RESEARCH AND PRACTICAL APPLICATIONS

Quantum start-ups, quantum investments, and quantum patents: driving the quantum technology revolution

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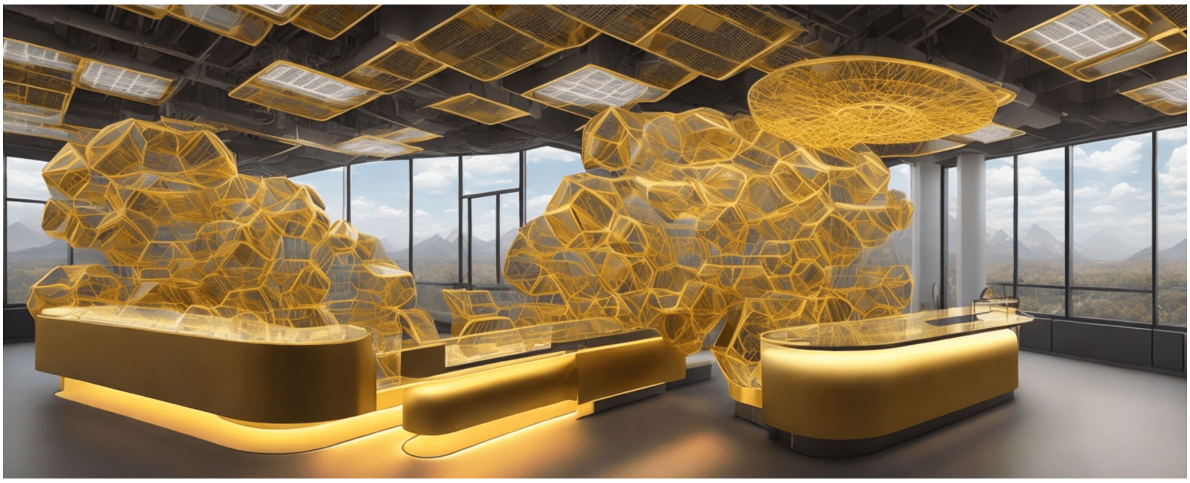

Quantum wires and planet Earth. Conceptualization: Luisa Quiroga

Quantum technologies have the potential to revolutionise various industry segments through its unprecedented capabilities in high-performance supercomputing, unconditionally secure communications, and ultraprecise sensing. At the forefront of this transformation are quantum start-ups, driving innovation and commercialisation in the field. These entrepreneurial ventures are attracting significant investments to fuel research and development efforts, while seeking robust patent protection to safeguard their intellectual property. In this article, we will explore the world of quantum start-ups, delve into the landscape of quantum investments, and analyse the significance of quantum patents in driving growth and competitiveness in this exciting field.

The rise of quantum start-ups

Quantum technology potential

Quantum technology holds tremendous potential across various domains, offering unprecedented conceptual capabilities and solutions to complex problems. In this section, we explore some of the key areas where the potential of quantum technology is particularly noteworthy:

- Quantum computing has the potential to tackle specific tasks that require outstanding computational power by leveraging quantum properties such as superposition and entanglement. Quantum computers can conceptually perform certain calculations exponentially faster than classical computers, enabling potential breakthroughs in areas such as optimisation, simulation, and machine learning. Quantum algorithms aim at tackling complex problems in fields like cryptography, material science, drug discovery, and financial modelling, which may lead to advancements and discoveries that are currently unattainable.

- Quantum communication offers secure and tamper-proof transmission of data. Quantum key distribution (QKD) protocols leverage the principles of quantum mechanics to enable the exchange of cryptographic keys that are inherently secure against eavesdropping. Additionally, the distribution of unique quantum resources such as entanglement will make it possible to construct the future quantum internet, which will connect all manner of quantum devices, from computers to memories and sensors. Quantum cryptography provides unbreakable encryption methods by ensuring the security and privacy of sensitive information, and making it particularly valuable for institutions and industries that deal with highly confidential data, such as healthcare, finance, critical infrastructure, and government institutions.

- Quantum sensing and metrology exploit quantum properties to achieve unprecedented levels of precision in measuring physical quantities. Quantum sensors are able to provide highly accurate measurements of parameters such as time, temperature, magnetic fields, and gravitational waves. This technology has immense potential in applications ranging from healthcare and environmental monitoring to defence and industrial processes, enabling enhanced diagnostics, improved navigation systems, and advanced scientific research.

- Quantum-powered devices. Quantum-enabled technologies may offer important solutions in many different areas, over and beyond those already mentioned. Devices that produce quantum randomness are a paradigmatic example of this, with applications “beyond quantum” in classical computing, classical cybersecurity and all products or services where random prime numbers are key. Novel lasers, detectors, image processing devices, atomic clocks, and many other innovative new products may arise from taming quantum matter and processes at new levels.

The potential impact of quantum technology extends far beyond these areas. Quantum simulations will help us model and understand complex physical and chemical systems, leading to advancements in materials, science, and chemistry, with broad applications in many industrial sectors. Quantum machine learning techniques may also complement classical artificial intelligence to boost certain areas of data analysis and pattern recognition, unlocking insights and driving innovation. However, it is important to note that quantum technologies are still in their infancy, and several formidable challenges – such as scaling up quantum systems, reducing errors and noise, and improving stability – are yet to be overcome. Nevertheless, the significant amounts of ongoing international research and development efforts in this area are producing rapid advances, to the extent that the general consensus is not so much whether, but rather when these challenges will be overcome.

Factors driving quantum entrepreneurship

The emergence of quantum start-ups is fuelled by several factors that drive the development and commercialisation of quantum technologies.

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Firstly, recent technological breakthroughs in quantum hardware and software have made it possible to build more robust, integrated and scalable quantum systems. These breakthroughs have reinforced the promise of future practical applications in computing and unlocked potential for communications and sensing, and thus created opportunities for quantum start-ups.

Secondly, in certain areas, there is a growing appetite to support deep-tech technologies with the potential to offer global breakthroughs in the medium term. Quantum technologies and their applications are a perfect example. This interest creates a favourable environment for quantum start-ups to thrive.

Thirdly, governments and private investors have recognised the strategic importance of quantum technology. Government agencies, venture capital firms, and corporate investors provide financial backing, infrastructure support, and mentorship programmes to foster the growth of quantum start-ups.

Quantum start-up ecosystem

The quantum start-up ecosystem consists of various elements that nurture and support entrepreneurial ventures in the quantum field:

On one hand, several regions worldwide have established dedicated clusters and innovation hubs focused on quantum technologies. These physical locations bring together start-ups, researchers, investors, and industry experts, fostering collaboration, knowledge exchange, and business development.

On the other hand, quantum start-ups often collaborate closely with academic institutions and research centres. These collaborations facilitate access to cutting-edge research, talent, and specialised resources, enabling spin-offs and start-ups to leverage the expertise and infrastructure of established institutions.

Finally, incubators and accelerators play a crucial role in supporting the growth of quantum start-ups. They provide mentorship, access to networks, funding opportunities, and business development resources, helping start-ups to navigate the challenges of commercialisation and scale their operations.

Notable quantum start-ups

Several notable quantum start-ups have emerged, each focusing on specific areas of quantum technology and developing innovative solutions:

- Quantum computing and quantum algorithms: These start-ups are actively engaged in developing quantum computing technologies, platforms, and software, and contributing to the advancement of the field. With each company bringing its own unique approach and expertise to the challenges of building practical and scalable quantum computers:

Company	**Location**
IonQ	College Park, Maryland, USA
Rigetti Computing	Berkeley, California, USA
PsiQuantum	Palo Alto, California, USA
D-Wave Systems	Burnaby, British Columbia, Canada
Xanadu	Toronto, Ontario, Canada
Quantum Circuits Inc.	New Haven, Connecticut, USA
Q-CTRL	Sydney, Australia
Quantum Computing Inc.	Leesburg, Virginia, USA
Quantum Machines	Tel Aviv, Israel
Classiq Technologies	Tel Aviv, Israel
Cambridge Quantum Computing	Cambridge, Regne Unit
Quantum Brilliance	Canberra, Australia
Quantum Benchmark	Kitchener, Ontario, Canada
Universal Quantum	Brighton, Regne Unit
1QBit	Vancouver, British Columbia, Canada
Rahko	London, United Kingdom
Zapata Computing	Boston, Massachusetts, USA
Quantum Motio, Technologies	London, United Kingdom

IQM	Espoo, Finland
Horizon Quantum Computing	Singapore
Atom Computing	Berkeley, California, USA
Multiverse Computing	Donostia-San Sebastián, Spain
Kilimanjaro	Barcelona, Spain
C12 Quantum Electronics	Paris, France
Riverlane	Cambridge, United Kingdom
QC Ware	Palo Alto, California, USA
Quantum-SI	Now York, USA
Aliro Quantum	Boston, USA
Quandela	Massy, France

- Quantum communications and quantum cryptography: These companies are examples of start-ups actively working to advance quantum communication technologies, including quantum key distribution (QKD), quantum encryption, and secure quantum networks. They are pushing the boundaries of secure and efficient data transmission using the principles of quantum mechanics:

Company	**Location**
QuantumCTek	Hefei, China
Qubitekk	San Diego, California, USA
ID Quantique	Geneva, Switzerland/South Korea
QuintessenceLabs	Canberra, Australia
KETS Quantum Security	Bristol, United Kingdom
Quside	Barcelona, Spain
LuxQuanta	Barcelona, Spain
Single Quantum	Delft, Netherlands
Nu Quantum	Cambridge, United Kingdom
Qontrol Systems	Bristol, United Kingdom
Quantum Xchange	Bethesda, Maryland, USA
QphoX	Delft, Netherlands
Arqit	London, United Kingdom
Crypta Labs	London, United Kingdom
Quantropi	Ottawa, Ontario, Canada
SeQureNet	Paris, France
SpeQtral	Singapore
QKD Corp	Olching, Germany

- Quantum sensing: The field of quantum sensing is rapidly evolving, and there may be other notable start-ups emerging in different locations around the world. Some examples are:

Company	Location
Qnami	Basel, Switzerland
ColdQuanta	Boulder, Colorado, USA
Atomionics	Singapore
NVision Imaging Technologies	Ulm, Germany

Quantum investment landscape

Key investors in quantum start-ups

The quantum technology sector has experienced a surge in investment activity in recent years. Investors recognise the transformative potential of quantum technology and are eager to support innovative start-ups in the field.

Venture capital (VC) firms are a primary source of funding for early-stage and growth-stage quantum start-ups. These firms specialise in investing in high-potential, innovative companies with the aim of generating significant returns on their investments. Some prominent venture capital firms that have shown interest in quantum start-ups include Andreessen Horowitz, Sequoia Capital, Accel Partners, Lux Capital, A&E Investments, Amadeus Capital, Alchemist Accelerator, DCVC, Atomico, Quantonation, Octopus Ventures and SG Innovate.

Corporate investment and strategic partnerships in the quantum space have also been crucial. Large corporations and technology companies across various industries are investing in quantum start-ups, forming strategic partnerships to leverage their expertise or acquiring quantum start-ups to integrate their technologies into their existing product offerings. Companies like IBM, Google, Microsoft, Intel, Robert Bosch, and Airbus have established dedicated quantum divisions or invested in quantum start-ups to gain a competitive edge.

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Governments around the world recognise the strategic importance of quantum technology and its potential for driving economic growth and national security. Therefore, they not only provide financial support but also create a conducive environment for quantum start-ups through policy initiatives, infrastructure development, and collaboration platforms, including regulatory support to help quantum start-ups navigate the challenges of bringing their technologies to market. Government involvement is crucial in building a thriving quantum start-up ecosystem and ensuring the long-term success of the quantum industry. Examples of government funding agencies supporting quantum start-ups include the United States National Quantum Initiative, the European Commission's Quantum Flagship programme, and the Canadian Quantum Computing Strategy, to name a few.

Overall, the involvement of venture capital firms, corporate investors, and government funding agencies demonstrates the growing interest and confidence in the potential of quantum technology.

Investment strategies and challenges

Investing in the quantum sector comes with its unique set of strategies and challenges. However, first there are some important considerations to take into account:

- Due diligence is crucial when assessing investment opportunities in the quantum sector. Investors should evaluate the actual technological feasibility, market potential, and competitive landscape of a quantum start-up. Understanding the team's expertise, intellectual property portfolio, and business model is also essential in assessing the viability and scalability of the venture.

- Assessing the risks and rewards of investing in early-stage quantum start-ups is of critical importance. Early-stage quantum start-ups often face technical and commercialisation risks. Most quantum technologies are still in their nascent stages, and uncertainties remain as to their long-term feasibility and market adoption. Investors must carefully assess the risks associated with technological challenges, regulatory hurdles, and market dynamics, while also considering the potential rewards to be reaped by early movers in the quantum technology market.

- Quantum technology is a rapidly evolving field, and investors should have a long-term perspective when considering investments in this sector. While the technology holds immense potential, commercialisation and widespread adoption may take time. Investors need to align their expectations with the typical timeline of technological advancements and market maturity, understanding that quantum investments may require patience and sustained support.

There have been several successful acquisitions in the quantum space, which demonstrate the potential for substantial returns on investment in the sector. However, they also highlight the importance of continuous innovation, technical progress, and strategic partnerships for the long-term growth and success of quantum start-ups. Investors are also considering diversifying their portfolio by investing in a range of quantum technologies to mitigate risks and capitalise on the broader impact of quantum technology across multiple industries.

In conclusion, navigation of the quantum investment landscape, as a salient example of a deep tech investment, requires careful evaluation of investment opportunities, a risk-reward assessment, and the adoption of a long-term perspective. As the quantum technology market continues to evolve, investors who actively engage in this sector have the opportunity to shape the future of quantum technology and reap the benefits of this transformative field.

Quantum patents: protecting innovation

Patenting Quantum Technologies

Patents play a crucial role in protecting and incentivising innovation in the quantum technology landscape. They are instrumental in driving innovation and commercialisation, providing a competitive advantage, attracting investments, collaborations, and strategic partnerships that accelerate the translation of quantum innovations into practical applications.

Patenting in the quantum field covers a wide range of technologies. In quantum computing, patents may be sought for novel hardware designs, quantum software, error correction techniques and, optimisation methods, among others. In quantum communication, patents may tackle secure quantum key distribution (QKD) systems, quantum cryptography protocols, and quantum network architectures. Quantum sensing patents may cover innovations in high-precision measurement devices, quantum metrology techniques, and quantum-enhanced imaging systems. Building a strong quantum patent portfolio requires a strategic approach. Start-ups should identify their core innovations, assess the patentability of their inventions, and develop a comprehensive patenting strategy. This may include filing patents for key technologies, variations, and potential applications.

Quantum patent landscape

While the number of publications, which can be considered a measure of generic research activity in the field, has risen continuously over the last ten years, the evolution of patents in quantum technologies is much more recent and abrupt. Since 2010, patenting in quantum technologies was chiefly dominated by North American and Japanese companies, including tech giants such as IBM, Microsoft, Toshiba, NEC, NTT, Intel, Google, and Honeywell, or specialised companies such as the Canadian D-WAVE quantum computing company. From 2015 on, applicants from China have dominated the scene, with significant contributions from different types of actors, whether private companies, state-owned enterprises or research institutions. Patents by applicants from EU countries remained more static during most of this period, but featured a significant increase in the last couple of years, with companies such as Deutsche Telekom, IBM Deutschland, Bosch, Atos and Thales, as well as research organisations including CNRS and CEA playing a leading role.

Overall, patents submitted by EU research centres and start-ups were scarcer, despite the EU having a rich ecosystem of active spin-offs and start-ups. One potential explanation may be that technological innovation activity by EU smaller actors is more recent (the data analysed do not contain patents filed within the last 18 months), and patent counts will likely grow in the next few years. Quantum start-ups recognise the importance of patent protection and are strategically filing patents to establish a strong intellectual property portfolio, secure their competitive position, and attract investment and partnership opportunities. Start-ups often adopt a proactive approach to patenting, filing patents early to protect their core technologies and innovations.
Indeed, the EU-27 presents the largest number of start-ups and spin-off companies in quantum computation and quantum communication, followed by the United States. Nevertheless, relative to their population, Canada’s and the United Kingdom’s numbers are higher. In Europe, Germany, France and Spain stand out with the largest numbers, while the Netherlands, Austria and Switzerland showcase high per-capita figures. In Spain, the ICFO research centre is the main patents applicant, followed by its spin-off Quside Technologies (Barcelona), the Spanish National Research Council (CSIC), the large corporation Telefónica (Madrid), and Vigo University in Galicia.

Overcoming challenges and future outlook

Technological challenges

- Scalability challenges in quantum systems and infrastructure: scaling up quantum computing systems to accommodate more qubits and improve computational power is one of the primary technological challenges in the quantum field. Overcoming the limitations of current quantum systems and developing scalable architectures is crucial for realising the full potential of quantum technology. Elucidating algorithms that offer actual exponential speed-up beyond the few that are known today is also of paramount importance in view of practical applications.

- Reducing noise and errors in quantum computations and in communications and sensing: quantum systems are prone to errors caused by environmental noise and decoherence. Researchers are actively working on developing error correction techniques for computing and improving the stability of quantum systems to minimise errors and enhance the reliability of quantum computations and communications. Dramatic improvements are needed to achieve many-qubit fault-tolerant quantum computing.

- Enhancing quantum hardware and stability: obviously, the robustness of quantum hardware plays a crucial role in the performance of quantum systems. Advancements in material science, fabrication techniques, and cooling technologies are necessary to improve the stability, coherence time, and control of qubits. Enhancing quantum hardware is key to achieving more robust and accurate quantum operations.

Regulatory and ethical considerations

- Quantum communication holds the promise of highly secure and unbreakable encryption. However, it also raises concerns regarding acceptability and adaptation to current networks and systems. Developing robust security protocols and addressing these concerns is vital to ensure the safe and widespread adoption of quantum communication technologies.

- Quantum technologies have the potential to disrupt various fields, including cryptography and future artificial intelligence. Ethical considerations surrounding the use of quantum technologies, such as the impact on encryption standards and potential biases in quantum algorithms, need to be addressed to ensure responsible and equitable deployment of quantum solutions.

- As quantum technologies advance, regulatory frameworks and standards will need to be established to address safety, security, and ethical implications. Governments and international organisations play a crucial role in developing appropriate regulations and standards to guide the responsible development and deployment of quantum technologies.

Conclusions

Quantum start-ups, quantum investments, and quantum patents are an instrument of paramount importance in driving the rapid advancement of quantum technology. Start-ups will be harnessing the potential of quantum computing, communication, and sensing, as well as quantum-powered technologies, to create innovative solutions, products and services that address complex problems. Investments in quantum start-ups are fuelling research and development efforts and propelling the commercialisation of quantum technologies. Patents play a vital role in protecting intellectual property, promoting innovation, and attracting further investments.

As the quantum technology landscape continues to evolve, it is crucial to address technological challenges, establish regulatory frameworks, foster collaboration, and envision the potential impact of quantum technology on various industries and society as a whole. In summary, with continued support and collaboration, quantum start-ups will be at the forefront of shaping the future of quantum technology and unlocking its full potential.

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