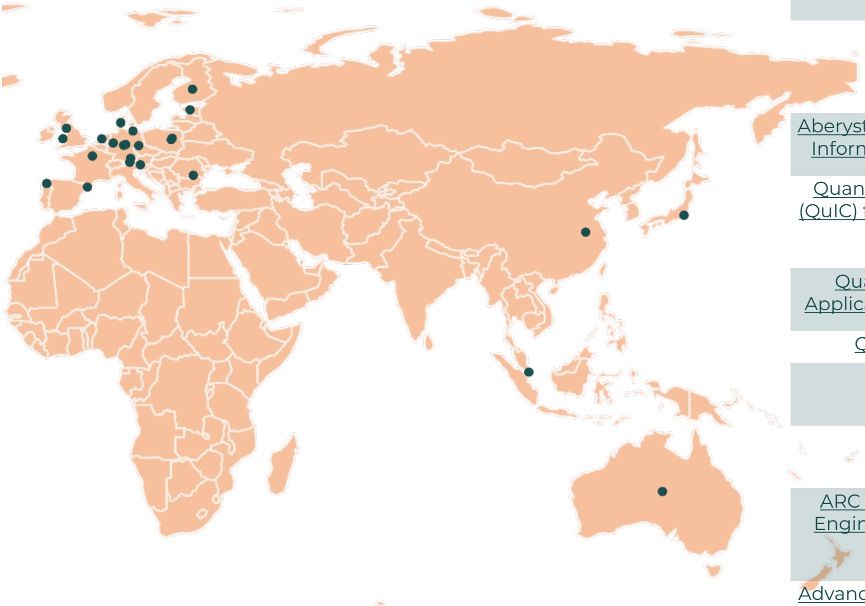
Source: **Cluster websites**

In the U.S., several collaborations between universities and national laboratories are driving important research in QIS.

Partnerships	Programs / Initiatives	Projects
MIT Lincoln Laboratory (DoD-owned FFRDC)	Quantum Information and Integrated Nanosystems (link)	• Compact Optical Trapped-Ion Array Clock • Superconducting Discrete Integrated Circuits Electronics • Diamond Magnetometer • Superconducting Electronics
Jet Propulsion Laboratory (NASA-owned FFRDC) & Caltech	Quantum Sciences and Technology Laboratories (link) Deep Space Optical Communications (DSOC)	• High performance frequency standards and miniature atomic clocks • Cold Atom Laboratory ISS facility payload development and science investigations • Quantum atom interferometer sensors and their applications in space • Microresonators, nonlinear optics, and photonic devices • Precision measurements and fundamental physics in space
Joint Quantum Institute (NIST funded), University of Maryland, and the Laboratory of Physical Sciences	Mid-Atlantic Quantum Alliance (link)	• Quantum Computing and Information Processing • Quantum Many-Body Physics • Quantum Control, Measurement, and Sensing
Argonne National Laboratory (DoE-owned) and University of Chicago	Quantum Information Science (link) (Leader of Q-NEXT)	• Advanced characterization of polytypic silicon carbide for quantum technologies • Creating bright single-photon sources on demand • Exploring lossy quantum computation • QuaC: A scalable, general-purpose quantum systems solver
SLAC National Accelerator Laboratory (DoE-owned) and Stanford University	Quantum Information Science (link) Q-FARM (link) (Also part of Q-NEXT)	• Qubit discovery and design • Quantum Systems Integration • Quantum Sensors • Integrated Platform for Quantum Photonic Networks
Lawrence Berkeley National Laboratory (DOE-owned)	Advanced Quantum Testbed (AQT) QUANT-NET (link)	• Quantum Control Hardware and Software • Quantum Imaginary Time Evolution (QITE) Algorithm • Randomized Compiling • Single Microwave Photonics
Pacific Northwest National Laboratory (DOE-owned) and University of Washington	Quantum Information Sciences (link) Founded the Northwest Quantum Nexus (NQN) (PNNL also part of Q-NEXT)	• Quantum algorithms and software implementations • Materials synthesis and characterization • Low temperature physics • Mitigation of environmental effects
SLAC National Accelerator Laboratory, Grainger College of Engineering (University of Illinois Urbana-Champaign), and University of Illinois at Chicago	Quantum Sensing and Quantum Materials (QSQM)	• Scanning qubit microscopy • Two electron Einstein-Podolsky-Rosen (EPR) spectroscopy • Nonlinear x-ray optics

Source: **Institute/Laboratory websites**

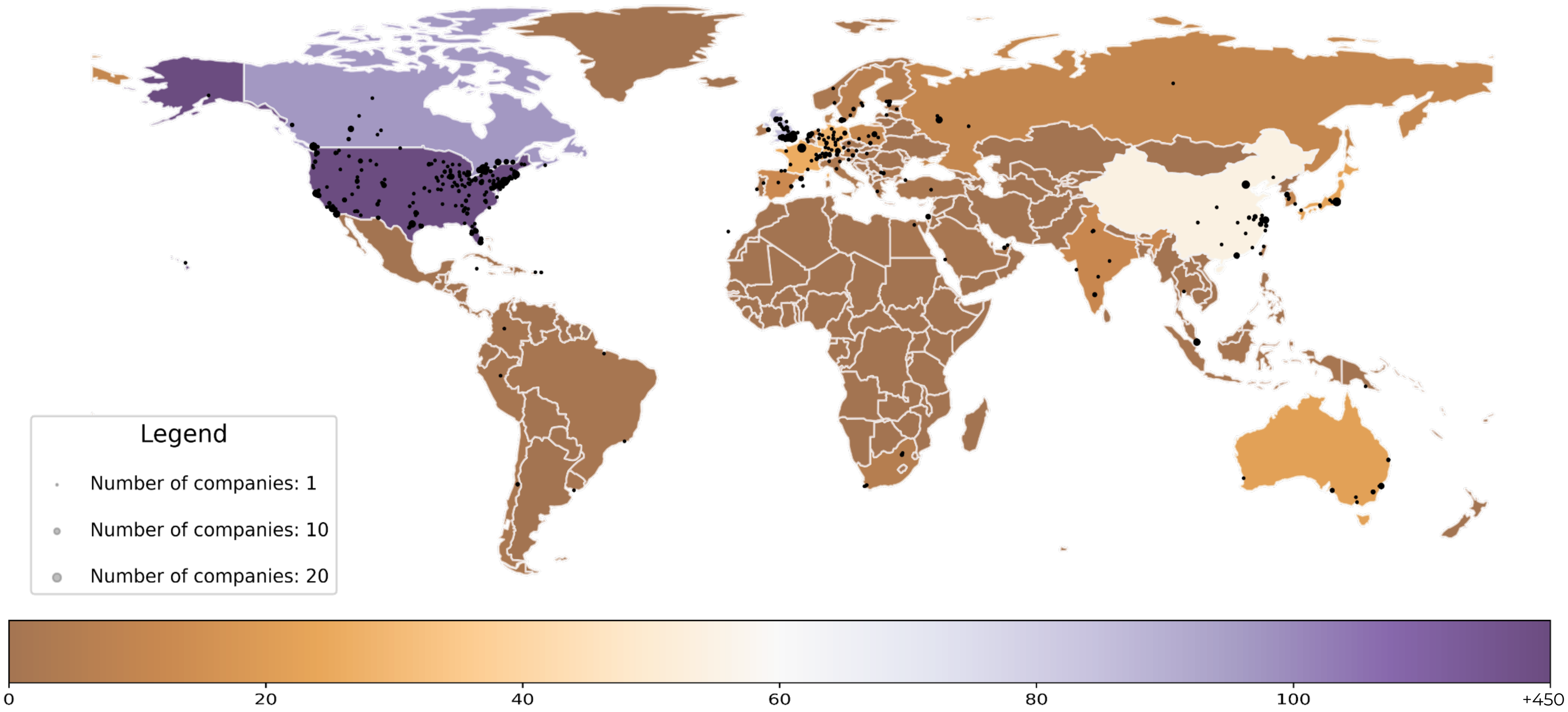
Outside North America, several similar clusters (hubs, initiatives, and coalitions) are helping to drive the QIS industry and R&D forward.



Name	Description
Quantum Business Network	Transforming the European Quantum Community into a strong Quantum Industry.
Quantum Alliance	Consortium of German Clusters of Excellence and research centers working in quantum science and technology.
Harwell Quantum Cluster	Harwell's Quantum Cluster is blazing a trail in the UK's quantum sector, unlocking its enormous potential – from drug discovery to finding the most efficient way for people to live sustainably.
AQTION	AQTION stands for "Advanced Quantum computing with Trapped IONs" and is a major research project funded by the European Quantum Technology Flagship. The AQTION project's goal is to develop and exploit a robust, compact ion-trap quantum computing demonstrator based on scalable quantum hardware and widespread industry standards.
Aberystwyth Quantum Structures, Information, and Control Group	This group focuses on quantum systems in interaction with their environment, and in particular the emergent field of quantum control engineering.
Quantum Industry Consortium (QuIC) for the European Quantum Industry	The Quantum Industry Consortium (QuIC) advocates, promotes, and fosters the common interests of the European quantum industry towards all quantum technology stakeholders.
Quantum Technology and Application Consortium (QUTAC)	QUTAC is a consortium composed of some of the largest German groups from business and industry that have joined forces to raise quantum computing to the level of large-scale industrial application.
Quantum.Amsterdam	Its foundation partners include QuSoft, Centrum Wiskunde & Informatica, University of Amsterdam, and Quantum Delta NL.
InstituteQ	InstituteQ is a collaboration of three Finnish organizations: Aalto University, University of Helsinki, and VTT Technical Research Centre of Finland.
Qworld	QWorld is a global network of individuals, groups, and communities collaborating on the education and implementation of quantum technologies and research activities.
ARC Centre Of Excellence For Engineered Quantum Systems	The ARC Centre of Excellence for Engineered Quantum Systems will build sophisticated quantum machines to harness the quantum world for practical applications. We will pioneer the designer quantum materials, quantum engines, and quantum imaging systems at the heart of these machines.
Advancing Quantum Architecture Group	The AQUA group is researching system organizations, circuit structures, and algorithms to accelerate the development of large-scale quantum computers.
Australian Quantum Alliance	The Australian Quantum Alliance's vision is for a thriving quantum industry in Australia that enables innovation, jobs, and economic prosperity.
Centre for Quantum Technologies (CQT)	The Research Centre of Excellence (RCE) in Singapore brings together physicists, computer scientists, and engineers to do basic research on quantum physics and build devices based on quantum phenomena.
QuantumCTek Co., Ltd.	QuantumCTek Co., Ltd. is a Chinese pioneer and leader in commercialized quantum information technology (QIT), now becoming one of the world's largest manufacturers and providers of QIT-enabled ICT security products and services.
Q4Climate	Q4Climate is an initiative that gathers the research and industry communities together around quantum and climate sciences with the goal of developing new insights into reducing the pace and impact of climate change.

Source: **Cluster websites**

The U.S., Canada, U.K., and China are the top economies for QIS headquarters.

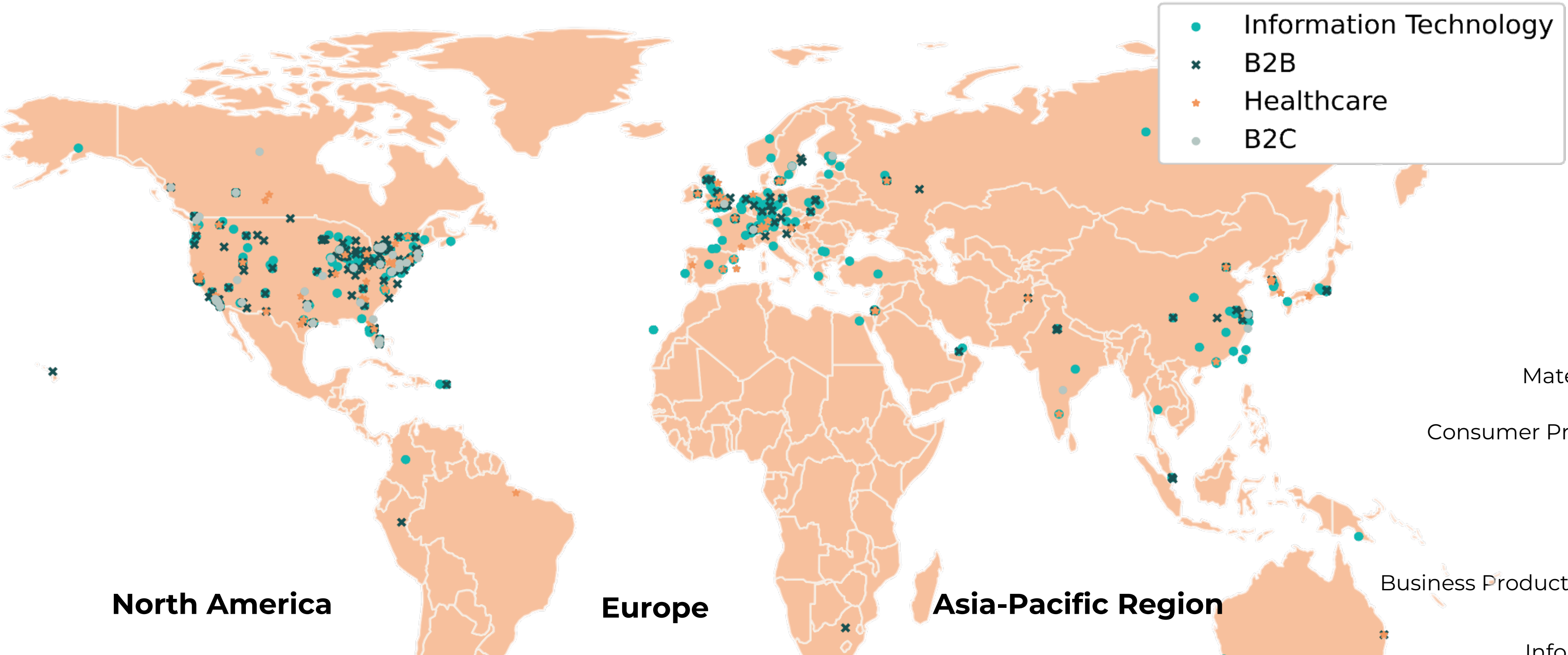


Top 20 HQ Locations for QIS Companies by Country

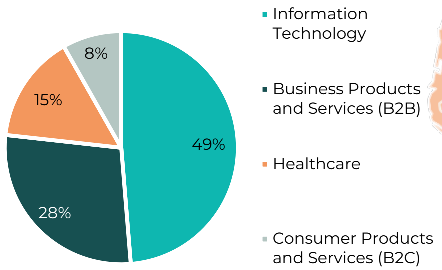
HQ Location (Country)	Number of Companies
United States of America	452
Canada	97
United Kingdom	85
China	54
Germany	29
France	26
Japan	23
Australia	22
Switzerland	17
Spain	13
India	12
Israel	12
Netherlands	12
Russia	11
Poland	11
South Korea	10
Singapore	10
Sweden	7
Denmark	7
Austria	6

Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

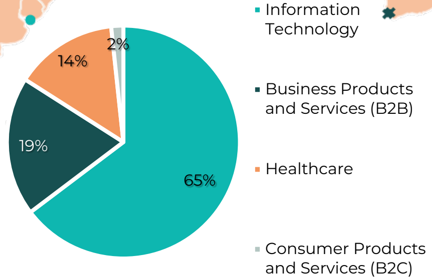
North America is slightly more diverse in QIS companies' primary industry than the rest of the world.



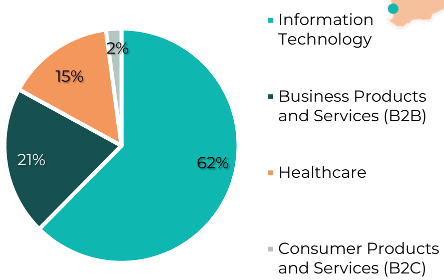
North America



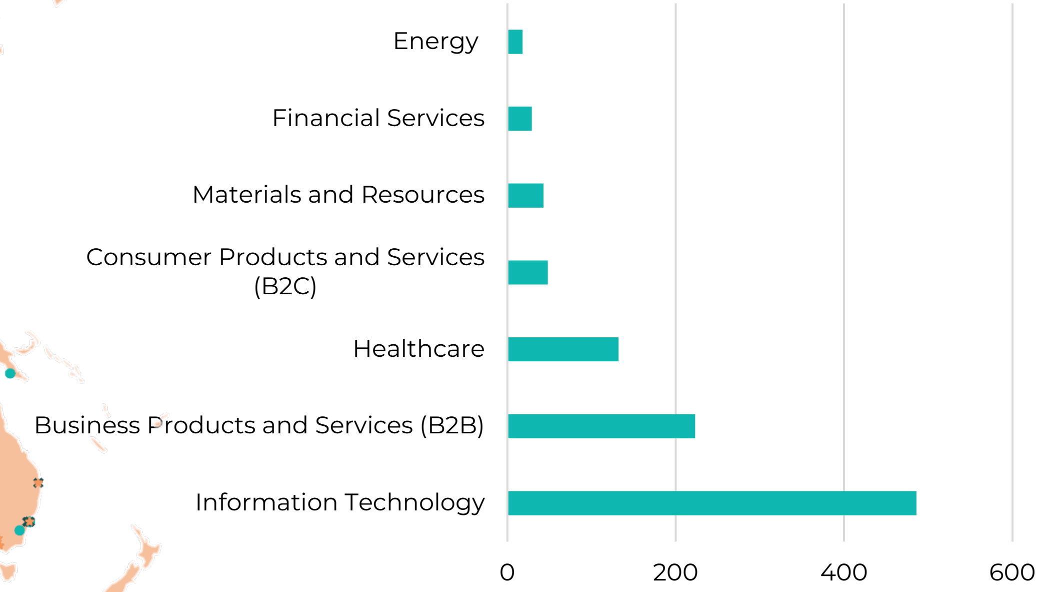
Europe



Asia-Pacific Region

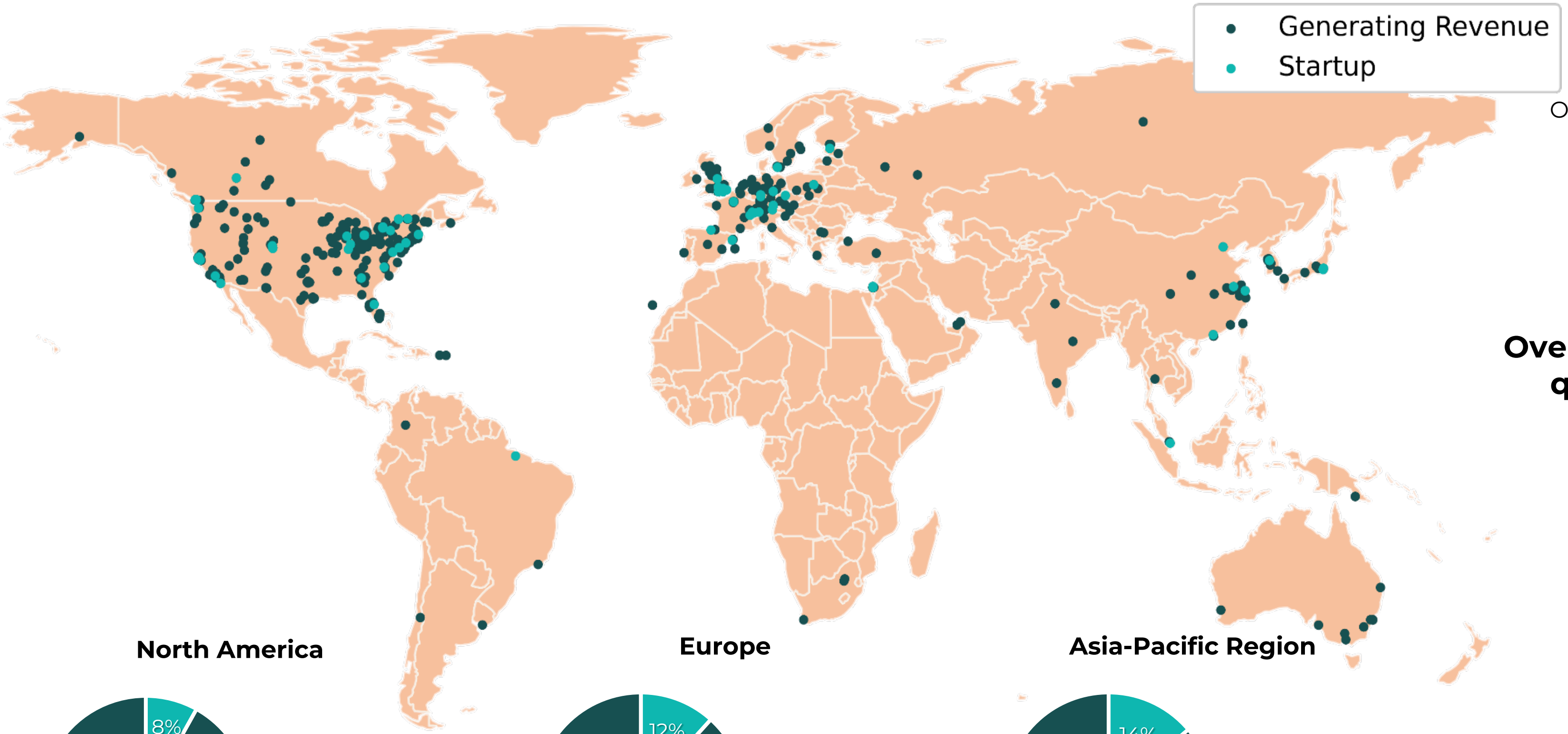


Worldwide Number of QIS Companies by Primary Industry Sector

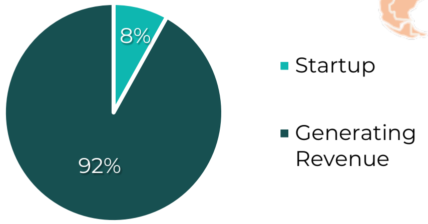


Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

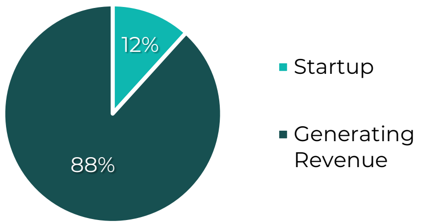
Many QIS companies worldwide are generating revenue.



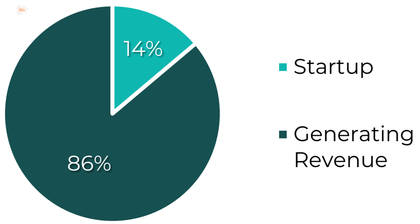
North America



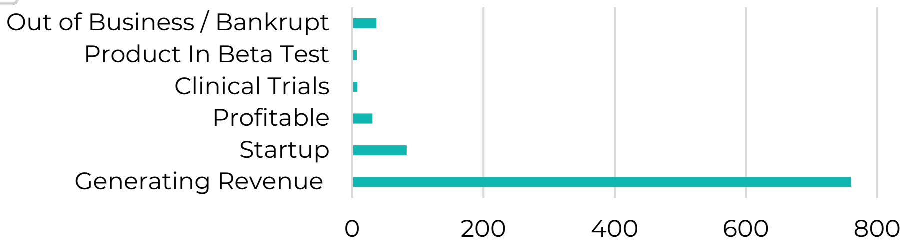
Europe



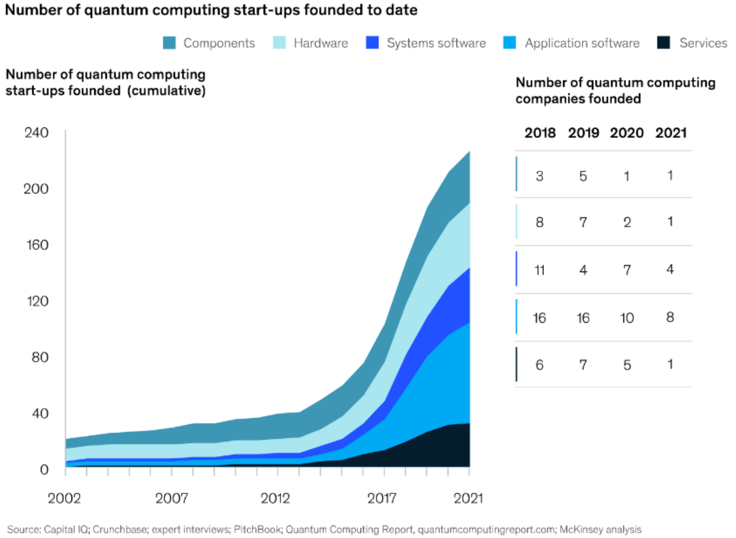
Asia-Pacific Region



Worldwide Number of QIS Companies by Business Status



Over the past three years, the rate of publicly announced quantum computing start-up founding has slowed.



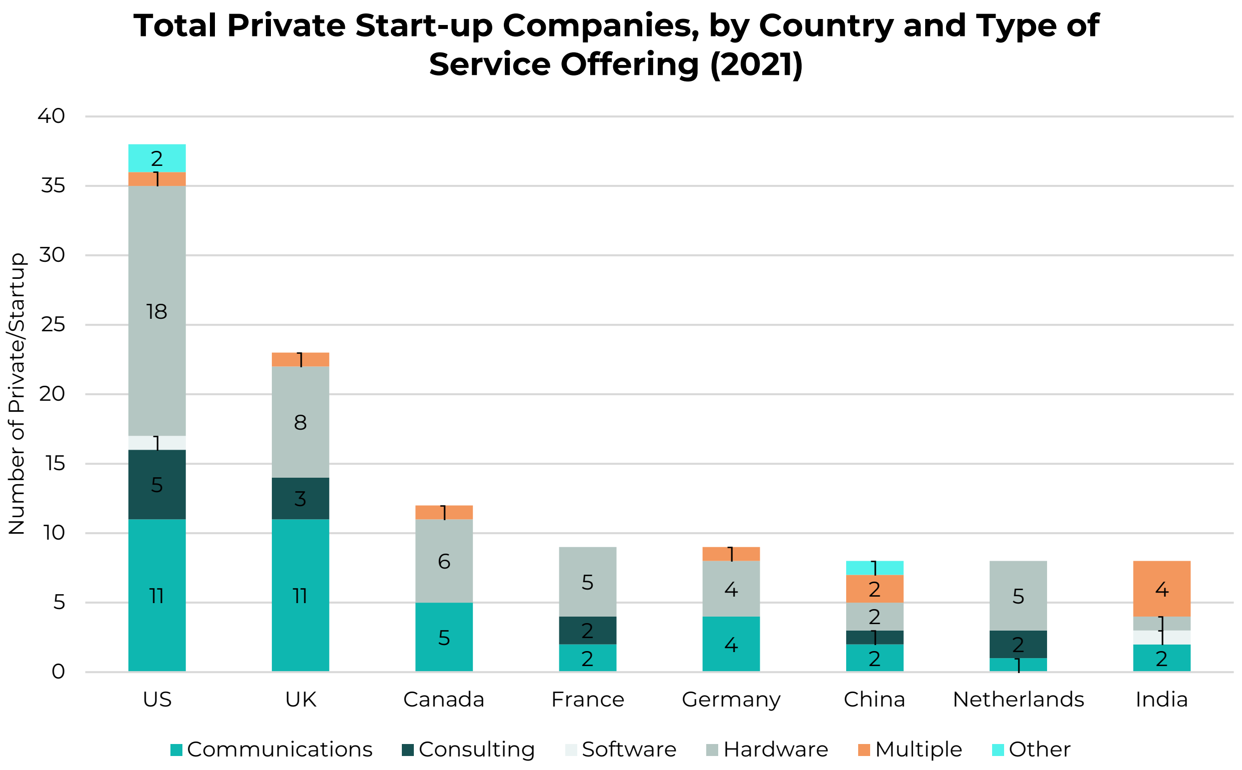
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

McKinsey Digital – Quantum computing funding remains strong, but talent gap raises concern (link)

QIS start-ups offering communication, consulting, and hardware services have increased globally.

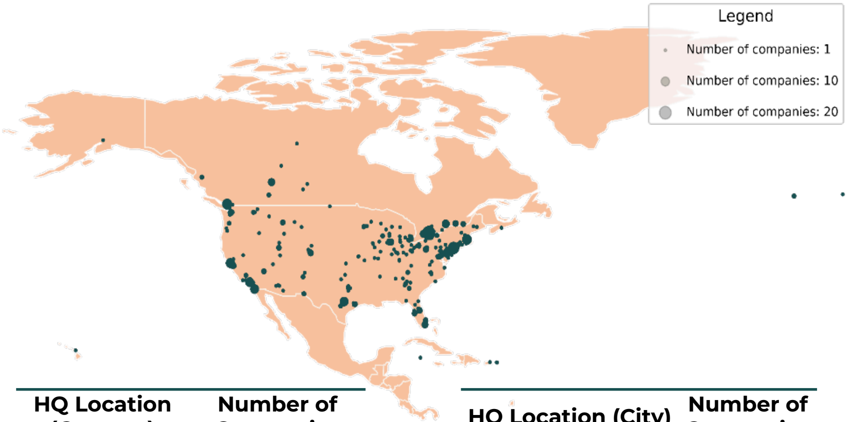
Private start-up companies are divided into the following categories based on the type of service they offer:

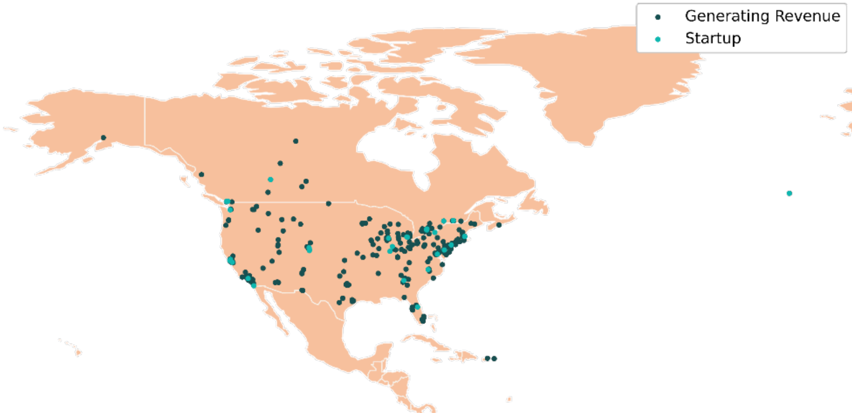
- Communication – includes all providers working in quantum communications and quantum cryptography, as well as companies providing QRNGs.
- Consulting – companies providing business and technical consulting services, but not developing standard software or hardware products.
- Software – includes both tools providers (compilers, simulators, qubit control software, etc.), as well as applications-focused software providers.
- Hardware – includes component manufacturers, quantum computing hardware developers, and full-stack suppliers.
- Multiple – companies participating in several of the segments listed above.
- Other – companies that work in other areas such as incubators, IP development, and cloud providers (not full-stack).

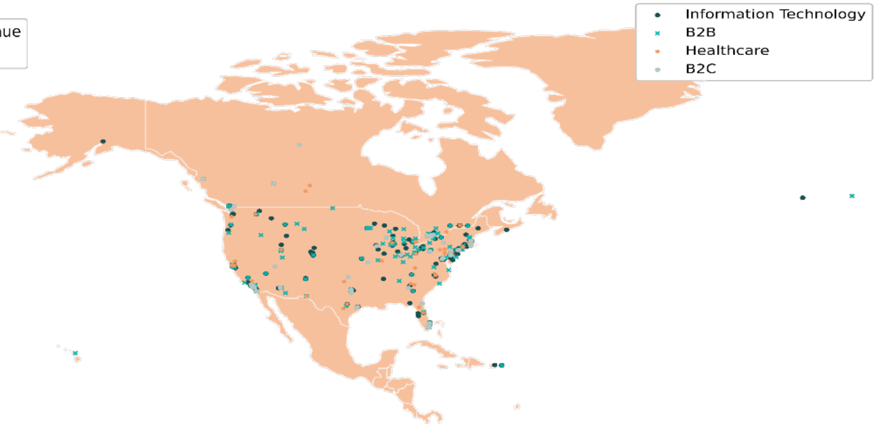


Note: All the start-ups mentioned have been founded in the last 10 years.
Source: Quantum Computing Report LLC

Most companies in North America have HQ in the U.S., are generating revenue, and focusing on information technology and B2B.



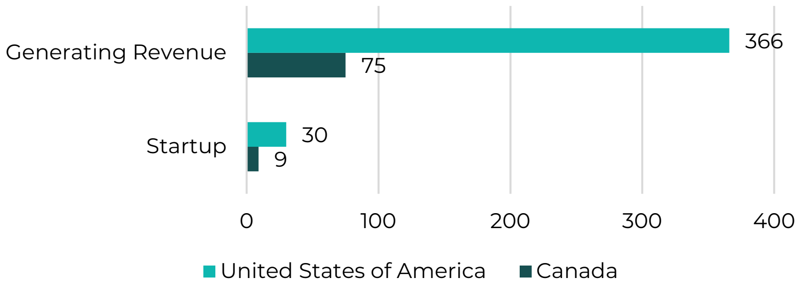




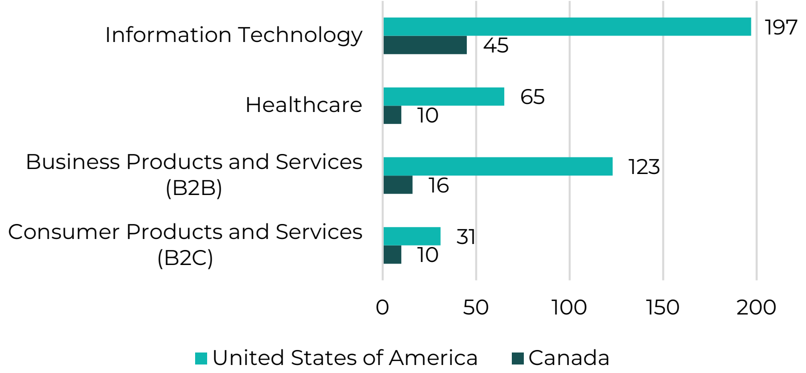
HQ Location (Country)	Number of Companies
United States of America	452
Canada	97

HQ Location (City)	Number of Companies
Toronto, Canada	21
New York, NY	16
Vancouver, Canada	12
Cambridge, MA	11
San Francisco, CA	10
San Diego, CA	9
Los Angeles, CA	9
Austin, TX	9
Ottawa, Canada	7
Wilmington, DE	7
Waterloo, Canada	6
Edmonton, Canada	6
Chicago, IL	5

North America Number of QIS Companies by Business Status



Number of QIS Companies in North America by Primary Industry Sector



Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

Notable QIS companies in North America

	D-Wave	Infleqtion	SeeQC	Quantinuum	SandboxAQ	IonQ	PsiQuantum	Ostendo	Isara
Description	Development and delivery of quantum computing systems, software, and services, and also a commercial supplier of quantum computers.	Developer of quantum sensing technologies intended increase the commercial availability of quantum technologies. Harness quantum mechanics to build and integrate quantum computers, sensors, and networks from fundamental physics to commercial products.	Developer of superconducting quantum technologies intended for a variety of quantum information processing applications. Technologies are developed and commercialized for quantum information processing applications, including quantum computers and simulators, quantum communications, and quantum sensors.	Developer of quantum computing applications catering to the automotive, pharmaceuticals, energy, chemicals, finance, logistics, life sciences, biotech, manufacturing, and defense sectors. Provides open-access architecture-independent quantum software.	Developer of an AI Quantum software designed to address significant business and scientific challenges. The company's platform develops practical AI and quantum technology solutions that address real-world business and computational challenges.	IonQ's next-generation quantum computer is the most powerful trapped-ion quantum computer. It makes its quantum systems available through the cloud on Amazon Bracket, Microsoft Azure, and Google Cloud, as well as through direct API access.	Manufacturer of the first utility-scale quantum computer intended to drive advances in climate, healthcare, finance, energy, agriculture, transportation, communications, and beyond. The company's approach is based on photonic qubits.	Designed a Quantum Photonic Imager platform purpose-built to create next-generation devices for consumer, enterprise, and defense applications, delivering on the promise of augmented reality glasses, the "metaverse," and light field holographic displays.	Developer of cyber-security software designed to provide agile quantum-safe security services. The platform offers software that utilizes quantum-safe algorithms and integration tools to provide a safe digital signature, message authentication codes, random number generators, securely transport symmetric keys, and key agreement schemes.
HQ Location	Burnaby, Canada	Boulder, CO	Elmsford, NY	Broomfield, CO	Palo Alto, CA	College Park, MD	Palo Alto, CA	Carlsbad, CA	Waterloo, Canada
Primary Industry	Computers, Parts, and Peripherals	Electronic Equipment and Instruments	Electronic Equipment and Instruments (Semiconductors)	Business/ Productivity Software	Business/ Productivity Software	Computers, Parts, and Peripherals	Computers, Parts, and Peripherals	Application Specific Semiconductors	Network Management Software
Last Deal	August 2022 Reverse Merger	November 2022 VC funding US$110M	November 2021 Grant US$2.15M	February 2022 Early-Stage VC US$25M	March 2022 Later-Stage VC US$1.5B	September 2021 Reverse Merger	March 2022 Private US$520k	January 2021 Secondary Transaction	April 2019 Grant CAN$7.2M

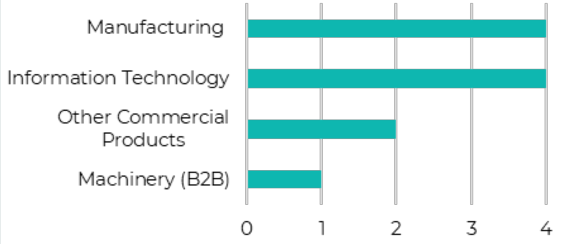
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

Washington is an active player in QIS.

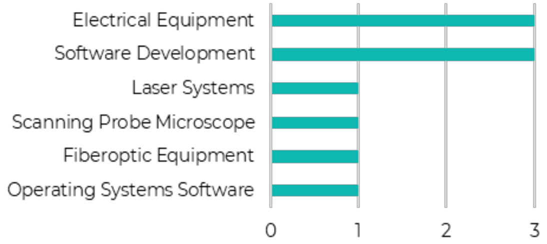
Category	Companies	Activities
Washington-based companies	Microsoft, nion, NLM Photonics, aws, Dotquant, QuantyCat, Ambit, nLIGHT, Boeing	• **Microsoft** – Microsoft Azure Quantum innovates across every layer of the quantum stack, from software and applications to control and devices. • **AWS** – Amazon Quantum Solutions Lab engagements are collaborative research programs that allow work with leading experts in quantum computing. • **Ambit** – developer of a cybersecurity platform intended to protect organizations with post-quantum encryption solutions. • **QuantyCat** – uses quantum computing, real-time optimization and simulation, cloud-based API, and more to help solve business problems. • **Boeing** – joined the Chicago Quantum Exchange for Quantum Mechanics Research.
Out of state companies with Washington offices or hiring in Washington State	IBM, D-Wave The Quantum Computing Company™, IONQ, Google AI Quantum	• **IBM** – hiring remotely to work on quantum computing and qiskit development. • **IonQ** – teaming up with PNNL on a new supply chain for Quantum Computing. • **D-Wave** – published an expression of interest for entry level and internships throughout the U.S., including Washington State. • **Google AI Quantum** – based in Santa Barbara with hubs in Seattle, Munich, and Zurich.
Other Notable Items	Pacific Northwest National Laboratory, Washington Nanofabrication Facility	• **PNNL** – Advancing development of several fields related to QIS and co-founder of Northwest Quantum Nexus. • **WNF** – open-access, nanofabrication facility at the University of Washington.

QIS companies HQ'd in Washington State by industry sector and code

Number of QIS Companies by Primary Industry Sector

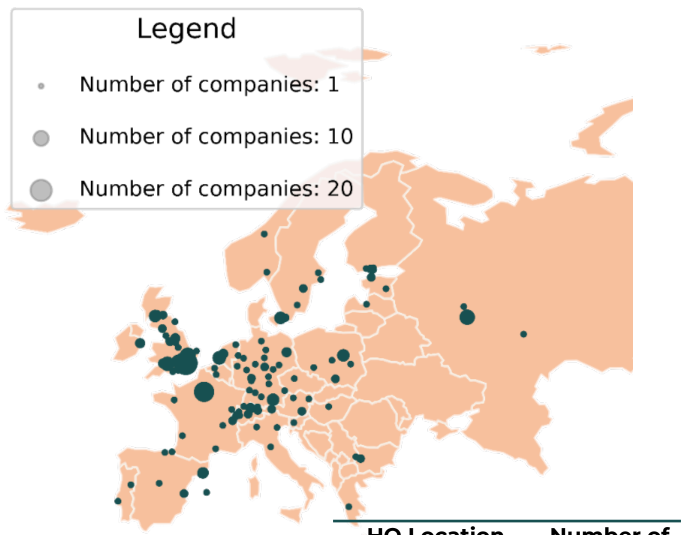


Number of QIS Companies by Primary Industry Code



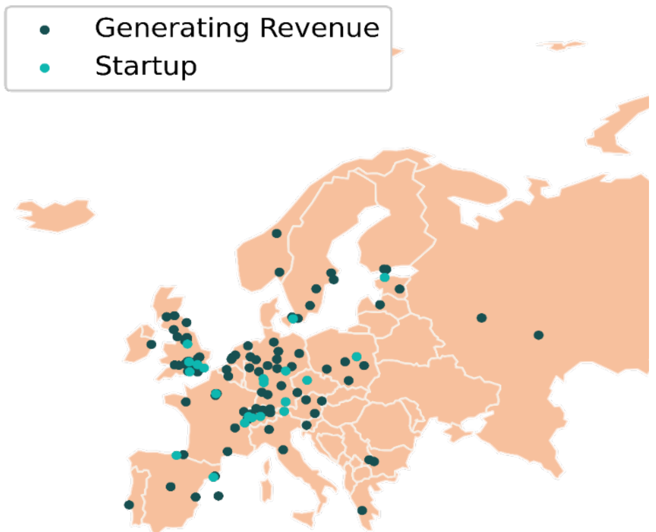
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**
Additional Filters: **"Localization – Washington State, U.S."**

UK, Germany, and France lead QIU in Europe. They are focused on information technology and B2B.

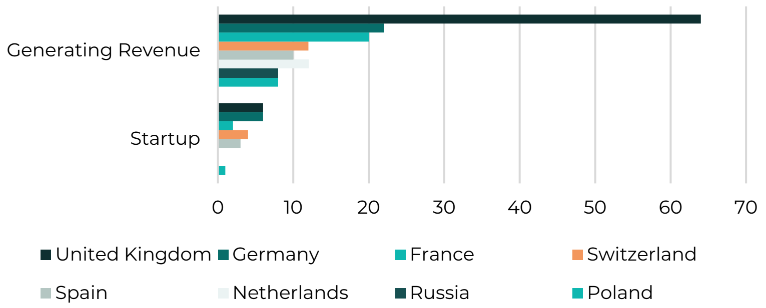


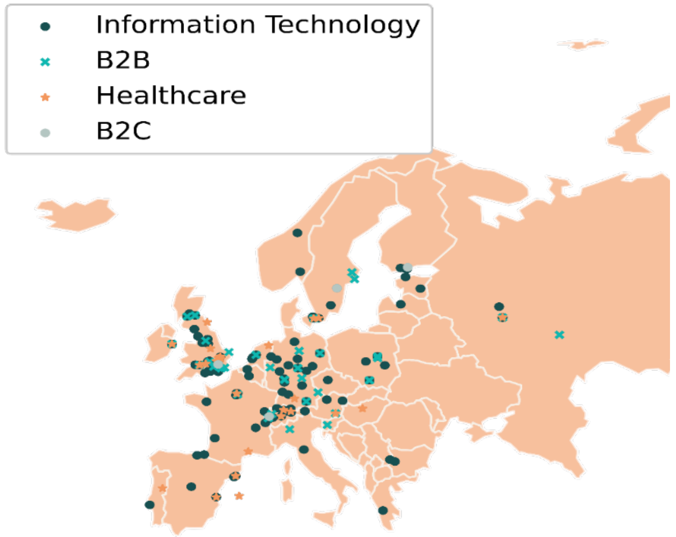
HQ Location (Country)	Number of Companies
United Kingdom	85
Germany	29
France	26
Switzerland	17
Spain	13
Netherlands	12
Russia	11
Poland	11

HQ Location (City)	Number of Companies
London, United Kingdom	21
Paris, France	15
Cambridge, United Kingdom	9
Moscow, Russia	8
Bristol, United Kingdom	7
Delft, Netherlands	6
Glasgow, United Kingdom	5
Munich, Germany	5
Warsaw, Poland	5
Copenhagen, Denmark	5

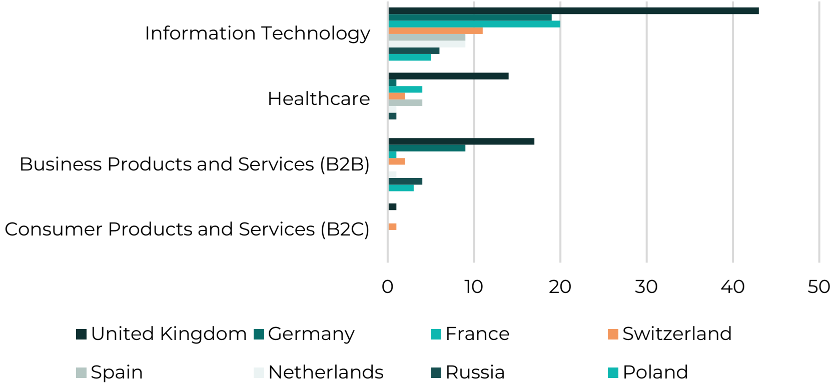


Number of QIS Companies in Europe by Business Status





Number of QIS Companies in Europe by Primary Industry Sector

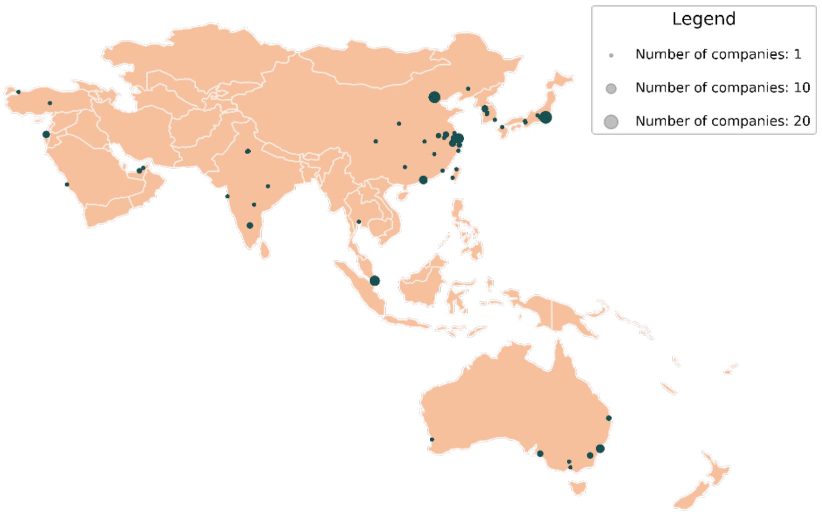


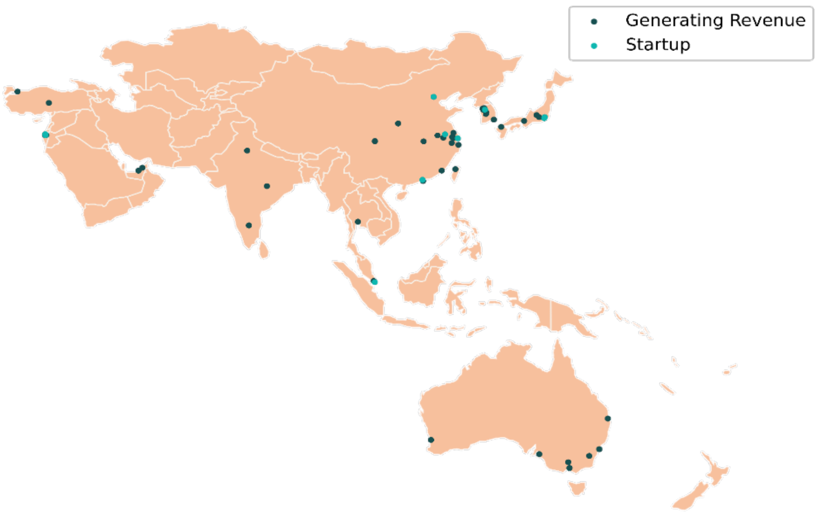
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

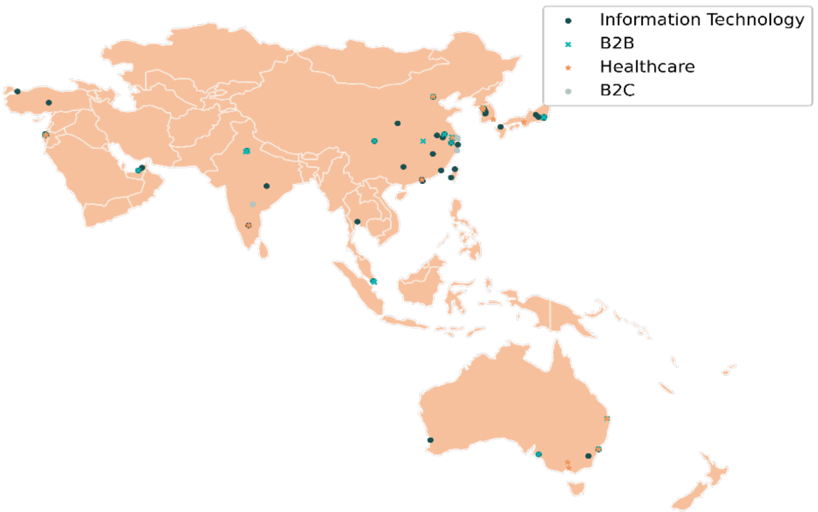
Notable QIS companies in Europe

	IQM	Cambridge Quantum Computing	ArQit	Planqc	ORCA Computing	Nanoco	Riverlane	Pasqal	QDI systems
Description	Developer of computer hardware designed to provide technical solutions through quantum technologies. The company's superconducting quantum circuits and quantum computing specializes in the development of high-speed quantum computers with application-specific processors and delivers on-premises quantum computers for research labs and supercomputing centers, providing complete access to its hardware.	Operator of independent quantum computing software company intended to build tools for the commercialization of quantum technologies. Designs software combining enterprise applications in quantum chemistry, quantum machine learning, and augmented cybersecurity, enabling clients to get access to effective methods of applying quantum computing in a variety of corporate and government use cases.	Supplies unique quantum encryption Platform-as-a-Service that makes the communications links of any networked device secure against current and future forms of attack, even from a quantum computer.	Developer of computer processors intended for scaling useful quantum advantage. It uses artificial crystals of light.	Developer of a novel quantum computer designed to increase the performance and scale of quantum computing. The company's processor and architecture leverage telecoms photonics and proprietary quantum memory technology, enabling clients for storage, synchronization, and buffering of quantum operation and improved performances.	Research, development, and manufacturing of heavy-metal-free quantum dots and semiconductor nanoparticles. Uses cadmium-free quantum dot (CFQD) technology to produce efficient, low-cost and lightweight solar cells, and offers enhanced color, energy efficiency, and seamless integration of high-efficiency lighting	Developer of quantum computing software designed to transform experimental technology into commercial products. Develops ultra-low latency quantum operating systems that accelerate quantum-classical hybrid algorithms to facilitate hardware R&D and develops algorithms to make optimal use of the full quantum computing stack.	Developer of full-stack quantum computer designed to simulate complex phenomena for scientific discovery and address general problems such as optimization, drug discovery and machine learning.	Developer of imaging devices designed to provide precise medial images using quantum dot technology. The company's devices are X-ray sensors that offer high-precision X-ray imaging and easy-to-use quantum dot material.
HQ Location	Espoo, Finland	Cambridge, United Kingdom	London, United Kingdom	Munich, Germany	London, United Kingdom	Manchester, United Kingdom	Cambridge, United Kingdom	Paris, France	Groningen, Netherlands
Industry Sector	Computers, Parts, and Peripherals	Business / Productivity Software	Other Communications and Networking	Computers, Parts, and Peripherals	Computers, Parts, and Peripherals	Application Specific Semiconductors	Operating Systems Software	Application Specific Semiconductors	Diagnostic Equipment
Last Deal	July 2022 Series A2 VC EUR 128M	November 2021 Merged with Honeywell Quantum Solutions to form Quantinuum	September 2021 Reverse Merger	June 2022 VC EUR 4.6M	June 2022 Series A VC $15M	October 2017 Development Capital GBP 8.6M	January 2021 Series A VC GBP 15.02M	June 2021 Series A VC EUR 36.11M	May 2022 Seed Funding EUR 1.3M

QIS in Asia is mainly in China, Japan and Australia, and focused on Information Technology.



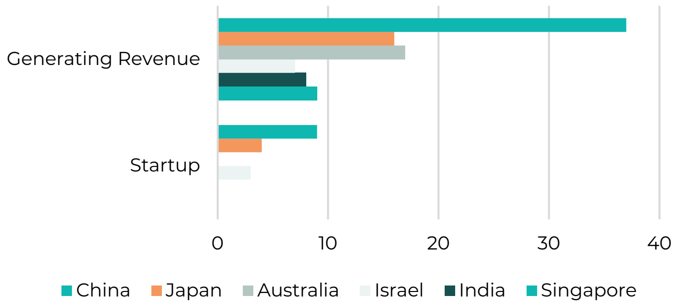




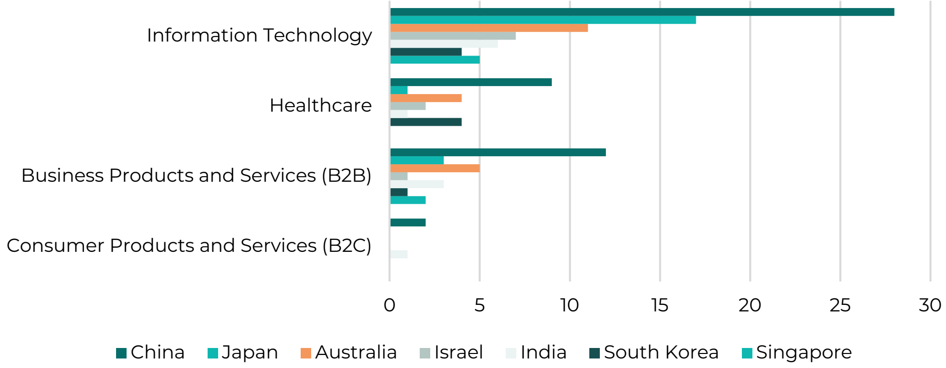
HQ Location (Country)	Number of Companies
China	54
Japan	23
Australia	22
Israel	12
India	12
South Korea	10
Singapore	10

HQ Location (City)	Number of Companies
Tokyo, Japan	14
Beijing, China	12
Shanghai, China	9
Singapore, Singapore	9
Sydney, Australia	6
Shenzhen, China	6
Suzhou, China	4
Hangzhou, China	4
Tel Aviv, Israel	4
Seoul, South Korea	3
Bengaluru, India	3

Number of QIS Companies in Asia-Pacific Region by Business Status



Number of QIS Companies in Asia-Pacific Region by Primary Industry Sector



Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

Notable QIS companies in Asia-Pacific region

	Zhejiang Quantum Technologies	Mesolight	QD Laser	Hengtong Optic-Electric Co	ClassiQ	Nanofiber Quantum Technologies	HYQ	Q-Ctrl	Quantum Machines
Description	Developer of quantum technology and quantum security encryption products and applications. Based on quantum technologies, the company's quantum network infrastructure products, quantum security encryption products and overall solutions are used in quantum government affairs, transportation, public security, finance, and other fields	Developer of quantum dot materials intended for display market and life science. The company provides Qdot products, enabling users to have critical materials of quantum dot and customized application services.	Development, manufacturing, and sales of semiconductor devices.	Provides fiber optic communication products in China and internationally, and is also focusing on providing quantum-secure communications and big data, among others.	Developer of quantum algorithm design software designed to tackle urgent and complex challenges in quantum computing development.	Developer of quantum technologies intended to provide quantum computers using nanofibers advanced engineering. Company specializes in quantum computers, quantum cryptography, quantum communications, and other technologies related to QIS.	Researcher and developer of ion trap quantum computers with more than 100 qubits with high fidelity and strong connectivity, and is expected to greatly accelerate the research on heuristic algorithms in the fields of new energy materials, chemical industry, nuclear energy, and biopharmaceuti cals, among others.	Developer of quantum control infrastructure software designed to overcome hardware error and instability across various applications of quantum technology.	Developer of next generation of quantum controllers designed to revolutionize computing. Quantum controllers translate quantum algorithms into pulse sequences, enabling organizations from across industries to run complex quantum algorithms and experiments in a smooth, intuitive way.
HQ Location	Hangzhou, China	Souzhou, China	Kawasaki, Japan	Souzhou, China	Tel Aviv, Israel	Tokyo, Japan	Beijing, China	Haymarket, Australia	Tel Aviv, Israel
Industry Sector	Electrical Equipment	Industrial Supplies and Parts	Industrial Supplies and Parts	Information Technology	Software Development Applications	Computer, Parts and Peripherals	Computer, Parts and Peripherals	Business/ Productivity Software	Computers, Parts and Peripherals
Last Deal	April 2022 Developmental Capital CNY 250M	January 2022 VC funding CNY 100M	February 2021 IPO JPY 4.61B	December 2020 Development capital CNY 5.04B	May 2022 Series B VC $48.5M	August 2022 Seed Funding JPY 200M	April 2022 Seed Funding CNY 100M	February 2022 Grant (US DOE) AUD 230k	December 2021 Series B VC $50M

Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

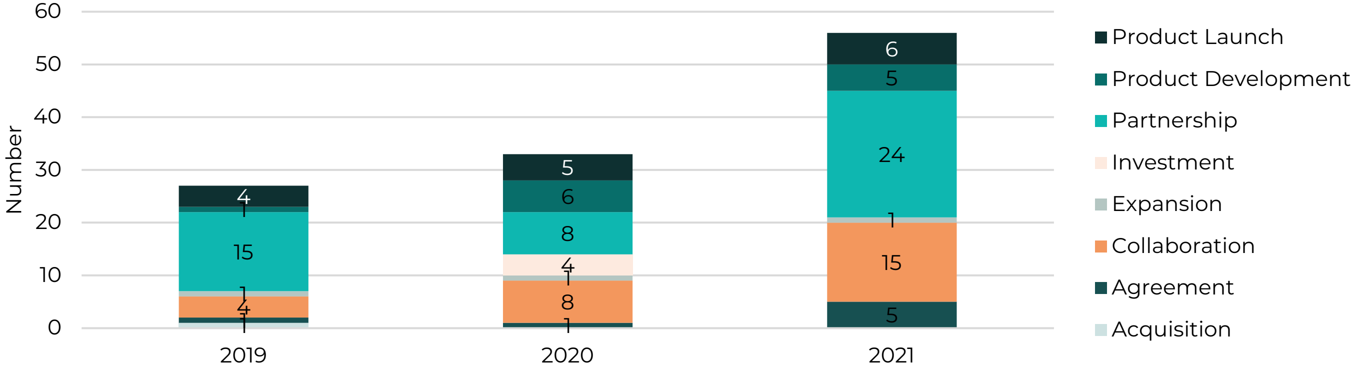
Strategic analysis of key players in the global QC market revealed that most adopted agreements, collaborations, and partnership strategies.

Product Launches and Developments
This is the end goal of a company seeking to bring a new offering to the market. Some companies operating in the quantum computing market focus on new product and technology introduction to enhance their business offerings and survive in this competitive environment. Many of the existing companies have upgraded their existing products and technologies with new features and applications to maintain their presence. Product development is the commonly adopted strategy by which companies expand their product portfolios.

Agreements, Collaborations, and Partnerships
Key players in the market enter into supply and R&D agreements, collaborations, or partnerships to benefit from the market reach of major market players and their product offerings to compete with others.

Acquisitions, Expansions, and Investments
Companies use business acquisitions and expansions to enlarge their product portfolios, enter new areas of business, or expand their global presence. Companies use investment from their own funds, as well as from third parties (private or governmental) to enlarge their R&D activities.

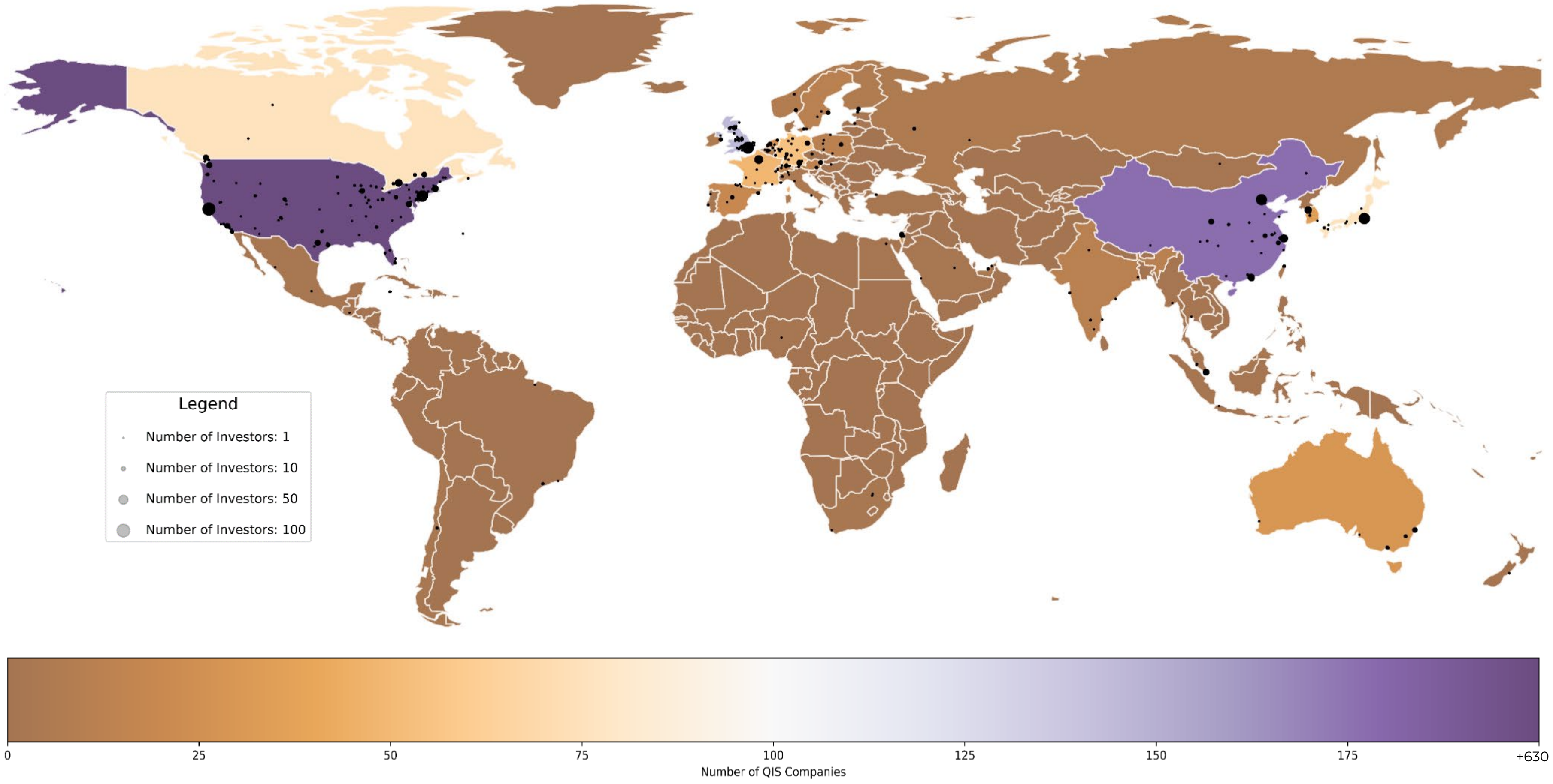
Developments in the global market for Quantum Computing Technology (2019-2021)



Distribution of the most followed strategies adopted by companies in the global market for Quantum Computing (2019-2021)

Source:
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing

Investor distribution is similar to QIS companies, focusing on North America, Europe, and Asia-Pacific region

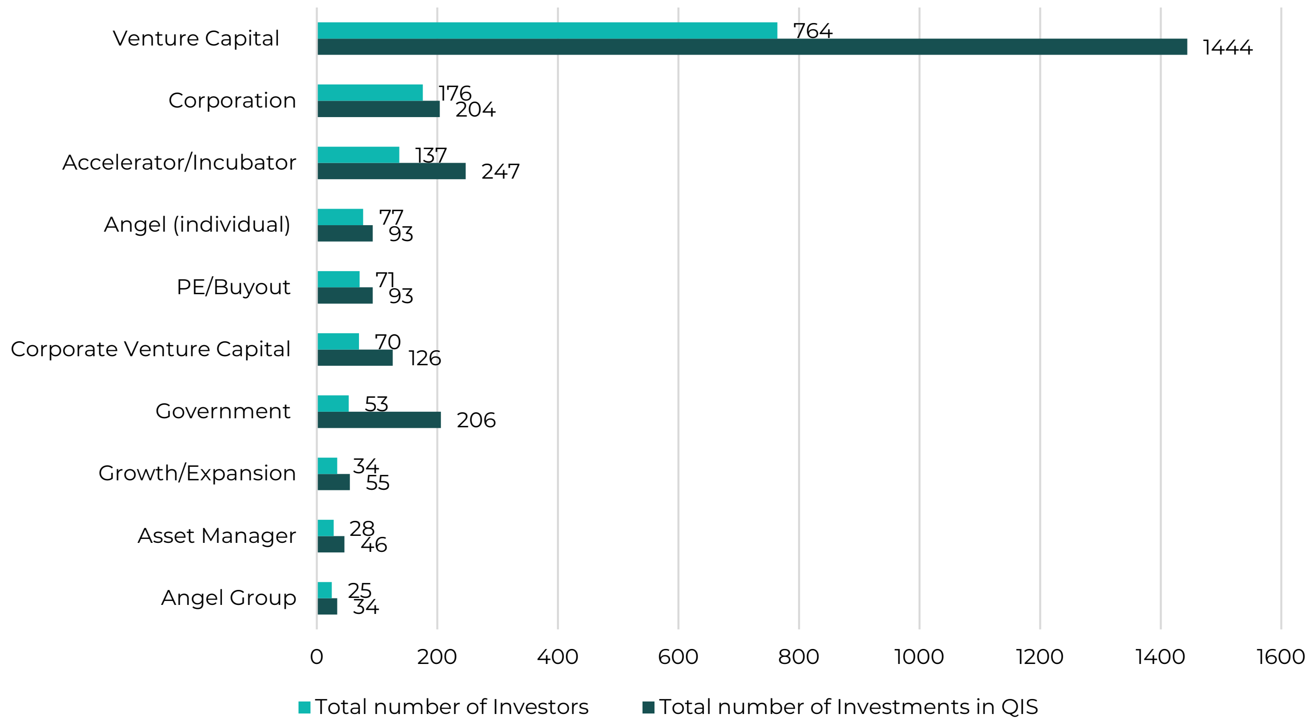


HQ Location	Number of Investors	Number of Investments in QIS
San Francisco, CA	92	152
London, United Kingdom	73	142
New York, NY	67	95
Tokyo, Japan	65	108
Beijing, China	62	94
Palo Alto, CA	38	103
Paris, France	37	78
Shanghai, China	33	51
Menlo Park, CA	32	78
Seoul, South Korea	27	37
Toronto, Canada	26	60
Shenzhen, China	24	38
Boston, MA	21	42
Singapore, Singapore	20	32
Seattle, WA	16	28

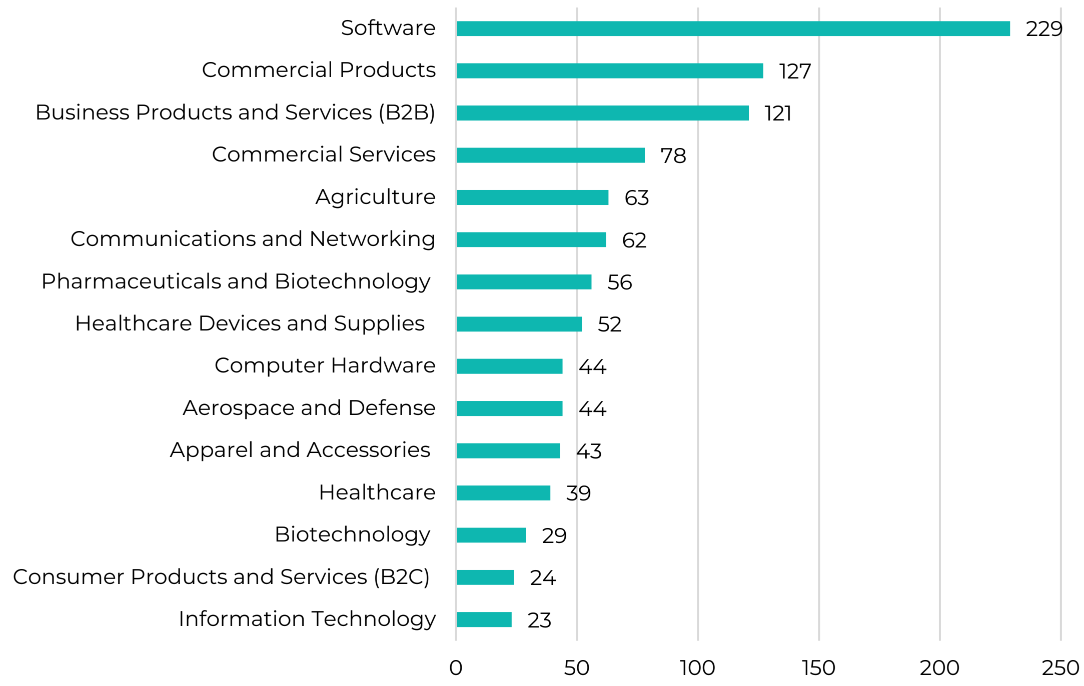
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

VC is the most common type of primary investment, leading both total number of companies and total number of investments.

Total number of investors and total number of investments in QIS, by Primary Investor Type (top 10)



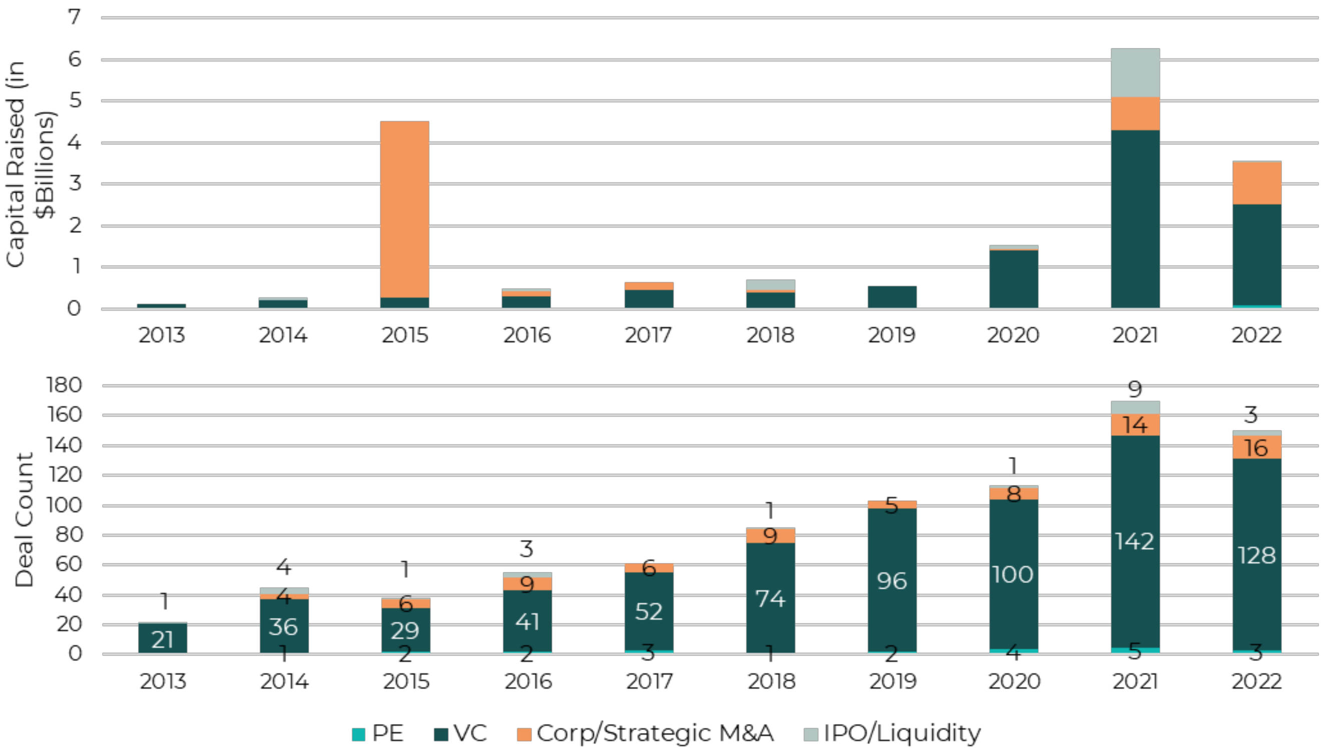
Total number of investors by Preferred Industry (top 15)



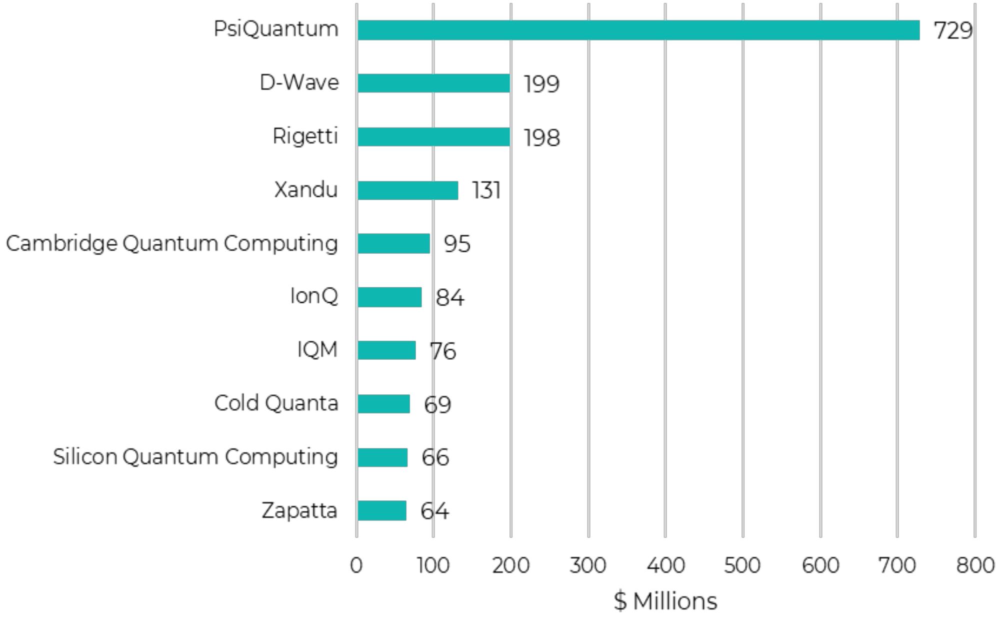
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

Deal count has been steadily increasing over the years, but less than other comparable emerging technologies.

Investments Over Time



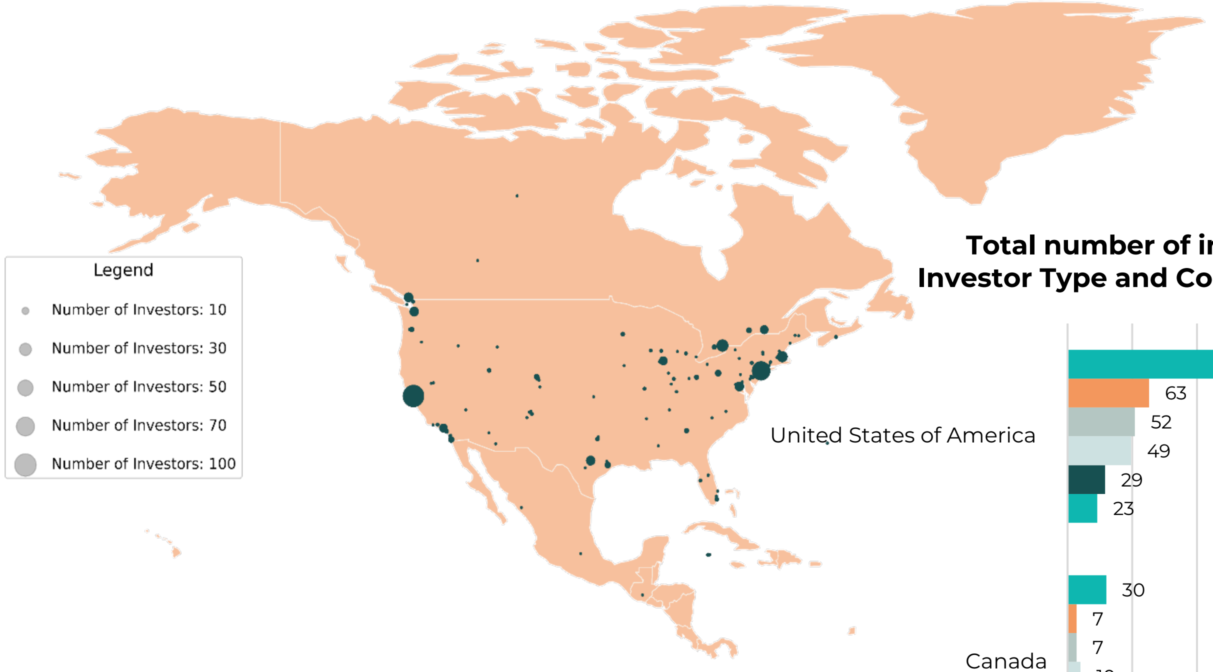
Total Equity Funding Worldwide in Quantum Computing Startups, 2021



Compared to other emerging technologies, such as blockchain and AI, equity funding in quantum technologies is still relatively low. This is likely because the impact of AI and blockchain is much more immediate, while some technologies like Quantum Computing will take five or more years for investors to see a return on investment.

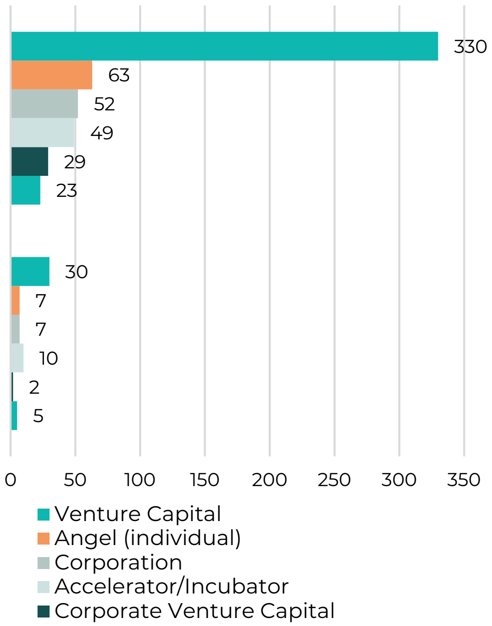
Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing
Quantum Computing: A Dossier on the state and outlook of the 5th generation of computing by Statista

North America has several active investors with a significant interest in QIS (some with close to 10% of their portfolio focusing on QIS)



HQ Country/Territory	Total number of Investors in QIS
United States of America	624
Canada	75

Total number of investors by Primary Investor Type and Country in North America



Top 10 Investors in QIS in North America

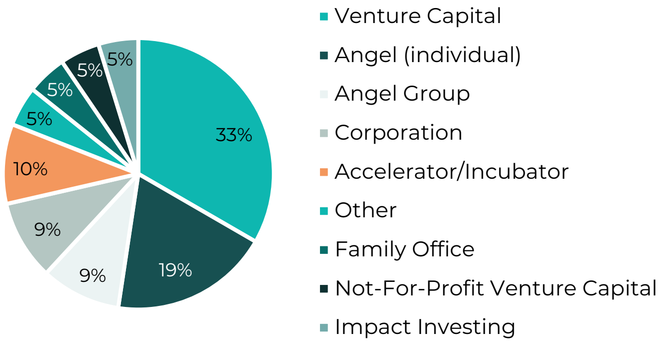
Investors	HQ Location	Primary Investor Type	Number of investments	Number of investments in QIS
DCVC	USA	Venture Capital	475	21 (4%)
Creative Destruction Lab	Canada	Accelerator/ Incubator	288	20 (7%)
In-Q-Tel	USA	Not-For-Profit Venture Capital	435	14 (3%)
SBIR/STTR Programs	USA	Government	508	12 (2%)
U.S. DHS	USA	Government	2640	12 (0.5%)
Y Combinator	USA	Accelerator/ Incubator	5542	11 (0.2%)
NSF	USA	Government	4042	11 (0.3%)
WorldQuant Ventures	USA	Venture Capital	111	10 (9%)
Alumni Ventures	USA	Venture Capital	1313	10 (1%)
DARPA	USA	Government	210	10 (5%)

Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

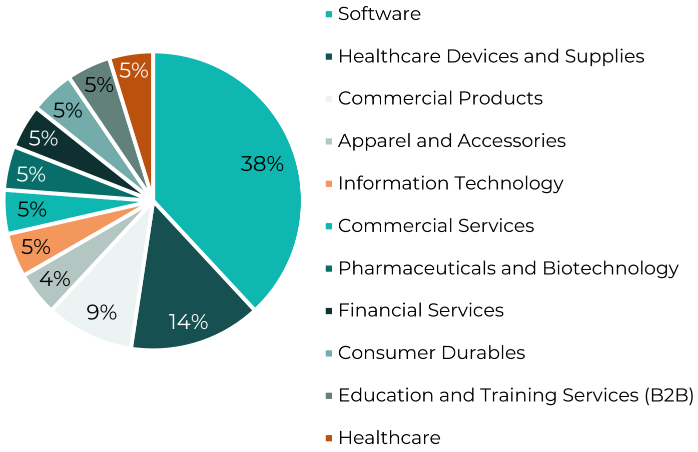
Identified Washington QIS investors are in Western Washington and largely focus on software, materials, and health.

Companies	HQ Location	Primary Investor Sector	Preferred Industry	Preferred Vertical	# of Investments	# of Investments in QIS
Aegis Group	Seattle	Corporation	Commercial Services	3D Printing	5	1 (20%)
Cray	Seattle	Corporation	Software	TMT	7	1 (14%)
SPIE Startup Challenge	Bellingham	Other	Healthcare Devices and Supplies	TMT	21	2 (10%)
Bellingham Angel Investors	Bellingham	Angel Group	Software	TMT	49	3 (6%)
William Gates	Seattle	Angel (individual)	Information Technology	TMT	69	4 (6%)
Jeffrey Bezos	Seattle	Angel (individual)	Software		38	2 (2%)
Grey Sky Venture Partners	Bellevue	Venture Capital	Commercial Products	HealthTech	19	1 (5%)
Paul Maritz	Seattle	Angel (individual)	Software	TMT	23	1 (4%)
The W Fund	Seattle	Venture Capital	Healthcare Devices & Supplies	CleanTech	29	1 (3%)
Calterraw Capital	Seattle	Venture Capital	Financial Services	B2B Payments	40	1 (3%)
Sahsen Ventures	Seattle	Venture Capital	Education & Training Services (B2B)	CleanTech	56	1 (2%)
Charlie Songhurst	Seattle	Angel (individual)	Software	TMT	185	3 (2%)
Acequia Capital	Seattle	Venture Capital	Application Software	3D Printing	439	7 (2%)
Amazon Web Services	Seattle	Accelerator/Incubator	Software	FinTech	71	1 (1%)
Bezos Expeditions	Mercer Island	Family Office	Software	FinTech	119	1 (1%)
E8	Seattle	Angel Group	Consumer Durables	Autonomous cars	123	1 (1%)
Breakthrough Energy Ventures	Kirkland	Impact Investing	Commercial Products	CleanTech	128	1 (1%)
WRF Capital	Seattle	Venture Capital	Healthcare	Digital Health	174	1 (1%)
Keiretsu Capital	Seattle	Venture Capital	Healthcare Devices & Supplies	CleanTech	192	1 (1%)
Bill & Melinda Gates Foundation	Seattle	Not-For-Profit Venture Capital	Pharmaceuticals & Biotechnology	EdTech	374	1 (0.3%)
Microsoft for Startups	Seattle	Accelerator/Incubator	Software	TMT	987	1 (0.1%)

Total Number of Investors by Primary Investor Type

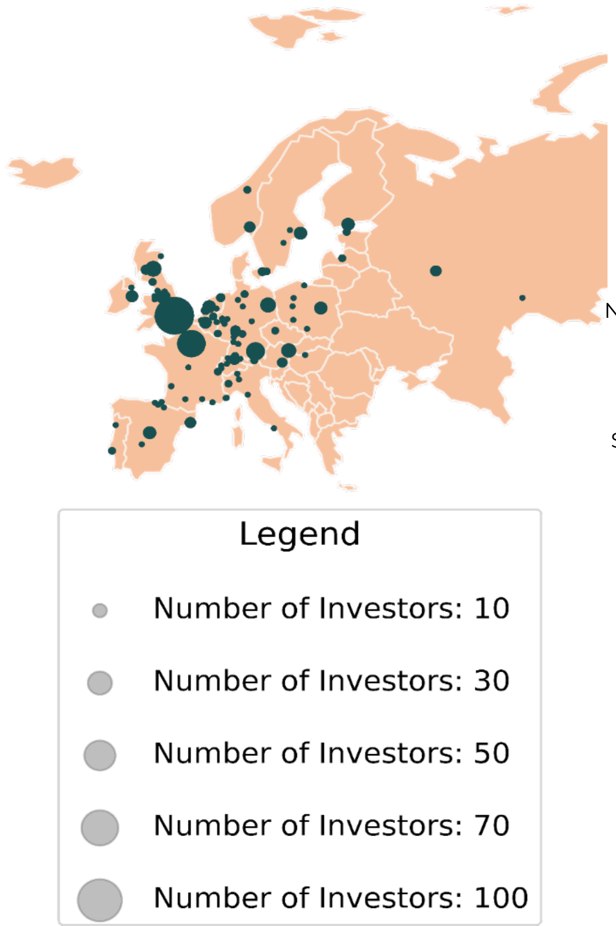


Total Number of Investors by Preferred Industry

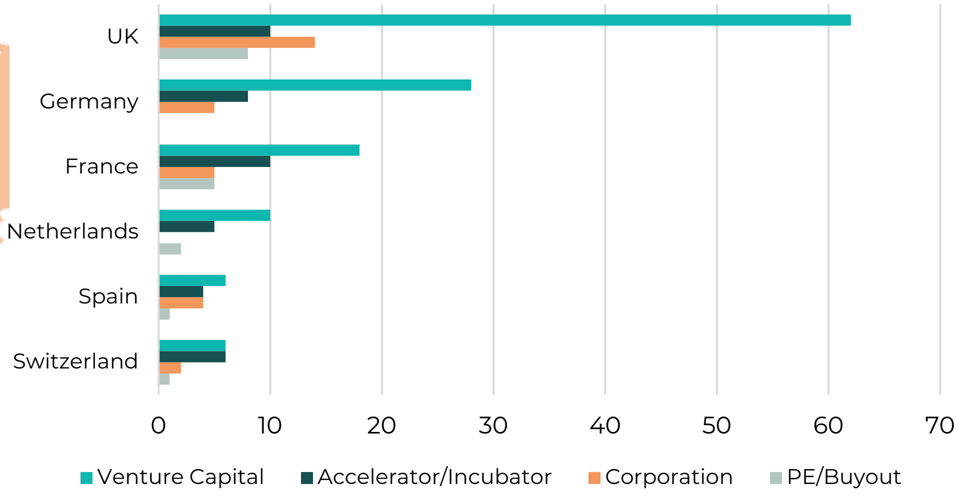


Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

In Europe, UK is leading in number of investors in QIS-related companies, followed by Germany and France.



Total number of investors by Primary Investor Type and Country in Europe



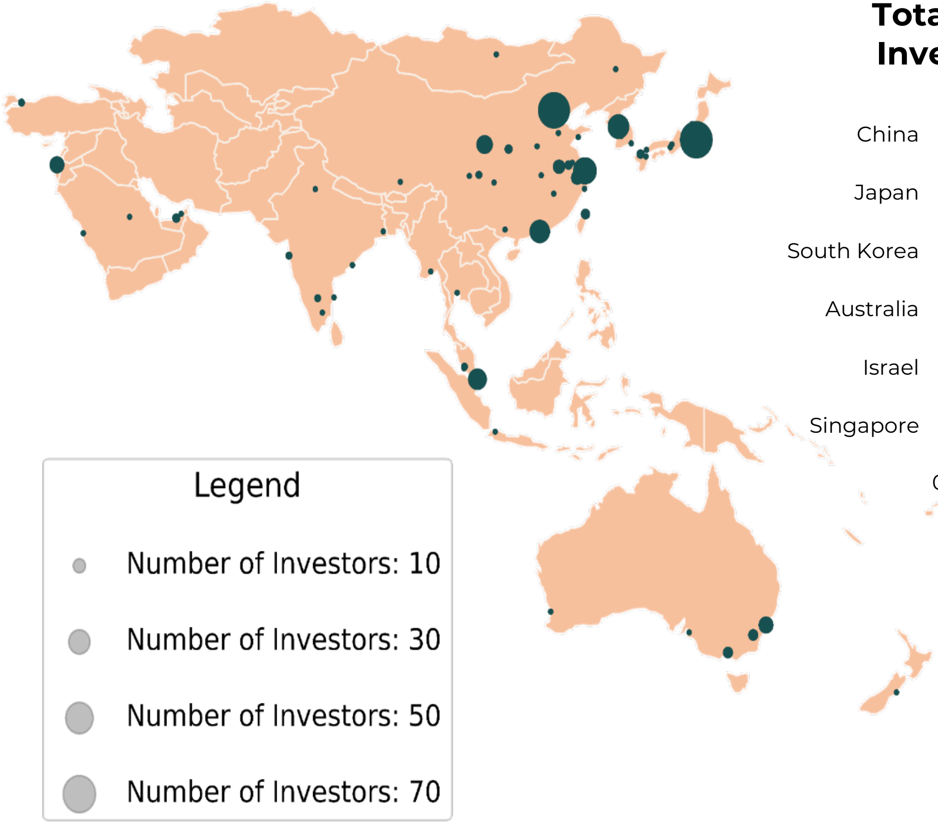
HQ Country/Territory	Total number of Investors in QIS
United Kingdom	146
Germany	54
France	49
Netherlands	24
Spain	19
Switzerland	18

Top 10 Investors in QIS in Europe

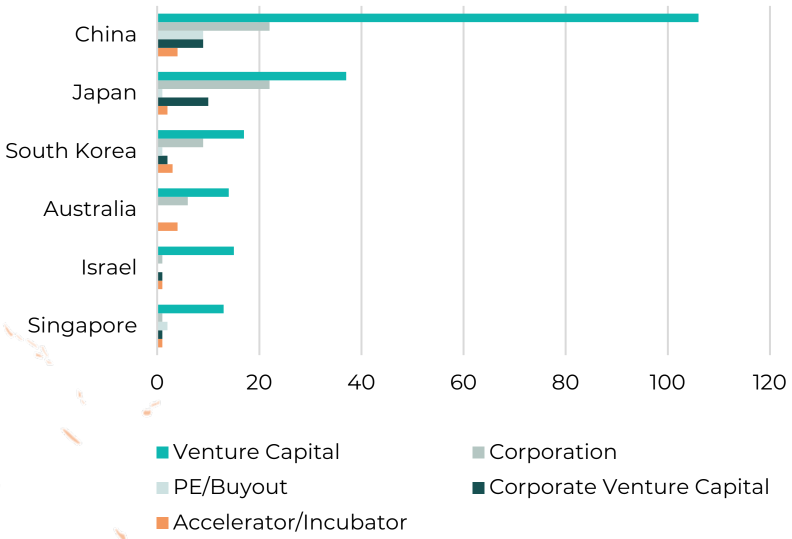
Investors	HQ Location	Primary Investor Type	Preferred Geography for Investing	Total Number of Investments in QIS (% of portfolio)
Innovate UK	Swindon, United Kingdom	Government	UK	68 (2%)
Quantonation	Paris, France	Venture Capital	Europe	28 (90%)
Parkwalk Advisors	London, United Kingdom	Venture Capital	UK	11 (4%)
Scottish Enterprise	Glasgow, United Kingdom	Venture Capital	Scotland	11 (1%)
High-Tech Gründerfonds	Bonn, Germany	Venture Capital	Germany	10 (1%)
IP Group	London, United Kingdom	Venture Capital	Asia, UK, US	7 (2%)
Venture Kick	Zürich, Switzerland	Accelerator/ Incubator	Switzerland	6 (1%)
Bpifrance	Maisons-Alfort, France	Sovereign Wealth Fund	France	0.2 (1%)
Maki.vc	Helsinki, Finland	Venture Capital	Northern and Western Europe	6 (8%)
Verve Ventures	Zug, Switzerland	Venture Capital	Europe	5 (2%)

Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

China and Japan are leading in QIS-related investment, but Australia, Saudi Arabia, and Singapore also have active investors in QIS.



Total number of investors by Primary Investor Type and Country in Europe



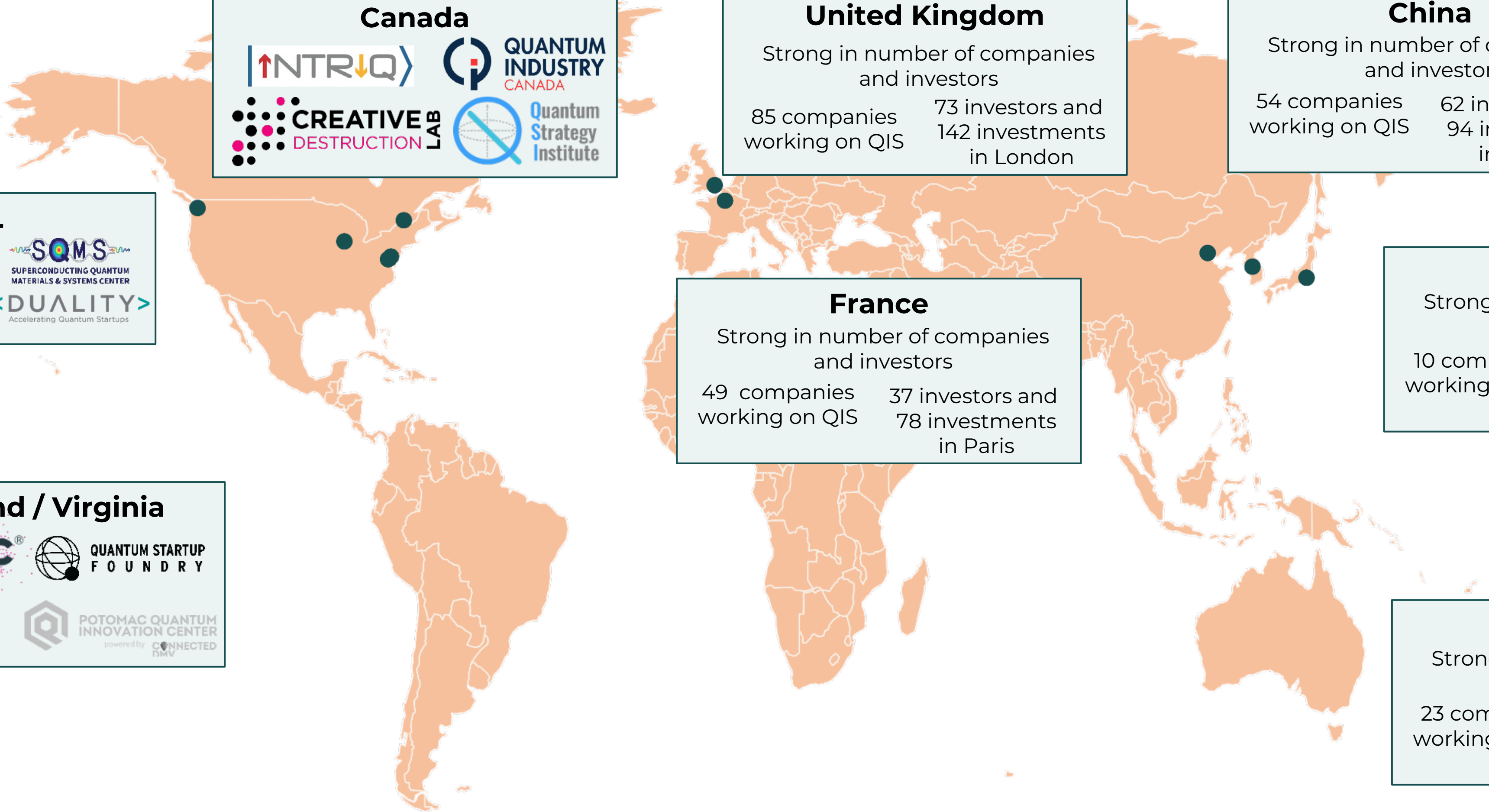
HQ Country/Territory	Total number of Investors in QIS
China	177
Japan	76
South Korea	35
Australia	29
Israel	27
Singapore	22
Hong Kong	19

Top 10 Investors in QIS in Asia-Pacific Region

Investors	HQ Location	Primary Investor Type	Preferred Geography	Number of Investments in QIS
Sequoia Capital China	Beijing, China	Venture Capital	China	8 (0.5%)
SGInnovate	Singapore, Singapore	Venture Capital	Singapore	8 (6%)
KAUST Innovation Fund	Thuwal, Saudi Arabia	Venture Capital	Asia, Canada, Europe, Middle East, North America, Northern Africa, Oceania, United States	7 (7%)
Samsung Venture Investment	Seoul, South Korea	Corporate Venture Capital	Asia, Europe, North America	6 (1%)
Legend Capital	Beijing, China	Venture Capital	China	6 (1%)
Main Sequence Ventures	Eveleigh, Australia	Venture Capital	Australia	6 (9%)
OurCrowd	Jerusalem, Israel	Venture Capital	Israel, United States	6 (1%)
5Y Capital	Shanghai, China	Venture Capital	China, Hong Kong, Taiwan	5 (1%)
Mubadala Capital-Ventures	Abu Dhabi, United Arab Emirates	Venture Capital	Bahrain, Europe, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, United States, Yemen	5 (5%)
TLV Partners	Tel Aviv, Israel	Venture Capital	Israel	5 (6%)

Source: **Pitchbook**
Keyword: **"Quantum Technology", "Quantum Sensing", "Quantum Computer", "Quantum Networking", "Quantum Control Software", "Quantum Optics", "Quantum Optimization", "Quantum Simulation", "Quantum Cryptography", "Quantum Cybersecurity", "Quantum Chemistry", Include related keywords**

Some of the most interesting Quantum Clusters around the globe



Canada
INTRIQ
QUANTUM INDUSTRY CANADA
CREATIVE DESTRUCTION LAB
Quantum Strategy Institute

Chicago, IL
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
CHICAGO QUANTUM EXCHANGE
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER
DUALITY Accelerating Quantum Startups

DC / Maryland / Virginia
UNIVERSITY OF MARYLAND 1856
QED-C
QUANTUM STARTUP FOUNDRY
MID-ATLANTIC QUANTUM ALLIANCE
POTOMAC QUANTUM INNOVATION CENTER powered by CONNECTED DMV

United Kingdom
Strong in number of companies and investors

85 companies working on QIS

73 investors and 142 investments in London

France
Strong in number of companies and investors

49 companies working on QIS

37 investors and 78 investments in Paris

China
Strong in number of companies and investors

54 companies working on QIS

62 investors and 94 investments in Beijing

South Korea
Strong in number of companies and investors

10 companies working on QIS

27 investors and 37 investments in Seoul

Japan
Strong in number of companies and investors

23 companies working on QIS

68 investors, 108 investments in Tokyo

3. Diversity and Workforce

Key Takeaways

- As a highly technical and emerging field, careers in QIS still demand a high level of education (Masters and PhDs).
- There are varied conventional and unconventional ways to help bridge the workforce gap.
- Washington State is well positioned to build a strong workforce in QIS due to its strong STEM background and university programs.
- **However, job offerings in the state currently do not meet workforce supply.**

Quantum is an educationally elite field – An analysis of quantum jobs postings showed more than half required candidates with PhDs.

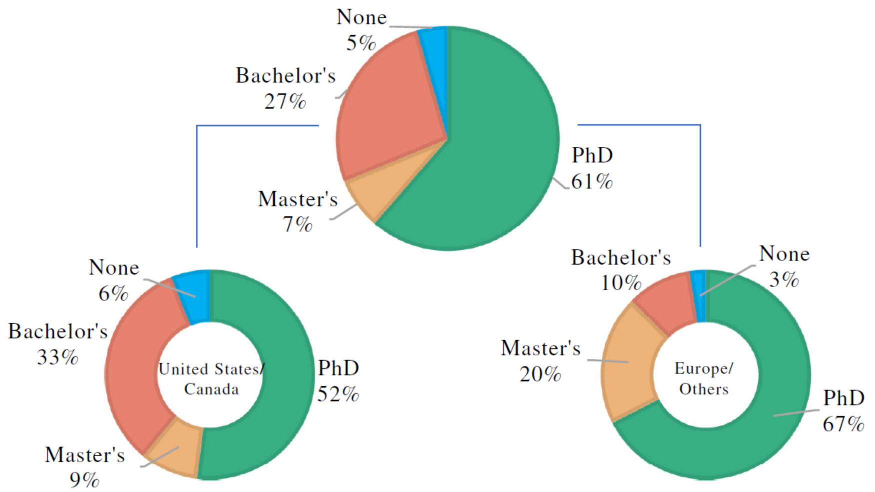


Fig. 1 Degree requirements for various job vacancies across (a) the world, and in (b) the United States/Canada, and (c) Europe/rest of the world.[35]

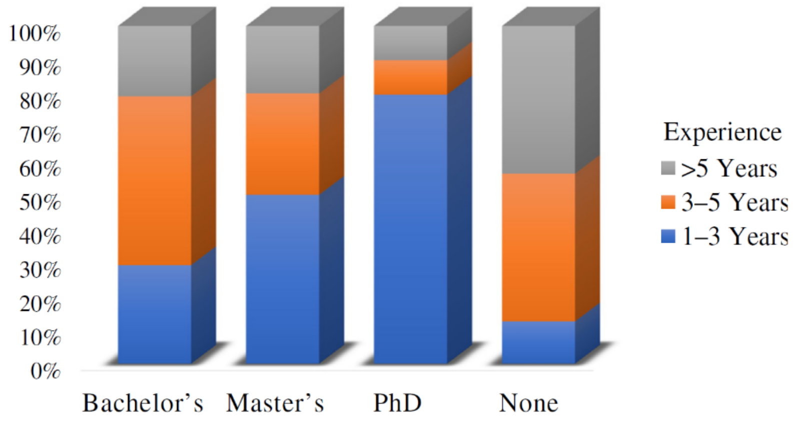
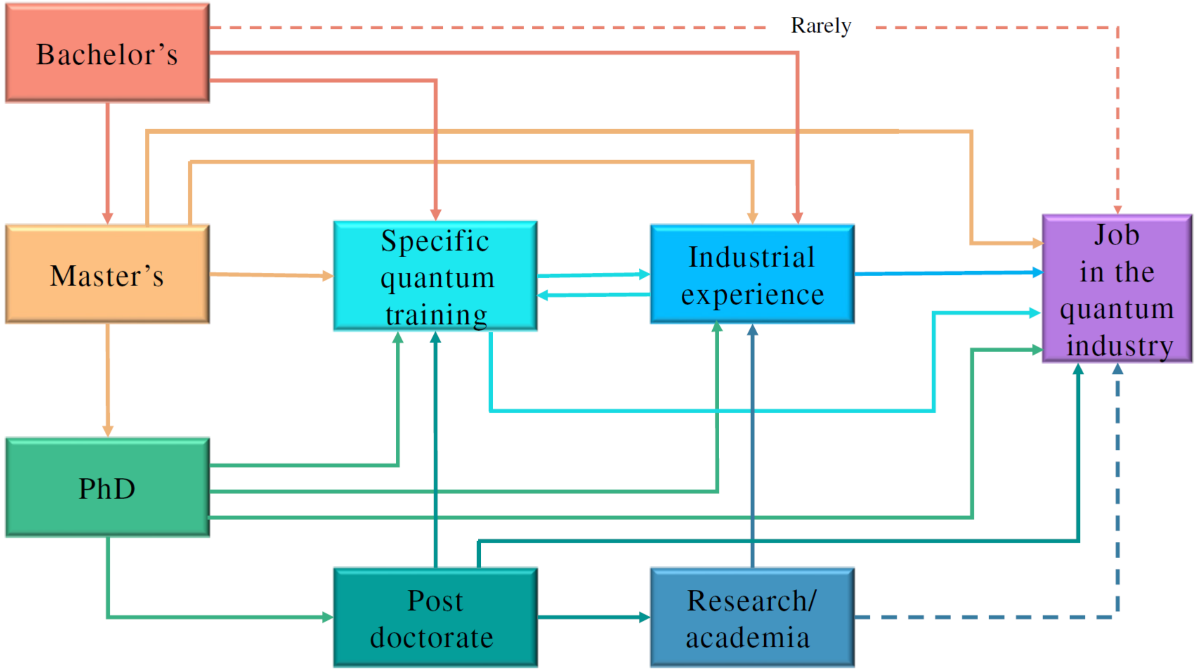


Fig. 2 Requirements of minimum professional experience in addition to degrees for various job vacancies available across the world.[35]

- An analysis of over 750 job postings showed that fewer years of work experience in Quantum are required for PhD holders compared to those with Bachelor's or Master's degrees.
- Around 37% of quantum-based roles in this study were from large corporations (e.g., IBM, Google, Microsoft, Quantinuum, Amazon, and IonQ).
- 42% of postings focused on the global quantum computing sector, 32% on quantum hardware, 13% on quantum software, 4% on quantum security, 3% on quantum communications and 2% on quantum sensing and imaging.
- Other requirements include expertise in a wide range of disciplines, such as physics, materials science, electrical engineering, computer science, chemistry, and mathematics.

Source:
Kaur and Venegas-Gomez (2022) Defining the quantum workforce landscape: a review of global quantum education initiatives. SPIE (DOI: 10.1117/1.OE.61.8.081806)

To develop QIS skills, candidates must combine education in specialized disciplines and hands-on training with real-world projects.



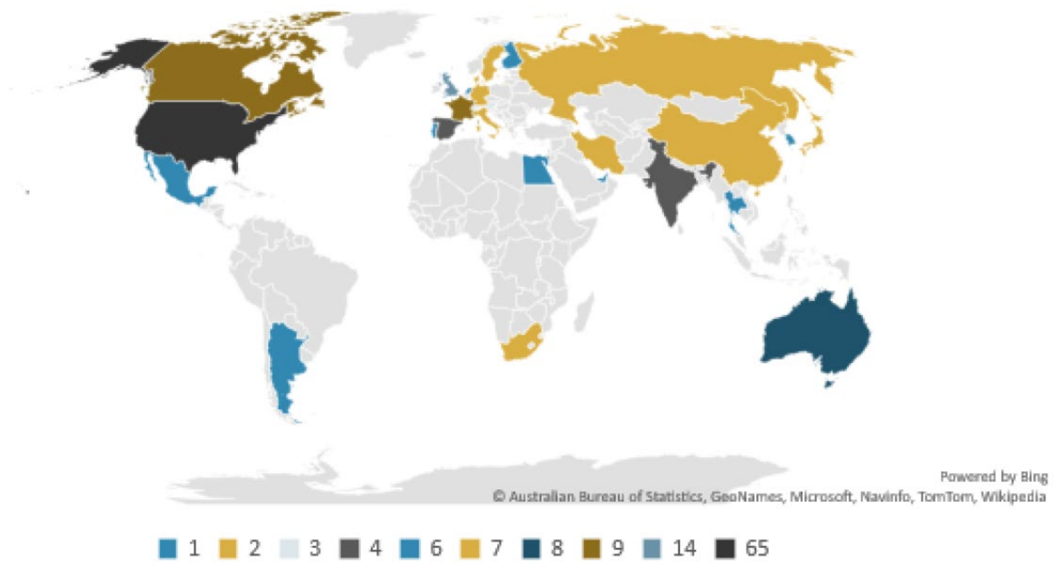
Career pathways for academic graduates leading to employment in the quantum industry.

- It is highly unlikely for candidates to get a job in quantum immediately after completing a bachelor's degree program.
- Employers are more likely to invest in candidates who have industry-specific experience or job-specific skills. Generally, these skills can be acquired either through advanced Master's degree programs or specific industrial training in quantum technologies.
- While, some secure a job in the quantum industry directly from higher education, these are most often directly related to quantum technology research.

Source:
Kaur and Venegas-Gomez (2022) Defining the quantum workforce landscape: a review of global quantum education initiatives. SPIE
(DOI: 10.1117/1.OE.61.8.081806)

There are currently 162 universities and institutions worldwide with educational programs and research activity in QIS.

Number of Universities Researching in Quantum Computing, 2021*



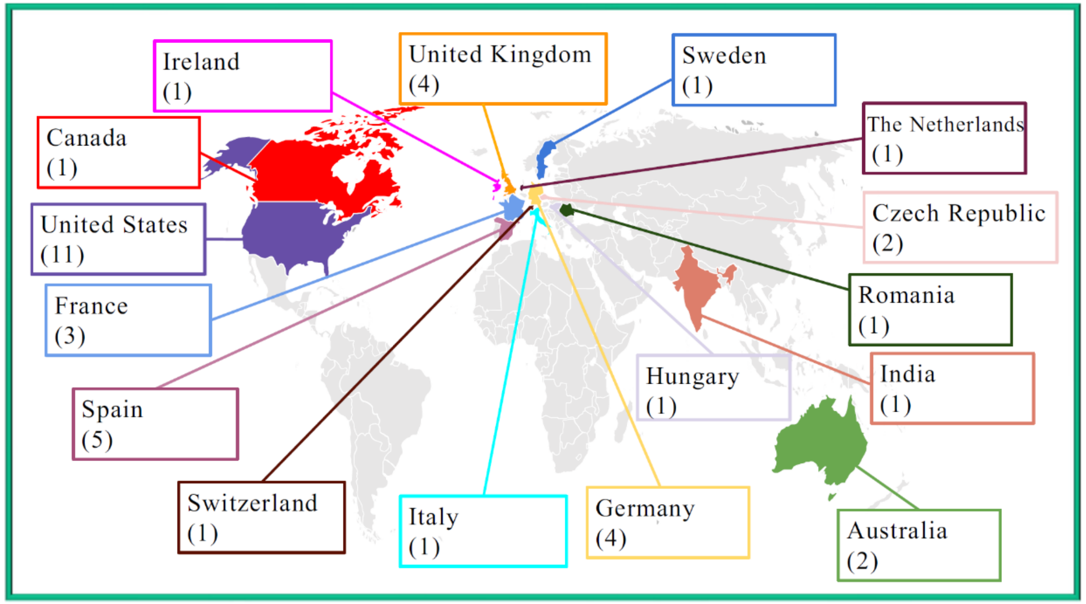


Fig. 4 Number of master's programs with a focus on quantum technologies across the world.

North America and Europe have over 30 universities offering Master's degrees in quantum science and technology. Despite efforts by universities worldwide, the number of quantum-related job postings still outstrips qualified talent by as much as three to one.

Source: **Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing**
Kaur and Venegas-Gomez (2022) Defining the quantum workforce landscape: a review of global quantum education initiatives. SPIE
(DOI: 10.1117/1.OE.61.8.081806)
McKinsey Digital – Quantum computing funding remains strong, but talent gap raises concern (link)

The talent gap for quantum technology jobs could be addressed with upskilling programs for talent in related disciplines.

Some universities are offering more specialized courses to help retrain qualified engineers, technicians, and business specialists in quantum technologies. Online courses also contribute to this goal:

- edX and Coursera offer academic-level courses focused on a more fundamental approach to quantum technology, with curriculum from prestigious universities (Delft University Technology, University of Toronto, Saint Petersburg, University of Colorado Boulder, École Polytechnique, and University of Maryland, among others)
- Quantum Resources and Careers (QURECA) offers an online training and recruitment platform that provides online courses and resources to fill the gaps in the existing quantum community
- MIT's Center for Quantum Engineering (CQE) offers online professional development quantum curricula "Quantum Computing Fundamentals" and "Quantum Computing Realities," a curriculum designed to bridge the academic gap between quantum science and quantum engineering
- Q-CTRL introduced Black Opal, an interactive platform for beginners designed to provide training to software engineers, security analysts, and data scientists in the fundamentals of quantum computing
- Microsoft collaborated with Alphabet X and Caltech's IQIM to release a quizzes-based course in quantum computing on Brilliant (link)
- Many more online learning resources available in platforms like Udemy, QPlayLearn, and GeeksforGeeks, among others

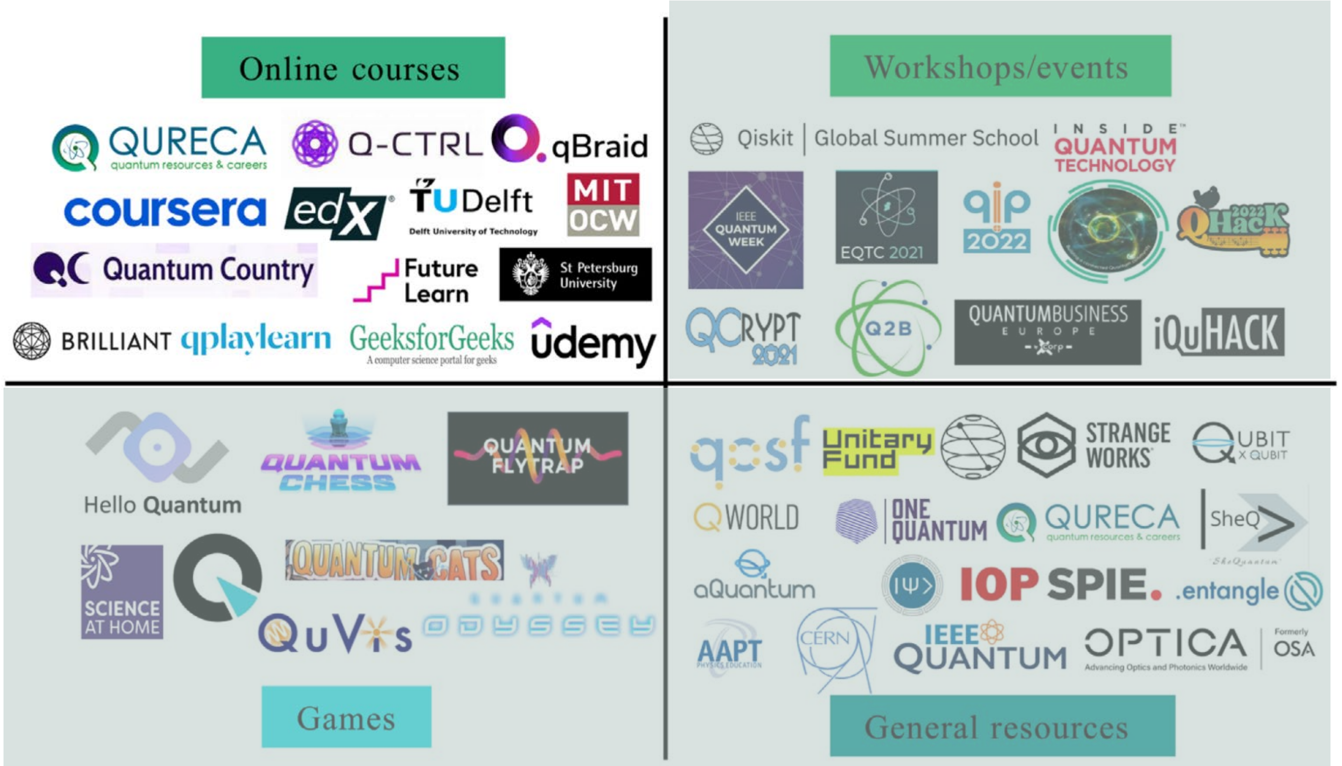


Fig. 5 Overview of global education and training resources available for the development of the current and future workforce.

Workshops and hackathons provide opportunities for learners to gain real-world experience and solve problems related to Quantum technologies.

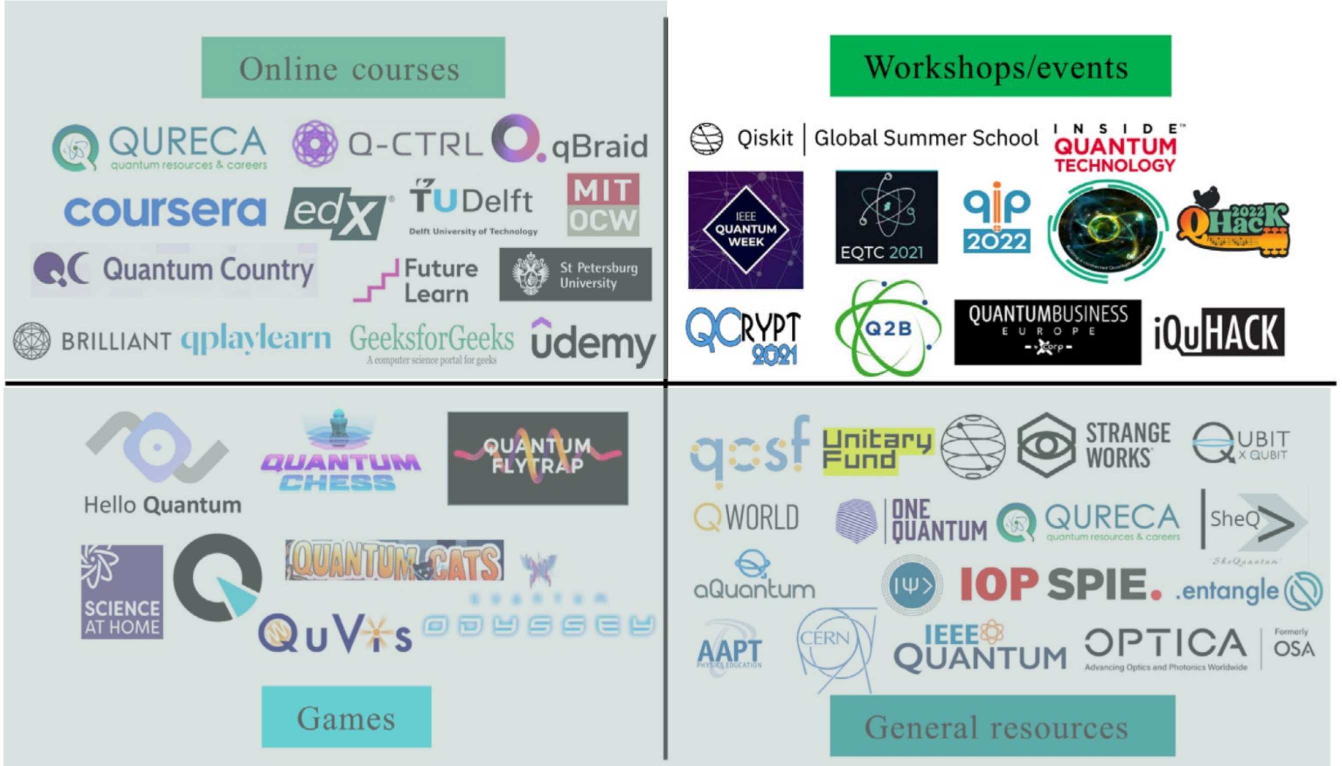
Workshops and hackathons are good ways to learn about quantum technologies, identify quantum applications in various industries, develop portfolio projects, and network with engineers, researchers, and academic/industry experts.

Workshops:

- Quantum Computing Lab Initiative by CINECA has been organizing the High-Performance Computing and Quantum Computing (HPCQC) Workshop since 2018
- Quantum Computing Theory in Practice (QCTIP) workshop held in the UK fosters discussion between theorists and practitioners of quantum computing

Hackathons:

- QHack by Xanadu
- Airbus Quantum Computing Hackathon (link)
- Big Quantum Hackathon by QuantX (link)
- Quantum Futures Hackaton by Quantum Open Source Foundation (QOSF)
- MIT iQuHACK (link)
- Quantum Coalition Hack (link)
- QPARC Challenge (link)



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Conferences provide excellent opportunities to network and learn new trends, ideas, and solutions.

Conferences in quantum technologies:

- Bring together quantum professionals, researchers, educators, entrepreneurs, champions, and enthusiasts to discuss the potential of quantum technologies
- Address recent advances in infrastructure development, education and training, and ground-breaking efforts in scientific R&D
- Exchange and share experiences, challenges, research results, innovations, applications, pathways, and enthusiasm on all aspects of quantum computing and engineering
- Promote communications between different stakeholders, industry leaders, researchers, engineers, scientists, and the general public
- Offer networking opportunities and industry engagements to foster the global quantum ecosystem

Some noteworthy recently held and planned conferences globally (in person or virtually) include:

- European Quantum Technologies Conference (EQTC) by the Quantum Flagship – Ireland/Virtual, Dec 2021 (link)
- Qcrypt – Taipei, August 2022 (link)
- IEEE Quantum Week – International Conference on Quantum Computing and Engineering (QCE) – Denver, Sept. 2022 (link)

- Conference on Quantum Information Processing (QIP) – Ghent, Brussels, February 2023 (link)
- Quantum 2.0 Conference and Exhibition by Optica (formerly OSA) – Denver, June 2023 (link)
- American Physical Society (APS) Meeting – Las Vegas, March 2023 (link)
- SPIE Quantum West – San Francisco, January/February 2023 (link)
- Quantum Business Europe (QBE) – Online, March 2023 (link)
- Practical Quantum Computing (Q2B) – Silicon Valley (Dec. 2022), Paris (May 2023), Tokyo (July 2023) – (link)
- Inside Quantum Technology – Quantum Communications and Quantum Security Event – The Hague, Netherlands, March 2023 (link)
- Economist Commercializing Quantum – London, May 2023 (link)
- Quantum.Tech – Commercial Application of Quantum Computing, Communications, and Sensing – London, UK, Sept. 2023 (link)
- Northwest Quantum Nexus Summit – Seattle, Jan. 2023 (link)

Source:
Kaur and Venegas-Gomez (2022) Defining the quantum workforce landscape: a review of global quantum education initiatives. SPIE (DOI: 10.1117/1.OE.61.8.081806)

Understanding quantum mechanics may seem intimidating at first, but employing games as an educational tool ensures engagement and a fun learning experience.

- IBM Hello Quantum is a puzzle game designed for nonexperts in building intuition and knowledge on how to apply quantum computing principles in coding quantum programs by visualizing just two qubits
- Quantum Chess is like ordinary chess but with a quantum twist to introduce an element of unpredictability, incorporating quantum principles such as superposition and entanglement
- Quantum Flytrap has created a virtual lab for playing games with photons to make undergraduate physics experiments more enjoyable and interactive
- ScienceAtHome Quantum Moves 2 is helping researchers solve and optimize the manipulation of qubits and make their contribution to cutting-edge quantum research
- Quantum Cats, an Angry Birds-inspired game that highlights quantum behaviors and the differences between quantum and classical physics

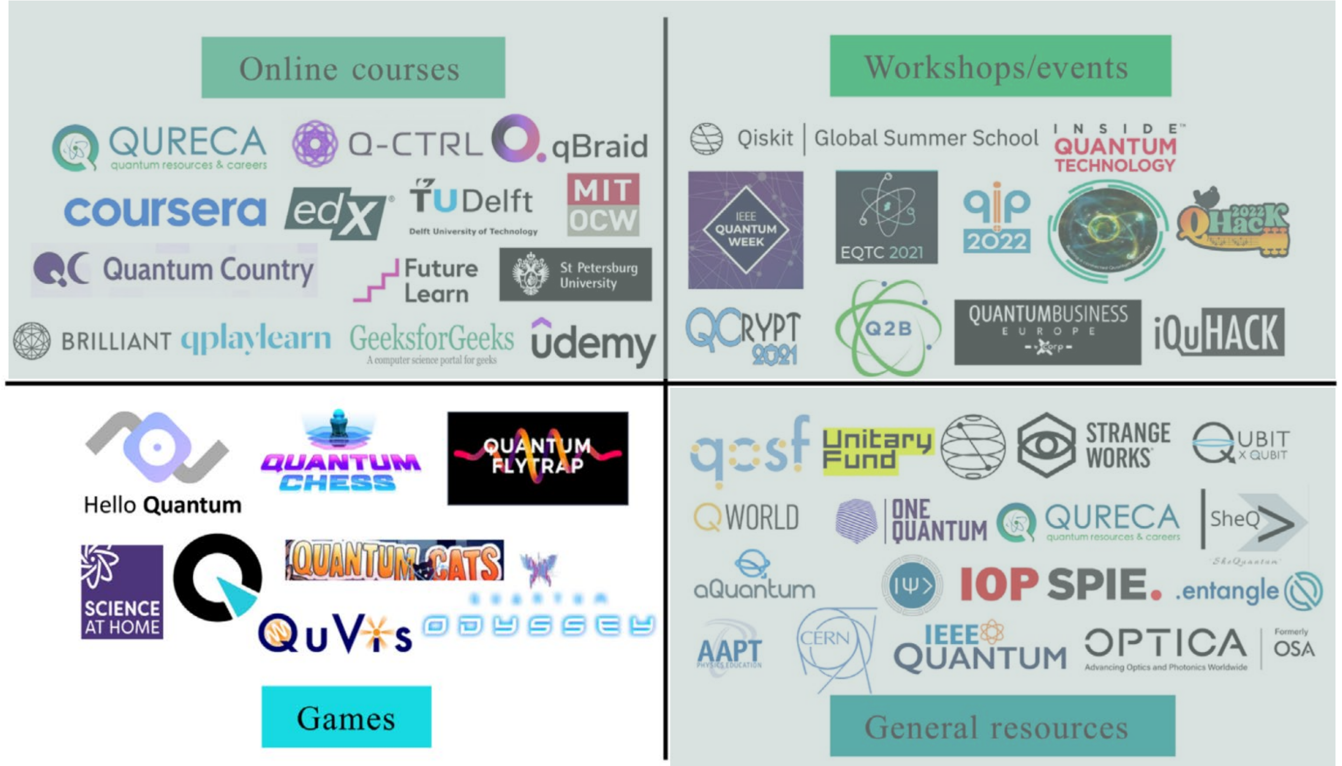

Fig. 5 Overview of global education and training resources available for the development of the current and future workforce.

A plethora of general resources is currently helping build and expand the quantum community to include everyone.

- QURECA, QWorld, and OneQuantum have established global quantum groups to create awareness about quantum technologies by enhancing student engagement through workshops, mentoring, career, and networking events and outreach activities
- SheQuantum is empowering women to contribute to the quantum field by facilitating quantum education through an e-learning platform
- Unconventional Computing Lab, Brazil Quantum, and aQuantum are educating and promoting quantum technologies in various communities by reducing language barriers
- Qubit by Qubit is aimed at educating high school and undergraduate students through hands-on and innovative programs, workshops, and courses
- Quantum Curious is a platform featuring a range of learning resources for anyone interested in quantum computing, even without a strong STEM background
- Q2Work aims to support and grow a quantum workforce that is diverse and equitable, offering both informal and formal learning opportunities for teachers, students and families
- QuSTEAM Initiative is a non-profit, membership-based organization serving a network of academic institutions and industry employers to facilitate a national scale-up of equitable and effective undergraduate quantum education. It offers resources for instructors, institute administrators and students

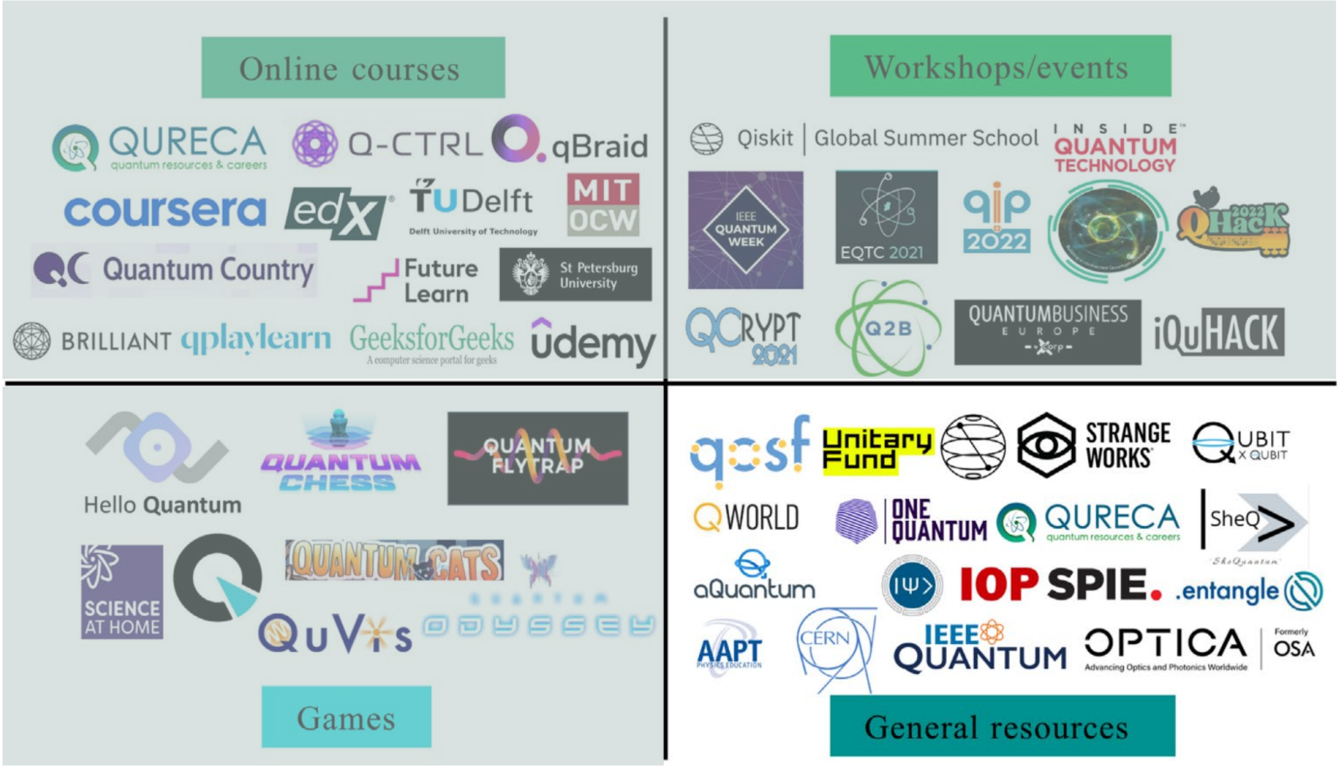

Fig. 5 Overview of global education and training resources available for the development of the current and future workforce.

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(DOI: 10.1117/1.OE.61.8.081806)

Some considerations from IBM's Roundtable on building a Quantum Workforce

Entice students to make the leap to quantum

- It's challenging to get students interested in quantum computing at a relatively early age – games can help.
- For quantum education to reach the broadest possible audience, it's crucial that educators reach students as early in their schooling as possible. The pipeline is "leaky" particularly for women and people of color at different points during their academic careers – these students drift away from STEM subjects if not adequately encouraged.
- Should be addressed early since quantum computing is still fairly new

Encourage an interdisciplinary approach

- Quantum computers require not only programmers and physicists, they also need people with electrical engineering expertise to develop the control electronics that read the quantum computer's signals, as well as material scientists to improve hardware, among others.
- Given the interdisciplinary nature of quantum computers, it is a disservice to silo quantum computing students into studying either hardware or computer science. It would most benefit the field to have professionals who understand both.

Avoid the hype – keep it clear and real

- Despite the urgent need of talent, be careful not to overpromise to students – quantum computing is still a nascent technology. Although the promise is there, many of the potential applications still lie in future advancements in quantum computing
- Use the limitations as inspiration while leveraging the challenges as very concrete learning opportunities
- The prospect of building a satisfying career in quantum computing must feel attainable for students, especially if the industry and academia desire to attract young people who might be reluctant to pursue STEM-related occupations. That means providing students with clear direction and informing them of the opportunities in the quantum field. If young people don't know how to get started with quantum computing and understand how their hard work will pay off in the end, they will end up moving on to other fields.

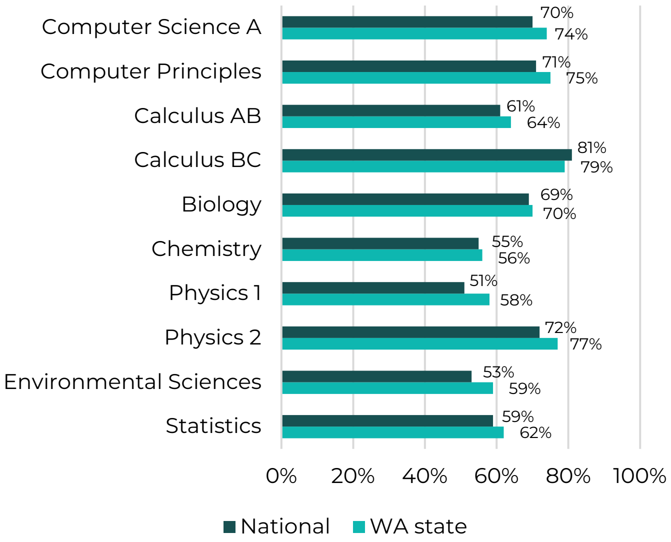
Source:
IBM Roundtable: Building a Quantum Workforce Requires Interdisciplinary Education and the Promise of Real Jobs
(link)

A QIS career starts with a strong STEM background, something that Washington has been investing on in order to cope with workforce demand.

2020 AP Exam Pass Rates

Washington students consistently outperformed national averages across nine STEM courses.

Percentage of students who score a 4 or higher on AP exams



STEM Degree Production

STEM degree and long-term certificate completions have steadily increased from 2014 to 2019.

Mid-level

Degree and certificate completions in STEM fields grew more than 15% between 2014 and 2019, with expanding Career and Technical Education programs playing an important role

Baccalaureate level

About 12,700 students completed a baccalaureate degree in 2019

Graduate level

Completions in Computer and Information Sciences grew by 70%, in Engineering by 9%, in Health by 16% and in all other STEM fields by 6%

The Gender Gap

Although girls and boys begin school with comparable math and cognitive skills, STEM achievement among female students tends to recede as they move through their education

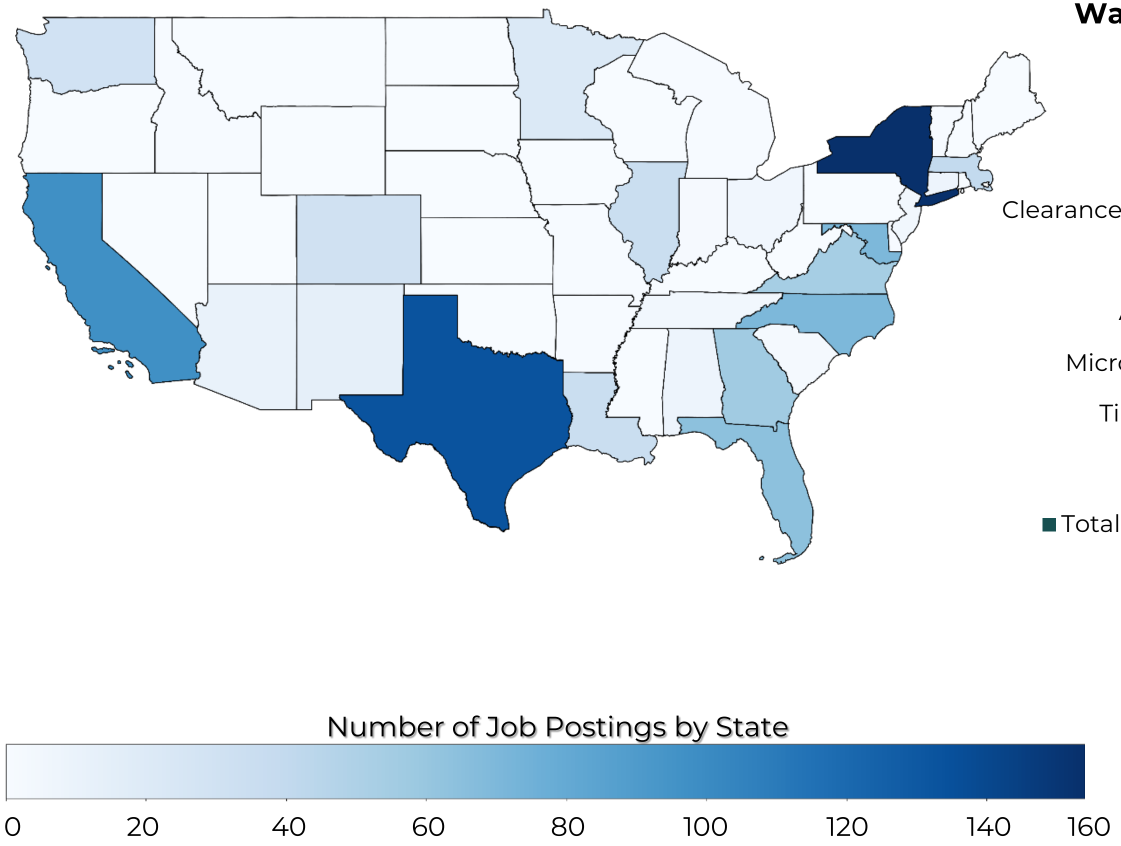
Post-secondary

Male students also complete STEM degrees in greater numbers than female students. In 2020, only 35% of students completing associate degrees or bachelor's degrees in STEM subjects and only 22% completing degrees in computer science were female.

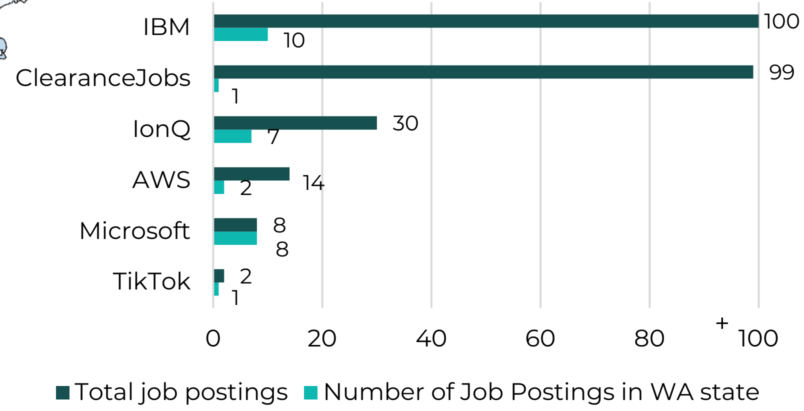
Despite best efforts, rapidly growing workforce demand is outpacing STEM degree productions. Over the course of the next 10 years, jobs in several STEM fields are projected to offer more than 63,000 opening to STEM graduates.

Washington State is producing more quantum professionals than it can place locally, thus exporting talent to other states.

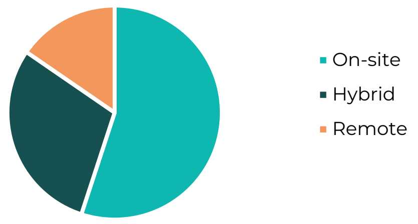
State	Number of QIS job postings	Companies hiring
NY	154	IBM, JPMorgan Chase & Co., ClearanceJobs, Point72, Booz Allen Hamilton
TX	133	IBM, ClearanceJobs, Lockeed Martin, Oasis Systems LLC, NVIDIA, Honeywell, Hess Corporation
CA	97	AWS, ClearanceJobs, HRL Laboratories, Atom Computing, Lawrence Livermore National Laboratory, Cisco, QC Ware, Elementl, Mastercard, Fujitsu, ByteDance, Oxford Instruments, TikTok, Boeing
MD	70	IonQ, ClearanceJobs, IBM, Northrop Grumman, SAIC, Latitude Inc, Leidos
NC	70	IBM, Honeywell, Fidelity Investments
FL	64	ClearanceJobs, Lockheed Martin, IBM
GA	56	IBM, ClearanceJobs, Keysight Technologies, Capgemini, Honeywell, Neudesic
VA	54	IBM, SAIC, ClearanceJobs, Honeywell, Booz Allen Hamilton, AWS, LinQuest, Raytheon Intelligence & Space
MA	40	QuEra Computing, MIT Lincoln Laboratory, Raytheon Intelligence & Space, Dash, AWS, CyberCoders, IonQ
DC	37	IBM, SAIC, ClearanceJobs, Inter-American Development Bank
WA (14th place)	30	IBM, Microsoft, IonQ, AWS, ClearanceJobs, TikTok, ByteDance



Washington State job postings compared with total job postings, by hiring company



Of the thousand job postings analyzed, only one third specify workplace type and half are for on-site jobs



Source: **Companies websites and LinkedIn**
Sample: **1000 job postings on LinkedIn**
Keywords: **Quantum Computing, Job Function: Information Technology, Engineering, Research**
Job postings dates between **February 15, 2022** and **October 23, 2022**
Search date: **October 24, 2022**

Many companies are offering remote positions and internships, which allows for workers to obtain a quantum job from anywhere.

Details regarding the types of QIS-related jobs that can be found in Washington State:

	Job Title	Location	Requirements
Microsoft	• 3D Modeler • Applied Researcher – Quantum Computing • Senior Packaging Engineer – Quantum • Computational Chemistry Incubation Lead • Senior Quantum Engineer – ASIC Design • Director, Growth Strategy and Planning, Mission Engineering • Senior Hardware Program Manager	Redmond, WA	Typically, Master's or PhD in mechanical, electrical, material engineering, computer engineering, physics or related field 2+ to 10+ years of experience, depending on the position and academic record
AWS	• Software Development Engineer, Quantum Computing • Software Dev Engineer	Seattle, WA	BSc in Computer Science, Physics or related field 1+ year of experience contributing for system design or architecture
IonQ	• Director of Manufacturing • Executive Assistant • Staff Engineer • Senior Quantum Applications and Solutions Scientist • Staff Software Engineer	Some positions are billed as remote, but the Director of Manufacturing and Executive Assistant are in Seattle, WA	BSc, MSc or PhD in physics, computer science, optical sciences, electrical/computer engineering, material science, or other related fields 2 to 10+ years of experience, depending on the position and academic record

- Microsoft, AWS, IonQ, IBM and others are hiring quantum-related workers in Washington State.
- Many other companies, including Intel, Infleqtion and Boeing are hiring in multiple locations across the U.S. for quantum-related jobs, but not in Washington State.
- Google, D-Wave, ByteDance, and SandboxAQ are offering remote research programs, entry level roles, and internships all over the U.S. (including Washington State) on a year-round roll out for individuals currently enrolled in MSc or PhD in math, computer science, or related fields. Durations can vary from a few months to a year.

Source: **Companies websites and LinkedIn**
Keyword: **Quantum**
Date: **October 2022**

4. SWOT Analysis

Washington State Quantum Information Science (QIS) SWOT Overview

Strengths

Research Environment
- Significant attraction of advanced research funding used to develop differentiated capabilities
- Washington Nanofabrication Facility (WNF) managed by University of Washington (UW) offers shared-use open-access space for fabrication

Industry
- Presence of important players in the field, e.g., Microsoft, AWS, Google, and IonQ
- Ample talent bolstered by strong university programs

Culture
- Collaboration between national lab (PNNL), academia (UW, WSU), and industry focused on quantum technologies
- Experienced angel investor community that understands material science investments

Strategy & Focus: Developing concentration of excellence in quantum optics, devices, and software

Weaknesses

Talent Retention
- Universities are producing more talent than can be employed by the emerging quantum start-up sector. Industry is not absorbing enough of them.
- Poor retention capacity of Washington graduates – many are foreigners that have a lot of trouble getting visas to continue working in the state.

Commercialization
- Intellectual property licensing and transfer between universities and academic continue to hinder collaboration.
- With demonstrated excellence in materials and software, there is no clear path for moving innovations in materials to productive use-cases without going out of state.

Opportunities

Collaboration
- Connection with other material clusters in the U.S. and clusters focusing downstream application that relate to Washington State economic drivers, e.g., healthcare, cybersecurity, AgTech
- Greater material cooperation between universities and PNNL in the quantum materials area
- Licensing, which opens up the research for anyone to use it and goes around IP Law. UW has not historically used Non-Exclusive Royalty-Free (NERF) licensing in QIS, which could help foster better collaboration between academia and industry

Talent
- Legislation and support to help foreign students get work visas
- Support for open-source solutions through NERF licensing collaborations

Threats

Talent Retention
- Loss of workforce to other regions
- Lack of visas for workforce results in exporting our talent

Infrastructure & Strategy
- Investment in infrastructure (e.g., WNF) needs to be obtained. The sector's longevity depends on vital strategy and support for shared resources. Lab resources require maintenance and must be funded accordingly.
- Globally, many regions are proactively developing strategies for their quantum sector. The U.S. economy is challenged to do so. In Washington State specifically, a lack of strategic development in quantum is creating divergent centers of excellence (materials and software).

5. Common Terms and Applications of QIS

The rise of Quantum Mechanics expanded the understanding of the often-counterintuitive behaviors of atomic and subatomic particles.

Wave-Particle Duality
Light and matter can exist both as waves and particles

Uncertainty Principle
There are certain sets of physical properties (such as position and momentum), and it is not possible to know both with absolute precision

Superposition
A quantum system can exist as a combination of two or more distinct states until it is measured (or interacts with the environment), when it would then "collapse" into a specific state

Entanglement
Two or more particles can interact in such a way that their quantum states become correlated, and remain so no matter how far apart they are, so that measuring one particle to be in a specific state instantaneously determines the state of the other

Tunneling
A particle can pass through an otherwise insurmountable barrier to a different location or energy state

Quantum Materials
Defined as those with novel entanglement or topological properties – materials with entanglement beyond the requirement of Fermi statistics and with topological responses

Broadly, there are three areas of technology in the second quantum revolution that are the focus of research and investment by industry and governments.

In recent decades, the increased ability to understand and manipulate these quantum phenomena led to the development of a variety of technologies that promise to bring significant economic and societal benefits, along with major security implications. The three major areas are:

Quantum Sensing and Metrology
Taking advantage of properties such as superposition and entanglement, and extreme sensitivity to the external environment, quantum systems are being developed into new types of sensors for highly sensitive, precise, and accurate measurements of time, gravity, acceleration and magnetic fields.

Quantum Communication
Advances in quantum technology will have a major impact on telecommunications and cybersecurity. Quantum computers will likely be powerful enough to decrypt currently secure data (secured by public key encryption systems). Scientists are developing *Quantum Key Distribution (QKD)* Systems, where encryption keys are shared in the form of quantum particles. Quantum communication can be additionally secured with *Quantum Teleportation*, which makes use of two entangled particles placed at different locations to transmit information.

Quantum Computing
While classical computers operate using bits of information with a vale of either 1 or 0, quantum computers use “quantum bits” (or quibts) that can simultaneously be 1 and 0 due to quantum superposition. In theory, this allows computations to be performed exponentially more quickly than by classical computers, especially factorization (with impact in cryptography and cybersecurity as mentioned above), search, optimization, and simulation.

There are three types of Quantum Computers, as defined by IBM

Quantum Annealer
The most basic form of quantum computing, whose computational power is no better than a traditional computer. It can perform one specific function and is restricted to applications in general sectors.
E.g., D-Wave developed this type of quantum computer and Google tested its performance, finding that is 3,600 times faster than a supercomputer and can solve a very specific optimization problem.

Analog Quantum
The first real form of quantum computer, supporting between 50 and 100 qubits. It has the capacity to simulate complex quantum interactions that cannot be done by any combination of conventional computing machines. It will apply to general areas and be suitable for the application of quantum chemistry, material science, optimization problems, quantum sampling, and quantum dynamics.

Universal Quantum
The ultimate quantum computer, with very high speeds, supporting more than 100,000 qubits. It will be the most powerful quantum computer, with complete application capacity in general functions such as secure computing, machine learning, cryptography, quantum chemistry, material sciences, optimization problems, sampling, quantum dynamics, and search.

There are many characteristics that separate Quantum Computing from Classical Computing.

Classical Computing	Quantum Computing
Data is stored in bits and only processes bits as either 1s or 0s at a time	Data is stored in quantum bits (qubits) and processes 1s and 0s at a time, creating many more possibilities simultaneously
Performs calculations in binary format, leading to slow and time-consuming operations	Calculations are based on the probability of the object, which speeds up operations
Can process a limited amount of data	Can process exponential quantities of data
Logical operations are performed through physical states (usually binary) and calculations occur in a sequential manner	Logical operations are performed using quantum states (qubits) and all calculations can occur simultaneously
Fails to solve too complex, massive problems	Deals with complex and large-scale problems
Uses standardized programming languages	Does not rely on any specific programming language. Different frameworks and programming languages used in quantum include: qasm, Qiskit (IBM), Cirq (Google), Forest/pyqil (Rigetti Computing), Q# (Microsoft), Ocean (D-Wave)
Used by everyone for everyday purposes	Systems are inherently complex and cannot be used for everyday purposes; they are typically used by scientists and engineers
Built with CPU and other processors	Has a relatively simple architecture and runs on a large number of qubits
Provides data security, but the methods are limited	Provides highly secure data and data encryption
Cheaper and easier to build	More expensive and difficult/demanding to build

Source:
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing

Quantum Computing can be achieved through many different technologies.

Technology	Description
Trapped-ions	In a trapped ion system, atomic ion qubits (calcium or ytterbium ions) are separated and trapped in an electric field. To store quantum information, the internal atomic state of the ion is used to represent the 0 and 1 qubit states. By pulsing the ions with a tuned laser, these systems can gate this information and perform calculations much faster than standard "classical" computers.
Quantum Annealing	In quantum annealers, all states can be represented as energy levels. These states are quickly simulated using qubit superposition and entanglement characteristics, and the lowest energy result is obtained. The lowest energy state gives the optimal solution or the most likely solution. All annealing methods are typically based on the Monte Carlo algorithm, which iterates a large number of random samples in a hypercube of dimension "N" to generate sample states.
Superconducting qubits	One of the leading technologies, which is aimed at significantly improving applications that require communication signal integrity and computing power. Charge qubits and flow qubits are the two main types of superconducting qubits, with the first being assigned to amplitude and the latter assigned to phase. A superconducting qubit can exist in a series of quantized energy states. It is a promising platform for fault-tolerant quantum computation.
Photonic qubits	Photons are the basic particles of visible light and are considered ideal carriers for quantum information because they interact little with their surroundings and can carry long distances without problems. Using this technology, it is theoretically possible to build a universal quantum computer using qubits (but in reality, it is difficult to achieve).
Topological qubits	Uses anyons, a type of particle found in 2D systems, to create a more stable quantum system. Anyons can move in relation to each other to influence their condition. The state is affected by the number of rotations around each other, which can create a type of braid, which is where the "topological" part of the name comes from.

Quantum computers are expected to be superior to classical computers in very specific applications.

Application	Description
Quantum-assisted Optimization	Optimization (the process of finding the best solution to a given problem from several possible options) is a major candidate for future execution in quantum computers and is a class of computational problems that offers quantum advantages over classical solutions. Quantum-assisted optimization uses optimization algorithms to solve optimization problems. Optimization algorithms are the tools and techniques used to achieve the optimality of the problem of interest. Almost every application needs to optimize something to minimize cost and energy consumption or maximize profit, performance, and efficiency. The search for optimality is further complicated by the fact that there is almost always uncertainty in real-world systems. Therefore, all end-consumer industries not only need robust but also optimal solutions. Complex optimization problems are difficult to solve on traditional computers because the algorithm takes time to navigate through all possible solutions. Quantum computers are especially useful for this function because they can process data exponentially faster than traditional computers.
Quantum-assisted Machine Learning	Quantum sampling can dramatically improve machine learning algorithms, which learn from data to make decisions or predictions. A quantum computer can process complex data exponentially faster than a conventional computer, allowing identification and recognition of items or patterns, including objects, faces, speech, and handwriting as fast as or faster than a human can perform such tasks. This ability is expected to lead to improvements in predictive analysis, search engines, and complex data analysis. These improvements could also lead to improvements in self-driving cars and robots with human-like dexterity. It could have a major impact by enabling automation of many positions in the services, manufacturing, and agricultural sectors that rely on pattern recognition, moderate manual dexterity, and decision making.
Quantum Simulation	Simulating or modeling chemical reactions and other material properties is one of the most anticipated applications of quantum simulation. Although the algorithms and heuristics used for simulations have improved significantly, many are limited by processing time. With quantum computing, a number of operations and processes used for simulations could be performed exponentially faster. Instead of spending years and hundreds of millions of dollars making and characterizing a relatively small number of materials, researchers could study millions of candidates in silico. Faster discovery pipelines will add great value across many industries, including pharmaceuticals, biochemistry, and engineering, where companies could create competitive advantages by refining their products and processing using quantum computing-based simulations.
Cryptography	Quantum cryptography is technology that uses the principles of quantum mechanics for encrypting messages. It helps protect personal information by providing security based on the basic laws of physics as opposed to computer technology and mathematical algorithms. In the age of digitalization, where computer networks are widely used for personal and commercial transactions and the transmission of sensitive information, there is a need for an encryption system that can prevent this information from being accessed by unauthorized third parties. (For more details on Quantum Cryptography, see next page)

Source:
Quantum Computing: Technologies and Global Markets to 2026 (Published February 2022) by BCC Publishing

There are a few emerging quantum cryptography start-ups developing several types of solutions.

Types of Cryptography Solutions	Description
Quantum Key Distribution	This technology solves one of the main tasks of cryptography, which is enabling guaranteed distribution of keys between remote users over open communication channels. This allows subscribers to generate a random key used in encryption or authentication. Quantum Crytography allows for a constant and automatic change of keys when transmitting messages in a one-time block cipher mode. E.g., UK-based start-up KETS
Quantum Random Number Generation (QRNG)	A frequent change of secret keys in quantum cryptography is possible, but it requires a large consumption of random numbers. The QNRG chip generates a sequence of numbers that forms the basis for strong passwords. The numbers are so random that anticipating the generator becomes difficult. Additionally, the QRNG chip also implements another feature of quantum cryptography — notification of any attempts to intercept messages. E.g., Canadian start-up Quantum Numbers Corp.
Digital Post-Quantum Signature	Protocols for electronic digital signatures exist to ensure the integrity of electronic documents, as well as the authenticity and non-repudiation of their authors. With the advent of quantum computers, digital signature algorithms potentially lost their durability since they were based on problems that classical computers could solve with less efficient algorithms. A quantum hash function with a set of qubits converts the original key into a quantum state, which increases the security of signatures. E.g., French start-up CryptoNext
Quantum-Safe Cryptography	Advancements in quantum computers have enabled cracking commonly used encryption algorithms like RSA and Elliptic Curve Cryptography (EEC) with speed compared to traditional computers. Quantum-safe cryptography addresses this security threat by updating the certificates with quantum-safe protocols. The main success in the field of quantum-safe cryptography was the creation of practical encryption algorithms based on lattice theory. These algorithms are based on linear algebra and include the problem of finding the shortest vectors. E.g., Singaporean company Sixscape
Post-Quantum Encryption	Commonly used encryption algorithms and other Advanced Encryption Standards (AES) such as 128 bits or 256 bits are easily crackable with the help of quantum and cloud computing. Post-quantum encryption allows for implementing algorithms to crack any passwords relatively quickly based on current encryption algorithms. E.g., Taiwanese company Flipscloud

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