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Uncovering technology for business

Application of Quantum Technologies in Business and Trainings on Quantum Technologies

Current Scenario and Future Trend

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1. Application of Quantum Technology in Business

1.1 Background

Quantum technologies are increasingly recognized as a transformative force across various industries. The transition from classical to quantum computing is poised to revolutionize fields that rely on complex computations, simulations, optimization, and secure communications. Quantum technology, encompassing quantum computing, quantum communication and security, quantum sensing, and quantum simulations, is evolving rapidly, with applications emerging in finance, healthcare, logistics, and manufacturing (IQM, 2024; McKinsey & Company, 2024; Meige et al., 2022; World Economic Forum, 2024).

The quantum computing, a prominent aspect of the quantum technologies, is listed as an important field of Deep Tech Technologies by the European Institute of Innovation and Technology (EIT) (European Institute of Innovation & Technology (EIT), 2023). Deep Tech is a phenomenon that refers to advanced and emerging technologies which have the potential to revolutionize industries, disrupt existing markets, or create entirely new ones. However, like many other fields of Deep Tech, such as 5G communications and Web 3.0, quantum technology requires extensive investments in research and development (R&D) and time to be mature to be fully utilized in real business applications. On the other hand, quantum computing promises high competitive advantage for businesses and significant entry barrier for competitors due to its complex underlying intellectual properties, similar to many other Deep Tech Technologies (de la Tour et al., 2019).

In recent years, quantum computing has achieved some significant milestones. One of the biggest recent breakthroughs is Google's quantum chip, *Willow*, which reportedly performed a benchmark computation under 5 minutes that would potentially take around 10 septillion years (25 zeros after 1) to perform by the fastest classical supercomputer exists in the world now. This chip also has the potential to reduce the error in quantum computing exponentially to a record low compared to any other existing quantum computers (Neven, 2024). Such innovation is a testament to the commitment of the big tech giants to promote the quantum technology and its immense potential to bring a transformative change in the world.

According to a survey conducted by D-Wave among enterprises, 21 percent of respondents stated that they have either already adopted quantum technology in their business to some extent or planning to adopt by the next 12-18 months. This adoption rate is 50% higher compared to that of the year 2022 (Daigle, 2024). As quantum technologies evolve, Gartner has provided estimates on the future of the quantum computing business in one of its reports (Gupta, 2024). According to Gartner, the quantum computing business will be at very initial phase from 1 to 3 years starting from 2025. In 2030, the industry will observe some specific use cases for the next 3 to 5 years (D-Wave, 2020; IBM, 2024). The technology is expected to be mature by 2035 with expanded ecosystems and wide adoption.

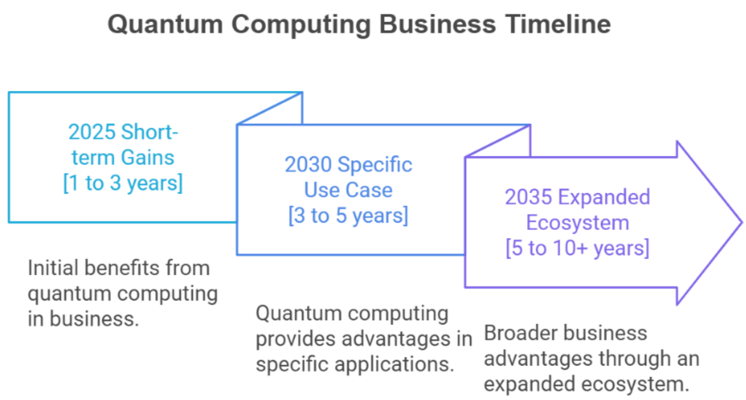

Figure 1. *Quantum Computing Business Timeline.*

Note: This figure is adapted from the report 'What Is Quantum Computing? And Why Executives Should Care'. *Gartner*. September 20, 2024. https://www.gartner.com/en/articles/quantum-computing

However, despite all speculations and assumptions, globally the quantum technology industry has gained more than 40 billion euro (42 billion USD) public sector investments. With another 8.15 billion euro (8.5 billion USD) investment in the global start-up ecosystem (McKinsey & Company, 2024). According to a report of the World Economic Forum, the global market of quantum technology is expected to be more than 100 billion euro (106 billion USD) by 2040 (World Economic Forum, 2024). With increasing effort in the field of quantum technology from both the public and private entities, it is expected that quantum technology will generate more value for businesses and create new avenues for aspiring professionals in the near future. According to a report by the Quantum Insider (2024), there will be around 250 thousand new jobs in the field of quantum technology by 2030 which is likely to increase by more than 840 thousand in 2035. It is high time for entrepreneurs, business leaders, professionals, and students to get familiar with quantum technology and stay ahead of this emerging race.

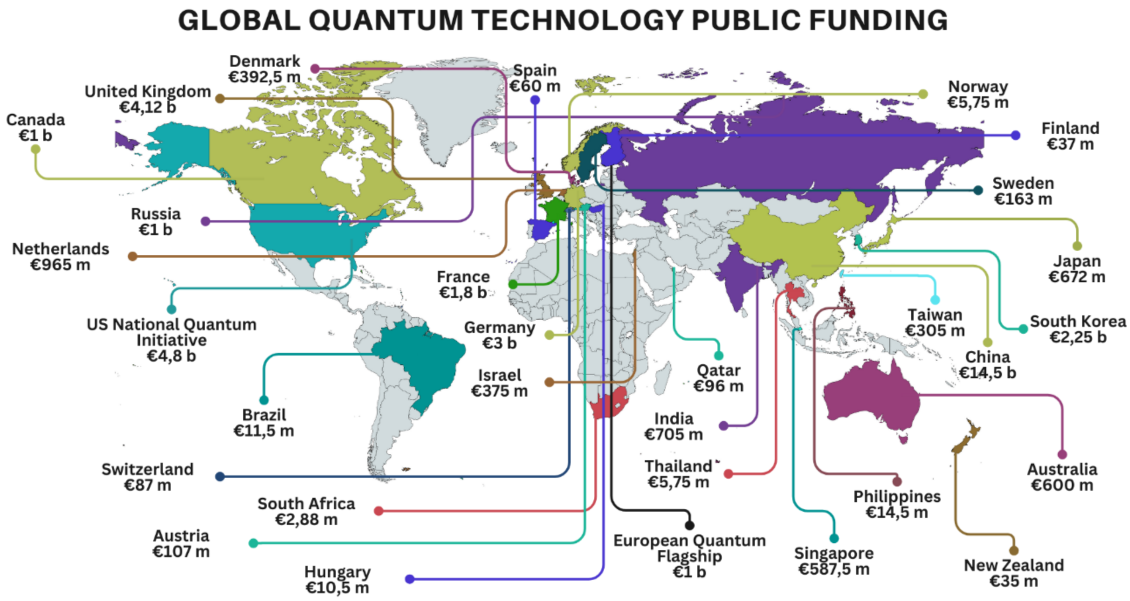

Figure 2. *Global Quantum Technology Public Funding.*

Note: The data is adapted from the report 'Quantum Initiatives Worldwide 2024'. *QURECA*. Updated on October 23, 2024. https://www.qureca.com/quantum-initiatives-worldwide/ (Accessed on December 28, 2024). The data is converted to Euro (€) from USD ($).

1.2 Quantum Technology Categories

Quantum technology is an umbrella term which includes various fields that utilize the quantum principles. According to the current stage of technological advancement, we can divide quantum technology into four major fields as shown in the following Figure 3; Quantum Computing, Quantum Communication & Security, Quantum Sensing, and Quantum Simulation.

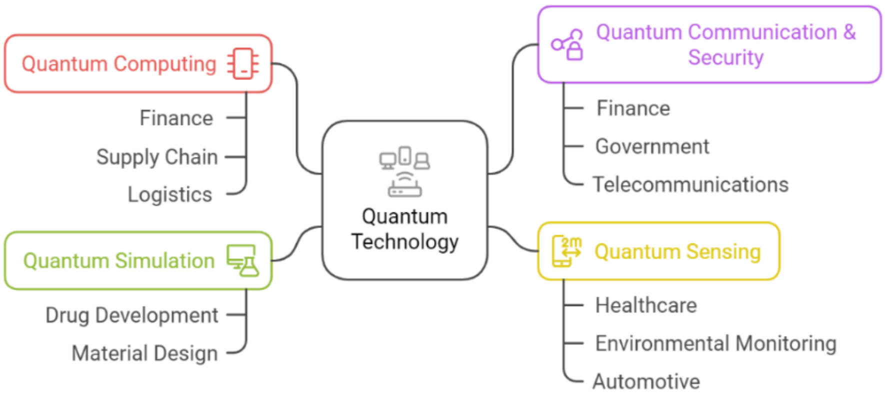

Figure 3. *Major Fields of Quantum Technology.*

1.2.1 Quantum Computing

Quantum computing utilizes quantum mechanics to perform computations beyond the reach of classical computers. Quantum computers have the potential to solve certain complex problems, making them invaluable for industries like finance, pharmaceuticals, and logistics. Quantum computing's unique capability to process multiple states simultaneously allows it to process and optimize vast datasets for decision-making, which is currently being applied various industries including supply chain optimization, logistics planning, investment portfolio optimization, and so on (KPMG, 2021; Meige et al., 2022).

1.2.2 Quantum Communication & Security

Quantum communication, through technologies like Quantum Key Distribution (QKD), provides unbreakable data encryption, which is critical as quantum computing advances. Businesses are particularly interested in quantum communication for secure data transfer in finance, government, and telecommunications sectors (How & Cheah, 2023; Meige et al., 2022). Quantum networks, though in early stages, promise highly secure communication channels that would mitigate risks associated with sensitive data transmission, ensuring privacy and protecting against cyber threats (Ukpabi et al., 2023).

1.2.3 Quantum Sensing

Quantum sensing allows precise measurements of variables such as magnetic fields, gravity, and temperature. Quantum sensors are expected to improve precision in sectors such as healthcare, environmental monitoring, and automotive industries. Applications include advanced medical diagnostics, environmental sensing, and infrastructure monitoring, offering the potential to detect even minute changes in magnetic or gravitational fields with unprecedented accuracy (Bova et al., 2021; Meige et al., 2022; Ukpabi et al., 2023).

1.2.4 Quantum Simulation

Quantum simulators provide a promising tool for performing complex simulation tasks. Previously, analog quantum simulators, which do not utilize gate-based qubit systems, were primarily used as laboratory tools for conducting quantum physics-related simulations. However, with the advancement of technology, gate-based, general purpose state-of-the-art computing technology now enables users to apply quantum simulations to solve more industry-specific problems. Use cases include biological molecule simulations for drug development and biochemical process simulations for new designing new materials (Meige et al., 2022).

1.3 Theory of Quantum Computing Simplified

Quantum computing is a revolutionary approach to computation that leverages the principles of quantum mechanics to perform calculations that are infeasible for classical computers. Unlike classical computers, which use bits as the smallest unit of information (represented as either 0 or 1), quantum computers use quantum bits or **qubits**. Qubits can exist in a superposition of states, meaning they can be both 0 and 1 simultaneously. This property allows quantum computers to explore multiple solutions to a problem at the same time, enabling them to solve certain types of problems exponentially faster than classical computers.

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1.3.1 Classical Bits

In classical computing, the smallest unit of information is a **bit**, which can exist in one of two states: 0 or 1. Mathematically, a bit can be represented as:

$$Bit \in \{0,1\}$$

For example, a classical computer might represent the number 5 as a sequence of bits: 101.

1.3.2 Quantum Bits (Qubits)

A **qubit**, on the other hand, is the quantum analogy of a classical bit. Unlike a classical bit, a qubit can exist in a **superposition** of states, meaning it can be in a combination of 0 and 1 simultaneously. Mathematically, the state of a qubit is represented as a vector in a two-dimensional complex Hilbert space (Ezratty, 2021):

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Here:

- $|\psi\rangle$ is the quantum state of the qubit.
- $|0\rangle$ and $|1\rangle$ are the basis states, analogous to classical 0 and 1.
- α and β are complex numbers representing the probability amplitudes of the qubit being in state $|0\rangle$ or $|1\rangle$, respectively.
- The probabilities of measuring the qubit in state $|0\rangle$ or $|1\rangle$ are given by $|\alpha|^2$ and $|\beta|^2$, where $|\alpha|^2 + |\beta|^2 = 1$.

For example, a qubit in an equal superposition of $|0\rangle$ and $|1\rangle$ can be written as:

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

This means there is a 50% chance of measuring the qubit as 0 and a 50% chance of measuring it as 1.

1.3.3 Key Principles of Quantum Computing

Superposition: A qubit can exist in a state that is a combination of 0 and 1, this phenomenon is referred to as superposition. This means a quantum computer can process a vast number of possibilities simultaneously. For example, while a classical computer would need to evaluate each possible solution one at a time, a quantum computer can evaluate many solutions in parallel.

Entanglement: Qubits can be entangled, meaning the state of one qubit is directly related to the state of another, even if they are physically separated. This phenomenon allows quantum computers to perform complex computations more efficiently by correlating information across qubits.

Quantum Interference: Quantum algorithms are designed to amplify the probability of correct solutions and cancel out incorrect ones through interference. This ensures that the most likely answer to a problem is the one that emerges from the computation.

Quantum Gates: Quantum gates manipulate qubits through operations that change their states. These gates are the building blocks of quantum algorithms, similar to how logic gates are used in classical computing.

1.3.4 Types of Quantum Computers

Quantum computers can be broadly categorized into two types based on their computational approach:

1. **Gate-Based Quantum Computers**:

These computers operate similarly to classical computers but use quantum gates to manipulate qubits. Quantum gates are represented by unitary matrices that act on the state of qubits. For example, the Pauli-X gate (quantum NOT gate) is represented as (Ezratty, 2021):

$$q \; - \boxed{X} - \; q'$$

with associated unitary matrix:

$$x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Some other common quantum gates are Pauli-Y, Pauli-Z, Hadamard (H), CNOT, Toffoli, SWAP, and Fredkin gate. Gate-based quantum computers are universal, meaning they can perform any quantum computation given enough qubits and gates. Examples of gate-based quantum computers include IBM's quantum computers, Google's Willow, and Rigetti's quantum computing devices.

2. **Quantum Annealers**:

These computers are designed to solve optimization problems by finding the minimum energy state of a system. Quantum annealers use the principle of adiabatic quantum computation, where the system evolves slowly from an initial state to a final state that represents the solution to the problem. They are not universal quantum computers but excel at specific tasks like optimization. These devices utilize so called low-quality qubits, positioning them between classical supercomputers and gate-based universal quantum computers in terms of performance. However, they are more error-prone, and all quantum annealing algorithms require some pre-processing on classical computers. The most well-known example is D-Wave's quantum annealer (Ezratty, 2021).

1.3.5 Architecture of Quantum Computers

The architecture of quantum computers typically consists of the following layers:

Quantum Hardware: The physical qubits and control systems that perform quantum operations.

Quantum Gates and Circuits: Quantum algorithms are implemented as sequences of quantum gates, which manipulate qubits. These sequences are called quantum circuits.

Quantum Compilers: Compilers translate high-level quantum algorithms into low-level instructions that the quantum hardware can execute. They optimize the circuits to reduce errors and improve efficiency.

Quantum Algorithms: These are the high-level algorithms designed to solve specific problems, such as Shor's algorithm for factoring or Grover's algorithm for search.

Classical Interface: Quantum computers are often used in conjunction with classical computers. The classical interface manages input/output, pre-processing, and post-processing of data.

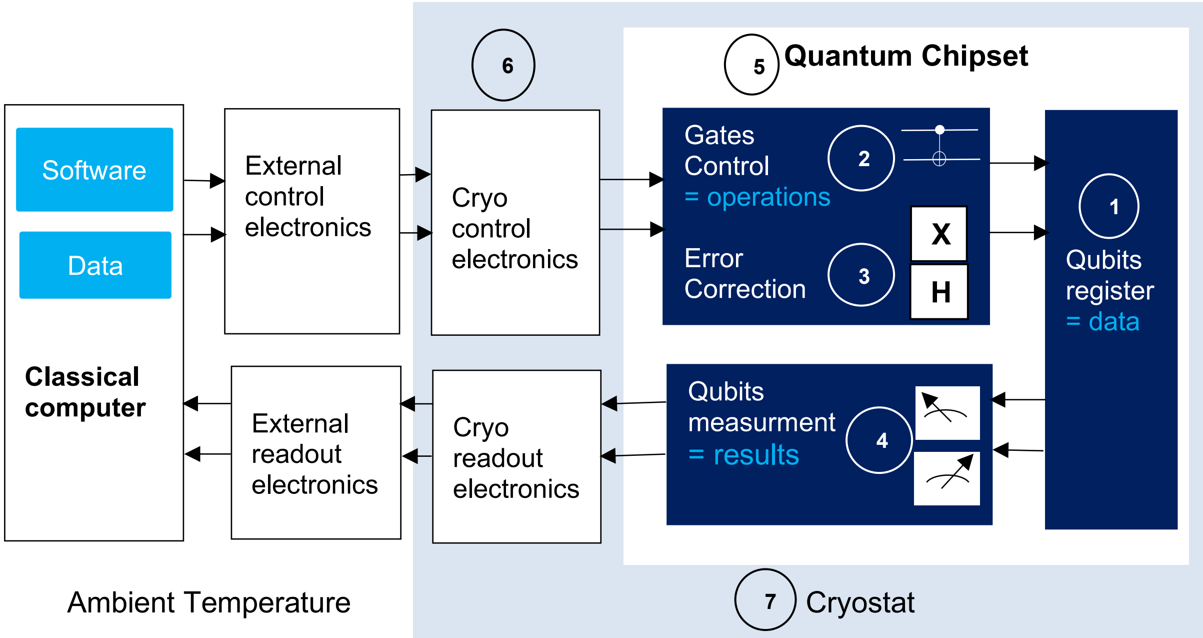

Figure 4. Architecture of Quantum Computers (Ezratty, 2021).

1.4 Quantum Computing Tools for Business

The technology of quantum computing is still in a premature stage and setting up a physical quantum computer requires significant investment and involves substantial technical complexity. To address these challenges, major quantum computing companies offer Quantum Computing as a Service (QaaS) solution, similar to cloud computing, to make quantum computing more accessible to businesses. Developers can access quantum computers from their classical computers through the cloud to explore the potential applications of quantum computing in their business use cases. Many big tech companies, including IBM, D-wave, Amazon, Microsoft, and Google offer such QaaS solutions. The following tables lists prominent QaaS tools along with the specifications of their underlying quantum computing technologies.

Table 1. *Existing Quantum Computing Tools for Businesses.*

QaaS	QPUs (Quantum Computers)	Programming Language	Software Development Kits (SDKs)
IBM Quantum Platform	Gate-based superconducting qubits (Eagle, 127 qubits)	Python	Qiskit, Qiskit Aer, IBM Quantum Composer.
D-Wave Leap	Quantum annealers (Advantage, 5000+ qubits)	Python	Ocean SDK.
Amazon Braket	IonQ (trapped-ion qubits), IQM, Rigetti (superconducting qubits)	Python	Braket SDK.
Microsoft Azure Quantum	Rigetti (superconducting qubits), Quantinuum, IonQ (trapped-ion), Pasqal (neutral-atom), QCI (error correction)	Q#, Python	Microsoft Quantum Development Kit (QDK), Quantum simulator in QDK.
Google Quantum AI	Willow processor (superconducting qubits)	Python	Criq.
rigetti QCS	Superconducting qubits (Ankaa-3, 84 qubits)	Python	Forest SDK, Quil, Rigetti Quantum Virtual Machine (QVM).
IONQ	Trapped-ion qubits (Aria, 25 qubits)	Python	Integration with Amazon Braket and Azure Quantum, IonQ simulator.
QUANTINUUM	Trapped-ion qubit (System Model H2, 56 qubits)	Python	tket, Quantinuum simulator.
XANADU	Photonic quantum computers (X8)	Python	PennyLane, Strawberry Fields simulator.

Note: The above table is constructed based on available public information up to January 23, 2025. Xanadu introduced their latest photonic quantum computer, Aurora, on January 22, 2025. Aurora contains 35 photonic chips (24 qubit source chips, 6 multiplexer chips, and 5 quantum processing unit (QPU) chips) and promises better scalability compared to Xanadu's X-series quantum computers. However, Aurora's integration into Xanadu's cloud service is not reported (Vernon, 2025).

1.5 Industry-Specific Applications

According to a recent report by McKinsey & Co. (2024), quantum computing is estimated to unlock over €1.9 trillion in business value by 2035. Though the challenge still remains in terms of hardware limitations, software unavailability, talent shortage, and so on. The primary application areas for quantum computing include finance, healthcare and life sciences, supply chain and transportation management, and manufacturing industries. The following figure illustrates the major application areas of quantum computing for businesses.

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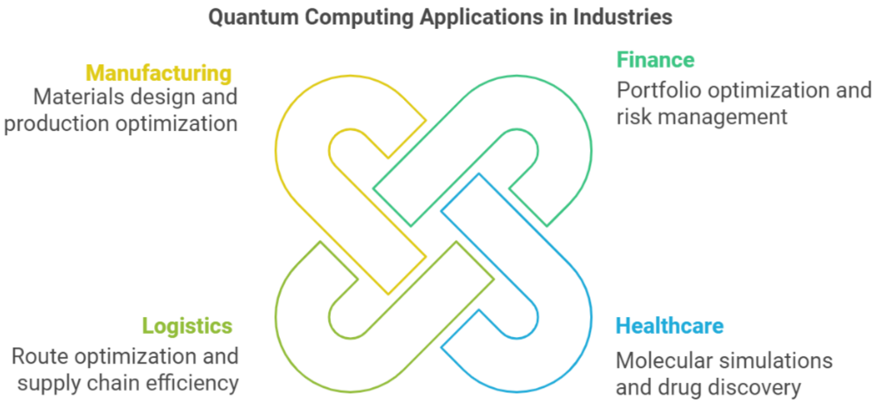

Figure 5. *Quantum Computing Use Cases.*

1. **Finance:** The financial industry stands to benefit significantly from quantum computing's optimization capabilities. For instance, quantum algorithms can optimize asset allocation, portfolio risk management, and fraud detection. Financial institutions are already exploring quantum-inspired algorithms to model financial markets and assess risk, which could yield faster and more accurate predictions (Nurmi et al., 2022; Sodhi & Tayur, 2022).

2. **Healthcare and Pharmaceuticals:** Quantum computing's ability to simulate molecular structures and reactions is valuable in drug discovery and genomics. For example, quantum simulations can reduce the time needed to develop new drugs by predicting molecular interactions accurately. Pharmaceutical companies are leveraging these capabilities to create personalized medicine solutions and identify potential drug candidates faster than conventional methods (How & Cheah, 2023; Meige et al., 2022).

3. **Logistics and Supply Chain Management:** Optimization is a core challenge in logistics, and quantum technology can significantly enhance efficiency. Quantum algorithms for route optimization, inventory management, and supply chain logistics can streamline operations, reduce costs, and improve delivery times. Companies like D-Wave have demonstrated how quantum-inspired solutions can cut computation times drastically, as in logistics route optimization where results that once took hours can now be achieved in minutes (D-Wave, 2020; How & Cheah, 2023; Saltan &

Hyrynsalmi, 2022).

4. **Manufacturing and Automotive:** The automotive industry can benefit from quantum simulations for materials science applications, such as battery research and lightweight materials for electric vehicles. Quantum technology's optimization algorithms are also applicable in scheduling and production optimization, enabling manufacturers to enhance productivity while minimizing waste (Bova et al., 2021; Saltan & Hyrynsalmi, 2022).

The following table lists a few companies that already have implemented quantum computing to some extent to solve some of their specific business problems.

Table 2. *Use Cases of Quantum Technology across Various Industries.*

Quantum Application	Company	Technology	Reference
Portfolio Optimization	Quantbot Technologies	Quantum-Inspired Optimization	Sodhi & Tayur (2022)
Drug Discovery	GSK , Astex Pharmaceuticals	Quantum Computing for Molecular Simulation	Sodhi & Tayur (2022)
Route Optimization	Save-On-Foods	Hybrid Quantum-Classical Computing	D-Wave (2020)
Financial Risk Management	JP Morgan Chase	Quantum Machine Learning	Sodhi & Tayur (2022)
Battery Design	Volkswagen	Quantum Simulation	Volkswagen (2022) Delgado et al. (2022)
Secure Communication	KETS Quantum Security	Quantum Key Distribution (QKD)	Bova et al. (2021)
Quantum Computers	IBM	Quantum Computing	Saltan & Hyrynsalmi (2022)
Logistics and Supply Chain	D-Wave (collaboration with logistics companies)	Quantum-Inspired Optimization	D-Wave (2020)

1.6 Training Needs in the Field of Quantum Technology

In a recent study, Greinert et al. (2024) stakeholders from 34 companies working in the field of quantum technology, including SMEs, start-ups, and large corporations, to identify the skill needs within the industry. The study reveals that, with the progress of quantum technology, the industry has seen an increasing need for junior professionals and engineers with quantum awareness along with highly trained experts like PhDs. Since many companies offer classical-quantum hybrid solutions, SMEs see upskilling classical engineers with quantum awareness as an option to leverage these solutions.

Statistics show that around 46% of interviewees emphasized the need for engineering roles, 17% highlighted physics-related roles, and only 11% mentioned business-related roles. This indicates high demand for engineers in the field of quantum technology. In terms of training needs, quantum awareness is identified as the most demanding topic for business people whereas engineers need tailored training and hands-on experience on both quantum software and hardware. The following figure illustrates the quantum training needs as identified by Greinert et al. (2024).

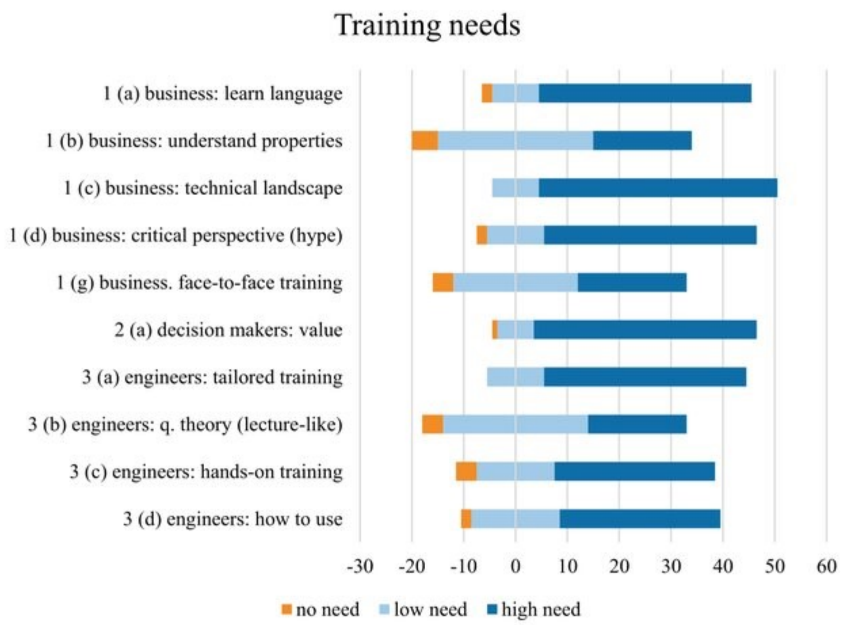

Figure 6. Quantum Training Needs (Greinert et al., 2024).

2. Existing Courses & Trainings on Quantum Technology

The ongoing efforts of promoting education on quantum technology are primarily led by the big tech giants working in this field. One of the top players in the field of quantum technology, International Business Machines Corporation (IBM), offers extensive learning resources on quantum computing from basics to advance through their IBM Quantum Learning platform. D-Wave Systems Inc., another leading quantum computing company, also provides free courses, training, and webinars on quantum computing. Google also offers learning resources on quantum computing through Coursera and on their own platform. However, most of these courses are focused on specific tools aiming to prepare workforces for businesses to utilize their quantum computing system. In addition to these courses, established online learning platforms like MIT xPRO, Oxford University Continuing Education, Stanford Online, etc. offer various courses on quantum technology. These courses widely vary in terms of target audience, focus topics, and difficulty level.

In Europe, initiatives like Quantum Flagship, European IT Certification Institute (EITCI), and QuTech Academy offer different courses and certifications on quantum technology ranging from beginners' level to professional. European quantum computing companies like IQM from Finland offers comprehensive training on quantum computing through their IQM Academy initiative. Besides all these institutional efforts, there exist some courses available on online platforms like Udemy which are taught by different individuals. A list of existing courses on quantum technology along with their target audience, focus topics, and other relevant information is given below.

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Table 3. Existing Courses on Quantum Technology.

Course Name	Organization	Mode	Type	Target Audience	Prerequisites	Focus Area	Programming Content (QC)	Duration	Certification	Course Link
Series of Courses	IBM	Online - Recorded	Free	Basics to Advanced	Linear Algebra, Real Analysis, & Python Programming	Basic Science, Quantum Computing - Hardware, Software, Algorithm, Business, and Use Cases	Qiskit, IBM Quantum Composer	Series of lectures	Yes	Link
Series of Courses	D-Wave	Online – Recorded with Live Support	Paid	Basics to Advanced	Python, Familiarity with Matrix Operations, Math Equations, & Graphs	Quantum Programming	Ocean SDK, D-Wave Leap	Series of lectures	Yes	Link
Series of Course & Tutorials	Google	Online - Recorded	Free with paid certificate	Students, Educators, Researchers	Python Programming	Quantum Computing – Simulation, Error Correction, AI	Stim, Cirq, TFQ, Crumble, OpenFermion	Series of lectures	Yes	Link
Series of Courses	Microsoft	Online - Interactive	Free	Developers, Professionals, and Students	Linear Algebra, Familiarity with Azure and VS Code	Quantum Computing – Basics, Programming	Q#	Series of lectures	Yes (Badge)	Link
A Practical Introduction to Quantum Computing	CERN	Online - Recorded	Free	Scientists, Engineers, Students, STEM Graduates	Linear algebra, Python (Basics)	Quantum Computing - Hardware, Software, Algorithms, ML	Qiskit, D-Wave Leap	Series of lectures	No	Link
Quantum Computing Course in Quantitative Finance	CQF	Online - Recorded	Paid	Quantitative Finance Professionals, Data Scientists	Finance, Mathematics, Python	Quantum Computing - Software, Finance Applications	Qiskit	6 Month+	Yes	Link
EITCA/IS Information Technologies Security Academy	EITCA Academy	Online - Recorded	Paid	IT Professionals, Cybersecurity Specialists	No formal prerequisites	Cryptography, Network Security, Penetration Testing	No	150-180 hours	Yes	Link
Quantum Technologies	FedLearn	Online - Self-paced	Paid	Generalists, STEM Enthusiasts	None	Bsics of Quantum Technology & QT Economy	No	90-120 minutes	Yes	Link
IQM Academy: Foundations of Quantum Computing	IQM Quantum Computers	Online - Interactive	Free	Students, Educators, Enthusiasts	None	Basic Science, Quantum Computing - Hardware, Software	Qiskit	Self-paced	No	Link
Quantum Computing Essentials	University of Jyväskylä	Online - Self-paced	Free	Generalists, Students, STEM Graduates	No formal prerequisites	Basic Science & Mathematical Concepts of QC	No	2 ECTS Each (Part A, B)	No	Link
Understanding Quantum Computers	Keio University	Online - Self-paced	Free with paid upgrade	Professionals, Students, STEM Graduates	Basics of maths & probability	Basic Science, QC - Hardware, Software, Algorithms	No	4 weeks (5 hours/week)	Yes	Link
Quantum Computing Fundamentals	MIT xPRO	Online - Self-paced	Paid	Professionals, Business Leaders	Basics of linear algebra, Q Mechanics	Quantum Computing - Hardware, Software, Algorithms, Simulations	Qiskit	8 weeks (4-6 hours/week)	Yes	Link
Quantum Science, Networking, and Communications	UChicago	Online - Live	Paid	Early/Mid-career Professionals	Linear algebra, probability, Python	Basic Science, Q Programming, Q Networking & Communication	Qiskit, SeQUeNCe	8 weeks	Yes	Link
Quantum Computing	Stanford University	Online, instructor-led	Paid	Graduate/Advanced Undergraduate Students	Linear algebra, probability, algorithms, Q Mechanics	Basic Science, Quantum Algorithms, Quantum Error Correction	Not Specified	10 weeks (9-15 hours/week)	Yes	Link
Online Quantum Skills Course	NQCC	Online - Self-paced	Free (for UK residents)	STEM Students, Early-career Professionals	No formal prerequisites	Basic Science, Quantum Computing - Hardware, Software	Yes (Not Specified)	3 months access	Yes	Link
Quantum Computing	University of Oxford	Online - Live	Paid	STEM Students, Professionals	Basics of linear algebra, Python programming	Quantum Computing - Hardware, Software, Algorithms, ML	Qiskit	2-day intensive course	Yes	Link
Quantum 101-Quantum 301	QuTech Academy	Online - Self-paced	Free with paid certificate	Basics to Advanced	No formal prerequisites for the 1st course	Quantum Computing - Hardware, Software, ML, Algorithms, Simulations	OpenQL	6 weeks/course (6-8 hours/week)	Yes	Link

Most of the above listed courses include some programming content in their syllabus for demonstrating quantum computing in practical aspects. With a big and active user community and comparatively easy access, IBM's quantum computing environment and their python-based framework Qiskit is the most used programming tool by the educators. Some other tools are D-Wave's Ocean SDK, D-Wave Leap, Criq, and Q# etc.

2.1 Methods of Quantum Technology Teaching

According to a report by Cervantes et al. (2021), 24% of 305 surveyed U.S. institutions offer at least one Quantum Information Science (QIS) course. Quantum computing education has emerged as a multidisciplinary field, offering diverse teaching approaches tailored to various audiences, from high school students to professionals. Studies suggest that educators utilized different teaching methods ranging from hands-on programming-focused initiatives to abstract logic-based frameworks, emphasizing accessibility while addressing the complexity of quantum concepts. Incorporating tools like IBM Qiskit, Q#, and visual interfaces, these programs aim to bridge the gap between theory and application. However, challenges such as steep learning curves, resource limitations, and varying student backgrounds remain prevalent. The following table presents the summary of key teaching approaches, their highlights, and challenges, providing a comprehensive overview of the evolving quantum education landscape.

Table 4. *Summary of Different Quantum Education Methods.*

Highlights	Challenges
1. Computer Science-Oriented Quantum Computing Education (Salehi et al., 2022)	
- Introduces quantum computing as a generalization of probabilistic computing through linear algebra, bypassing traditional physics-heavy concepts. - Uses task-based quantum programming with Qiskit to reinforce learning. - Pre/post-test results showed statistically significant knowledge acquisition across diverse	- Dense material makes it challenging for participants to complete tasks within a 3-day workshop format. - High-level abstract content might still be inaccessible for those without sufficient linear algebra or Python programming background. - Limited to basic knowledge as defined

Highlights	Challenges
STEM backgrounds. - Workshops were conducted in 10 countries for inclusivity.	by Bloom's Taxonomy.
2. Practical Software-Driven Quantum Computing Education (Mykhailova & Svore, 2020)	
- Focused on hands-on programming using Q# and the Microsoft Quantum Development Kit. - Emphasized algorithm implementation over theoretical proofs, making it accessible for undergraduates. - Utilized "Quantum Katas," an open-source set of programming exercises, for active learning and immediate feedback. - Final projects integrated programming with research, enhancing practical skills and teamwork.	- Steep learning curve due to the complexity of quantum programming assignments. - Programming competition tasks were considered too challenging by many students. - Lack of dedicated programming lab time hindered student progress. - High workload and advanced topics, such as quantum chemistry, were difficult for students with basic mathematical backgrounds.
3. Spiral Curriculum with Visual Representation in MOOCs (Liu & Franklin, 2023)	
- Utilizes a spiral curriculum to gradually build complexity, starting with visual representations of qubits and circuits. - Transitioned to mathematical notation after foundational concepts, ensuring no drop in engagement. - Modules were segmented with short, engaging video lectures to sustain focus. - Emphasized accessibility, requiring only basic algebra as a prerequisite.	- Retention rate decreased steadily across modules, though not drastically. - Visual representation sometimes caused students to struggle when transitioning to mathematical notation. - Misalignment between visual and mathematical concepts for entanglement required further refinement.
4. Hands-On Quantum Computing Education at Multiple Levels (Tappert et al., 2019)	
- Offered graduate courses, high school modules, and experimental demonstrations. - Utilized IBM Q Experience and Qiskit for practical exercises. - Emphasized mathematical foundations with weekly math sessions. - Integrated projects like Grover's Algorithm,	- Graduate-level course: Heavy workload with reliance on supplemental material. - High school modules: Limited coverage of complex topics like quantum algorithms. - Logistical challenges with IBM Q platform access and simulator wait

Highlights	Challenges
portfolio optimization, and machine learning using quantum computing. - High school curriculum introduced qubits, gates, and quantum concepts to encourage early adoption.	times. - Lack of standardized terminology in quantum computing led to confusion among students.
5. **Abstract Logic-Based Quantum Computing for Undergraduates** (Gatti & Sotelo, 2021)	
- Focused on abstract logic of quantum computing using Q# and Microsoft's Quantum Development Kit. - Practical programming emphasized, bypassing the need for prior knowledge of Quantum Mechanics or Modern Physics. - Covered foundational quantum algorithms (e.g., Grover's, Shor's) with hands-on projects for deeper learning. - Successfully implemented in a Latin American university, contributing to geographic diversity in quantum education.	- Time limitations restricted advanced topics like quantum error correction and fault tolerance. - Online delivery due to COVID-19 posed challenges for engagement and real-time feedback. - Diverse student backgrounds created variability in performance, with early-year students excelling in math but struggling with project implementation.
6. **Multi-Framework Quantum Programming for Beginners** (Carrascal et al., 2021)	
- Introduces quantum computing concepts using Qiskit, Cirq, PyQuil, Q#, and ProjectQ programming frameworks. - Practical exercises focus on arithmetic circuits (Vedral, Cuccaro, Draper adders). - Emphasizes graphical representations and tools for better understanding of circuits and quantum states. - Designed a structured four-step teaching roadmap: classical programming, graphical interface, framework usage, and algorithm exploration. - Surveys show high student engagement and motivation.	- Lack of consistent graphical output across frameworks (e.g., MQDK lacks visualizations). - Limited scope for advanced topics like fault tolerance or large-scale quantum memory due to hardware limitations. - Steep learning curve for frameworks with non-intuitive tools, such as Cirq's circuit adaptation requirements. - Variability in tool complexity impacts uniformity in teaching outcomes.
7. **Practical Programming-Focused Quantum Computing Education (CERN)** (Combarro et al., 2021)	

Highlights	Challenges
- Delivered through live and recorded lectures focused on hands-on quantum programming with minimal mathematical prerequisites. - Introduced topics not commonly covered in introductory courses, including quantum machine learning, annealing, and variational algorithms. - Utilized IBM Quantum Experience, D-Wave Leap, and Quirk simulators for practical exercises. - Surveyed participants showed significant perceived knowledge improvement, from 1.22 to 2.6 on a 5-point scale.	- Limited to introductory material due to time constraints (7 sessions, 14 hours total). - Diversity gap observed in participant demographics, with 88% male attendees. - Some participants reported challenges with advanced content despite practical emphasis. - High dropout rates after initial sessions in live attendance, though recorded versions mitigated impact.
8. Futures Thinking Integrated with Quantum Computing (Rasa et al., 2022)	
- Combined futures thinking with basic quantum computing concepts to foster agency and a pluralistic perception of futures. - Students engaged in scenario-building exercises (probable, possible, and preferable futures) and used backcasting techniques. - Quantum computing topics like superposition and entanglement introduced alongside socio-scientific problems. - Participants reported improved agency, creativity, and connections to future scenarios.	- Abstract nature of quantum computing made it difficult for students to relate to practical applications. - Limited time (20 hours across three sessions) constrained deeper exploration of quantum concepts. - Some students struggled with connecting futures thinking lessons with quantum computing topics, citing a lack of cohesive integration.
9. Hands-On Quantum Computing for High-School Students (Angara et al., 2022)	
- Introduced using "unplugged" activities like doughnuts to visualize qubits and entanglement. - Practical programming with IBM Qiskit and Jupyter notebooks to simulate quantum circuits. - Included quantum games like Entanglion to reinforce concepts interactively. - Covered foundational topics (e.g., superposition, entanglement) with minimal prerequisites, making quantum computing	- Time constraints limited in-depth exploration of quantum algorithms. - Online workshops faced interactivity challenges due to limited student engagement in virtual settings. - Advanced topics like teleportation and programming faced comprehension difficulties among students with no prior programming experience. - Low retention rate beyond

Highlights	Challenges
accessible to high-school students.	introductory concepts.
10. Teaching Quantum Computing Without Prerequisites (Temporao et al., 2022)	
- Targeted audiences without formal mathematical or programming backgrounds. - Focused on quantum computing fundamentals using hands-on programming tools like Qiskit. - Covered quantum gates, circuits, and basic algorithms (e.g., Deutsch-Jozsa, Grover's) through guided exercises. - Participants appreciated the low barrier to entry and practical emphasis. - Employed active learning techniques such as collaborative problem-solving sessions.	- Advanced topics like Shor's algorithm were excluded to maintain accessibility. - Limited to small class sizes due to intensive one-on-one guidance requirements. - Short duration (one-week intensive workshop) constrained deeper conceptual learning. - Students with prior experience found the pace too slow.
11. Optics-Based Quantum Computing for High School Students (Walsh et al., 2020)	
- Introduced quantum computing concepts via classical optics, such as light polarization, before delving into mathematical formalism. - Incorporated real and virtual experiments using platforms like IBM's Quantum Composer and UT's Virtual Quantum Optics Lab. - Developed technical STEM skills (e.g., matrix algebra, Python programming) alongside conceptual understanding. - Encouraged collaborative problem-solving through group activities and cloud-based tools like Google Colab and Discord.	- Online learning during COVID-19 reduced group engagement and interactivity. - Limited time for advanced quantum computing concepts, such as error correction. - Students struggled to connect optics-based approaches to broader quantum computing applications. - High dependence on teacher expertise to integrate tools like Quantum Composer effectively.

Quantum technology is predominantly a physics-heavy subject. Learning quantum technology through physics-oriented approaches typically requires prior knowledge of the theory of light and waves, equivalent to at least one semester of modern physics coursework (Salehi et al., 2022). To make quantum technology accessible to a broader audience, educators have adopted alternative approaches. Among the studies listed above, over 80% (9 out of 11) of educators utilized different techniques other than physics-oriented methods. These approaches include introducing quantum principles through linear algebra and probability theory, gamification, programming-focused strategies, and futures thinking. Only Walsh et al. (2020) and Tappert et al. (2019) reported physics-oriented teaching approaches that include topics like light polarization and theoretical aspects of quantum mechanics. The alternative teaching methods are perceived as more effective in introducing quantum technology to multidisciplinary audiences with minimal familiarity with linear algebra, probability, graphs, and programming.

3. Current Challenges and Future Directions

While the potential applications of quantum technology in business are substantial, several challenges remain. Quantum computing hardware, for example, struggles with stability and error rates, as qubits are highly susceptible to interference and often require cryogenic environments (Meige et al., 2022). Companies like Nokia are advancing research in photonic and topological quantum computing, which could alleviate some of these challenges by allowing quantum computers to operate at room temperature and maintain stability over longer periods (Nokia, 2024). Additionally, hybrid quantum-classical computing solutions offer a near-term alternative, allowing businesses to gain computational advantages without waiting for fully scalable quantum systems (Meige et al., 2022).

Furthermore, the talent gap in quantum technology remains a significant barrier. Despite the growing number of universities offering quantum-related programs, there is a shortage of skilled professionals to meet the demand, necessitating early investment in talent development (How & Cheah, 2023). According to a recent report by Quantum Insider (Swayne, 2024), the demand for quantum specialists in the United States vastly outpaces supply. It is estimated that only one out of every three quantum job openings will be filled by 2025. Another survey conducted among members of the Quantum Economic Development Consortium (QED-C) revealed that nearly 60% of companies did not meet their hiring goals for quantum professionals in 2023. Additionally, when positions were filled, 80% of companies reported that it took between two to six months to fill an open role, with some taking up to a year (MeriTalk, 2024).

The quantum education landscape also requires refinement. While most existing courses are highly focused on quantum computing, there are limited learning resources available on topics like quantum communication and sensing, particularly for a generalist audience compared to those for quantum computing. This aspect of quantum education requires further attention. Developing more learning materials on quantum communication and sensing, specifically for generalist audience with little technical background, would help business owners, executives, and professionals to understand the use cases and potential of these emerging technologies.

A significant gap also exists in hands-on training opportunities. The lack of internships and practical experience leaves many graduates unprepared for real-world quantum technology careers. The private sector's involvement in facilitating more internships and hands-on training for aspiring students could help bridge this gap. However, such opportunities remain limited at present.

4. Conclusion

Quantum technology presents an array of transformative applications that promise to reshape business operations across industries. With advances in quantum computing, communication, sensing, and security, businesses can unlock new efficiencies, enhance security, and address previously unsolvable problems. However, as these technologies evolve, it is essential for businesses to stay informed, invest in quantum-safe encryption, and prepare their infrastructure and talent pool for a quantum future.

Experts emphasize that companies adopting a proactive approach to quantum readiness will be well-positioned to leverage these breakthroughs and gain a competitive advantage. While a deep understanding of the underlying physics and science of quantum technology is not necessarily essential for business stakeholders, a basic understanding of its working principles, along with knowledge of potential use cases and applications, will be sufficient to realize its transformative potential.

Co-funded by
the European Union

5. Acknowledgement

This work has been done as a part of the QUANTUM+ project, funded by the Erasmus+ initiative of the European Union (EU), project ID: KA220-HED-2B8276A3.

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Co-funded by the European Union