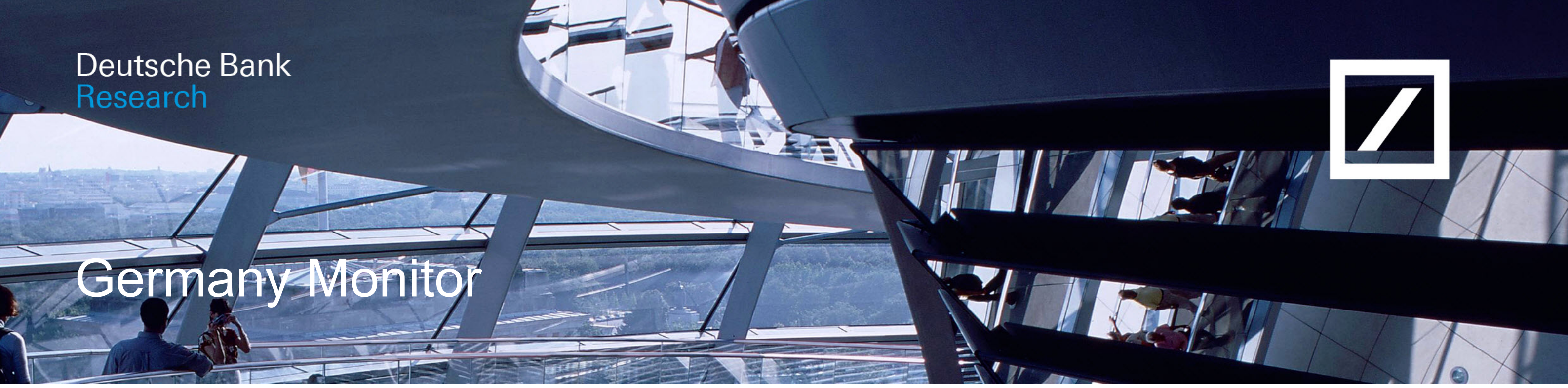

Economic-technological revolution through Quantum 2.0

New super technologies are within reach

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Quantum 2.0 super technologies will massively change our lives and work – and shape a new era. Advances in quantum research will enable companies to develop market-ready applications in a wide range of fields in the coming years – from quantum computers and quantum networks as building blocks of a new high performance quantum internet, quantum software and real-time applications for autonomous systems, to biomedicine, pharmaceuticals and space, novel nanotechnology-based materials, and many more.

Quantum 2.0 super technologies have the potential to enable enormous productivity and growth boosts over decades – as Quantum 1.0 has already done since the 1960s in building modern industrial and information societies. Innovation-friendly framework conditions will be decisive for this.

Already today there exists a quantum ecosystem of start-ups and large companies with the participation of more than 60 countries. While it is too early to predict with precision their future market sizes, the estimated global markets for various quantum technologies are above USD 1 tn (UK Government Office for Science, 2016: p. 56) led by photonics, semiconductors and cyber security.

Quantum technologies will further accelerate the impact of the digital transformation. It is essential for companies to decide whether they want to become "quantum-ready" – through a possible adaptation of business models and a new way of thinking in terms of data, processes and an innovative corporate culture including talent management.

Competition between companies will intensify because of Quantum 2.0. Regional and global supply and value chains could be broken up with new business models emerging. On an international and diplomatic level, quantum has the potential to support the achievement of political, economic and social goals and sustainable ecological transformation.

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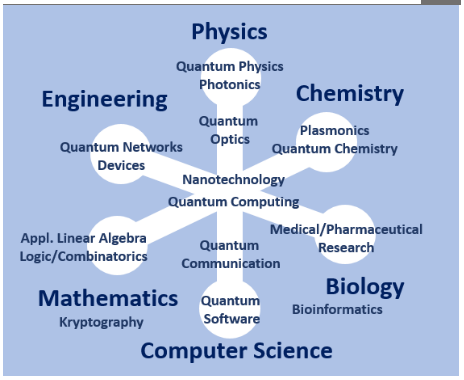
A. Introduction: Economy and society will change enormously through Quantum 2.0 technologies

At the beginning of the 20th century, Modern Quantum Mechanics emerged and with it the knowledge of the laws of nature in the subatomic range. Since then, light energy is no longer understood as continuously distributed in space, but it occurs as energy packets called photons or energy 'quanta',[1] a term that Max Planck introduced in 1901.[2] In addition to Planck, many other scientists in physics, chemistry and mathematics collaborated on the experimental and theoretical breakthroughs,[3] some of whom received Nobel Prizes, including Niels Bohr, Marie Sklodowska-Curie, Albert Einstein, Louis de Broglie, Werner Heisenberg, Erwin Schrödinger, Felix Bloch and Max Born. Since then, the boundaries of science have been constantly pushed further and applied research projects are being created in more and more areas.

Quantum research 1



Source: Deutsche Bank Research

Since about the year 2000, we have been in the initial phase of the second quantum revolution (Quantum 2.0). The year 2015 was designated by the United Nations as the "International Year of Light and Light-based Technologies".[4] [5] Meanwhile, the global race for new super technologies has gained momentum through large public investments in the billions of USD and the involvement of renowned research institutions and universities and is increasingly driven by private investments and the activities of international technology companies. Work is currently underway on Quantum 2.0 use cases across a wide range of industries and academic disciplines. How many years individual quantum-based applications will take to reach market maturity is the subject of divergent estimates. However, the corresponding quantum technologies are largely still in the research stage or cannot yet be used effectively on an industrial scale. It is expected that this will change dramatically in the next decade – and for some quantum technologies even sooner.

Today, quantum research and quantum technologies are rapidly evolving fields with many research-intensive subfields and a mix of technologies, some of which are interdependent or complementary and mutually reinforcing. Together with key technologies such as photonics, nanotechnology and artificial intelligence, Quantum 2.0 opens up new and fascinating perspectives that will shape a new quantum age that could have as decisive an impact on our future as the age of electricity since the 1920s and that of electronics since the 1960s. While a number of crucial technical and scientific breakthroughs are still needed for this to happen, it is important from a technical, entrepreneurial and investment perspective as well as for a society as a whole to look ahead and understand and discuss the opportunities and challenges.

1 Quantum [Latin] = how big, how much
2 Max Planck was awarded the Nobel Prize for Physics in 1918 for his discovery of light quanta.
3 An overview of the community of researchers involved is provided by a project of the MPI for the History of Science and the resulting publications: https://www.mpiwg-berlin.mpg.de/de/feature-story/die- netzwerke-der-fruehen-quantentheorie
4 https://www.light2015.org/Home.html
5 http://www.jahr-des-lichts.de/

Studies on the technology assessment of quantum technologies[6, 7, 8, 9] can help classify the effects of new technologies on the social, economic and ethical-social dimensions of a new quantum age. Warningly, Niklas Luhmann[10] has pointed out that "more than for any other society [...] promising research opportunities are available" and "at the same time [...] however, nescience and ignorance [are] increasing with it, and disproportionately so".

Regarding the impact of quantum technologies, topics arise such as:

Impact on society and individuals

— Democracy and media: Quantum internet, media competence, participation;

— Social effects of the acceleration of the worlds of work and communication;

— Social homogeneity in a high-tech information society;

— Ownership rights to personal and social data and sovereign identity.

Impact on innovation

— Quantum technologies and innovation management;

— Access to quantum technologies (e.g., by small and medium-sized enterprises);

— Impact of quantum technologies on individual industries and supply chains;

— Impact of specific innovations.[11]

Impact on security

— Cyber attacks with future quantum technologies;

— Risks of modern cryptography through quantum-based decryption and quantum codes,[12, 13] until post-quantum cryptography has been reached.

Impact on statistics & methodology

— Statistical measurement and analysis of the value contributions of digital services and individual technologies or technology sectors.

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6 Arge ITA-AIT Parlament (2021). Zukunft der Quantentechnologie: Quantencyberkrieg oder leistbares Quanteninternet für alle? Foresight und Technikfolgenabschätzung: Monitoring von Zukunftsthemen für das Österreichische Parlament. Austrian Parliament, Vienna

7 US Government Accountability Office (GAO) (2020). Science & Tech Spotlight – Quantum Technologies

8 Schweizer Wissenschaftsrat (2020). Quantentechnologie in der Schweiz. URL: https://wissenschaftsrat.ch/images/stories/pdf/en/Policy-analysis_SSC_2020_White-Paper-QT.pdf

9 Enzweiler, Kai et al. (2018). Quantencomputer. TAB - Büro für Technikfolgenabschätzung beim Deutschen Bundestag, Berlin.

10 Luhmann, Niklas (1997). Die Gesellschaft der Gesellschaft. Suhrkamp Verlag, Frankfurt a.M., S. 1111.

11 For example, in the EU quantum flagship project CiViQ, in addition to the technological aspects of a future integration of quantum communication (QKD) in optical telecommunications networks, questions about the long-term ethical-social changes are also to be taken into account. URL: http://civiQuantum.eu/

12 World Economic Forum (WEF) (2019). The Global Risks Report 2019. Geneva. 14th Edition.

13 BSI (2020). Status of Quantum computer development. Berlin.

This publication provides a brief introduction to the emerging quantum technologies and the opportunities and challenges associated with them, in order to exploit the potential of Quantum 2.0 not only technically, but also economically, ecologically, and socially.

B. The first and second quantum revolution

Quantum 1.0: The technology basis of modern industrial and information societies

Building on the findings of modern quantum mechanics and photonics, those technologies that today form the technical basis of the modern information society have emerged in multiple innovation cycles since the middle of the 20th century. Applications of the first quantum revolution (Quantum 1.0) have been developed since the 1950s and have been used industrially for decades. Modern electronics, quantum electronics,[14, 15] and opto-electronics are largely based on applied quantum theory.[16] In the field of computer and network technologies, the most important enabling technology is microelectronics[17], which enables integrated circuits on transistors and semiconductors in the micro range. Other basic technologies are optoelectronic components and transmission media (especially fiber optics technology) for ultra-high-speed data communication in modern networks. Further examples are microwave and laser technologies (e.g., industrial lasers for material processing), light diodes in CD and DVD scanners or burners, electrical household appliances with microelectronics, satellite and navigation systems, the internet and mobile communication with smart phones.

For decades, quantum-based technologies have enabled huge productivity and growth spurts. A study[18] published in 2019 with data from Eurostat for the period 2011-2016, states that industrially applied physics in the EU makes a net contribution to the economy of at least EUR 1.45 trillion per year – or 12 per cent – higher than retail trade (4.5 %), financial services (5.3 %) or construction (5.3 %).

Quantum 2.0: Future quantum super technologies

The research and development of Quantum 2.0[19] technologies have been happening for more than two decades through research institutes and industrial laboratories worldwide. One such field is quantum informatics, which deals with quantum networks, quantum sensors and quantum-based simulation with corresponding quantum software, among other things, and researches industrially relevant solutions and approaches.

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[14] In the field of quantum electronics, the Nobel Prize in Physics was awarded to Charles Hard Townes, Nikolai Bassow and Alexander Prokhorov in 1964.

[15] For laying the foundations of quantum electrodynamics, Richard Feynman was awarded the Nobel Prize in Physics in 1965, together with Shin'ichiro Tomonaga and Julian Schwinger.

[16] Mitin, Vladimir et al. (1999). Quantum Heterostructures: Microelectronics and Optoelectronics. Cambridge University Press.

[17] Aicher, Wolfgang et al. (1998). Technologische Grundlagen. In: Jung, Volker and Hans-Jürgen Warnecke Eds.) Handbuch für die Telekommunikation. Springer Verlag, Berlin/Heidelberg.

[18] European Physical Society (EPS) (2019). The Importance of Physics to the Economies of Europe. A study by Cebr for the period 2011-2016. Mulhouse, France.

[19] The term 'Quantum 2.0' for emerging quantum technologies was coined by Pritchard and Till in 2014 in a publication on the UK quantum technology landscape. They predicted that the technologies enabled by Quantum 2.0 would trigger a "second quantum revolution". Meanwhile, the term 'Quantum 2.0' is used in many publications and government programmes.

In key areas of industry and business, Quantum 2.0 will bring about profound changes that will lead to an increase in productivity, growth and competitiveness. This will enable a new generation of products and services, for example in the following areas:

Industry, production & logistics

— Optimisation of industrial production and processes in a wide range of areas through better planning and design tools;
— Quantum-based simulation techniques, e.g., for the development and simulation of new materials and manufacturing processes;
— Quantum-based optimisation calculations and improved measurement techniques in manufacturing and production;
— Quantum-based real-time models that lead to optimised route planning in quantum logistics and higher efficiency and effectiveness of supply chains, optimised traffic control and improved coordination of different modes of transport; and
— Quantum-based modelling is used, for example, in chemistry (computational chemistry) or biology (computational biology) to test new drugs and vaccines.
— New 3D and 2D materials can be explored and produced through novel nanotechnological fabrication and measurement techniques. Examples are graphene, quantum dots or nanocrystals.

Healthcare, medicine, pharmaceuticals and biotechnologies

— Quantum imaging and quantum sensing can significantly improve diagnostics and monitoring of patients – both in clinical and private settings;
— High-speed optical data transmission (VLC) for monitoring and positioning patients indoors;
— Quantum-based simulations can improve and accelerate the development of new drugs and vaccines;
— Applications of new methods (e.g., "quantum dots") in molecular biology; and
— Nanoscale bioimplants with quantum-based communication

Finance and insurance

— Risk calculations[20] (potentially in real time);
— Simulation and modelling of financial markets and purchasing behaviour;
— Chatbots and robo-advisors for more "human" sounding customer dialogues to offer better advice in real time with customer-tailored products (through Quantum-based modelling);[21]
— Acceleration of electronic payment transactions; and
— Identification of potential savings by analysing spending patterns and anomalies to propose improvements.

[20] https://arxiv.org/pdf/2103.05475.pdf
[21] Karasu, Ibrahim (2021). Auswirkungen auf die Banken: Quantencomputer und KI – erfolgreiches Zusammenspiel? KI-Note. Online Magazin. URL: https://www.ki-note.de/einzelansicht/auswirkungen-auf-die-banken-quantencomputer-und-ki-erfolgreiches-zusammenspiel

Working environment and communication

- Building and operating a quantum internet that will be dimensions faster than previous high-performance computer networks;
- Acceleration of communication and interaction with AI (quantum AI);
- High-speed visible light communication (VLC) at close range indoors with micro-LEDs;
- Micro-LED communication (VLC) in aircraft without electromagnetic effects (in-flight communication/infotainment);
- Real-time analysis of the behaviour of complex systems with very large numbers of participants; and
- Decision-making with quantum computers (fast simulation and combinatorics).

Climate research and ecological transformation

- Novel quantum-based model calculations in climate research;
- Optimised logistics (better traffic control);
- 'Green photonics', e.g., photonic instead of electronic applications and devices that use light instead of electricity, do not produce heat and thus avoid friction losses, enabling further miniaturisation at the nanoscale by eliminating cooling and fans;
- Realising a low-carbon society with smart city infrastructure and quantum internet; and
- Supporting global technology hubs to accelerate the technology transfer of green tech.

Entertainment and media

- New forms of entertainment and further possibilities that arise through quantum-based real-time feedback and the participation of a very large number of players or entire communities.
- A next generation of games in real time combined with augmented reality/virtual reality.
- Smart city infrastructure and quantum internet.

Retail and supermarkets

- Positioning of customers and route signalling to offers via VLC; and
- Optimised planning and logistics.

Quantum AI

- The combination with quantum computing could advance artificial intelligence in many aspects, e.g., in terms of computing capacity, the processing of large amounts of data (big data) in simulations and in analyses with high complexity (e.g., in combinatorics).
- PlanQK[22] is a German initiative to develop a platform and ecosystem for quantum-assisted artificial intelligence, led by a consortium and funded by the German Federal Ministry for Economic Affairs and Energy.

[22] https://planqk.de/en/partners/

Overview: From Quantum 1.0 to Quantum 2.0

The following table serves as a simplified didactic tool rather than a precise account of the history of innovation. However, it has proven useful in illustrating some aspects of the quantum revolution:

Comparison between Quantum 1.0 and Quantum 2.0 2

	Quantum 1.0	Quantum 2.0
Time period	20th century:	21st century:
	The century of the electron	The century of the photon
Modern quantum mechanics	Theoretical foundation (interference, superposition and entanglement)	Quantum computing, photonics, quantum gates, quantum algorithms, quantum information
	Schrödinger's equation	
Technologies	- Micro technology	- Nano technology (atom and subatom levels)
	Micro range = 1 mm/1,000	- Nano range = 1 mm/1 Mio
	- Electronics	- Quantum
	- Optics (laser, microwaves, fiber optics, atomic clocks)	- Photonics, plasmonics
Industrial utilisation	1950s – today:	In the future:
	Computers, lasers and masers, LEDs, GPS, magnetic resonance imaging, atomic clocks, satellite navigation, among many other innovations	Quantum information; quantum information technology and photonics, applications in different fields (partly as nanotechnology)
Communication	Computers, smart phones, electronic computer networks, internet	Quantum internet
		Quantum information networks,
		Complex sensor networks (Internet of Things; IoT)
Security	Conventional encryption	Post-Quantum cryptography
Artificial Intelligence (AI)	Machine learning (ML),	Quantum ML
	Deep learning	Quantum computing algorithms,
		Real time-feedback through quantum based simulations

Source: Deutsche Bank Research

From quantum research to the industrial use of quantum technologies

Several phases are necessary before ideas from basic research can be successfully used industrially.

From basic research to industrial utilisation 3

Source: Deutsche Bank Research

In the history of science and innovation research, there are countless examples of successful and sometimes revolutionary innovations, but also of a multitude of costly aberrations and failed attempts. One example of the development paths that stretch from basic research to industrial use, often over decades, is the invention of blue LEDs by three Japanese researchers, Shuji Nakamura,[23] Isamu Akasaki and Hiroshi Amano. For their development of LED semiconductors in the 1990s that emit blue light beams, they were awarded the Nobel Prize in Physics in 2014. Since the 1960s, after the invention of red and green LEDs, attempts had been made to produce blue LEDs as well. Only after a long series of breakthroughs in materials physics, in crystal growth, device physics and optical physics did this succeed through the production of so-called quantum wells, which are specifically designed molecular crystal structures (quantum films) that emit specific light frequencies as semiconductors. Today, white light is possible with LED spotlights thanks to blue light diodes in combination with the previously developed red and green light diodes. The use of LEDs as energy-efficient and environmentally friendly light sources leads to a significant reduction in global energy consumption and longer maintenance intervals compared to the previous use of incandescent or fluorescent lamps in private households, in companies and in transport technology, since 20-30% of the electricity in industrialised countries is consumed for lighting.

One of the hopes placed in the practical application of quantum technology is to be able to shorten the development times of future innovations up to market launch through simulations and model calculations and to increase the probabilities of success, for example in the development and testing of new materials and processes. Likewise, quantum technology in conjunction with "green photonics" can contribute to a smarter and more efficient consumption of energy and raw materials through a new generation of photonic devices.

C. Quantum technologies, photonics and plasmonics

Photonics[24, 25] and quantum technology overlap as research areas, since light is based on photons[26] and is a complex phenomenon that has electromagnetic radiation as energy quanta and consists of both light waves and light particles. Quantum technology systems use light in atomic and subatomic dimensions. Currently, research and work are being done on a new generation of photonic devices in succession to electronic devices.

Plasmonics[27] is one of the most important fields of photonics, which deals with the cultivation of tiny crystal and fibre structures on the atomic scale that can transmit laser signals with high power and serve as components for future quantum information networks. The term plasmon refers to a quantum of light when excited by energy radiation in solids, for example the diffraction of light in a crystal. This exploits the ability to focus and guide light below the diffraction limit[28], which will enable a new generation of highly miniaturised photonic devices, radically new fibre optic technology or photonics-based computer chips.

Examples of industrial applications from nano-photonics are novel nano-scale structures such as quantum wires, tailored quantum dots as single photon sources, holographic optical elements (HOEs) and photonic crystals (PhCs),

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23 Nakamura, Shuji (2000). The Blue Laser Diode. The Complete Story. Springer-Verlag, Berlin/Heidelberg. 2nd edition. (First edition 1997)

24 Phos [Greek] = Light

25 The term photonics was coined in 1967 by the French scientist Pierre Aigrain ("La photonique") and defined as follows: "Photonics is the science of harnessing light. Photonics includes the generation of light, the detection of light, the management of light by guiding, manipulating, and amplifying it and, above all, its use for the benefit of mankind."

26 Wöhrle, Dieter (2015). Was ist Licht? Chemie in unserer Zeit, Vol. 49 (6), pp. 386–401.

27 Christensen, Thomas (2017). From Classical to Quantum Plasmonics in Three and Two Dimensions. Springer International, Cham.

28 For the experimental discovery of electron diffraction by crystals, Clinton Davisson and George Paget Thomson received the Nobel Prize in Physics in 1937.

which can be fabricated since the early 2000s through advances in manufacturing technology. These devices enable both further miniaturisation at the nanoscale and increase the performance of integrated optical circuits[29] as the basis for future computers and quantum networks.

Another example from photonics is short-range Visible Light Communication (VLC), for which an IEEE standard has existed since 2015 and its industrial introduction has begun.[30] Li-Fi (Light Fidelity)[31] has the potential to replace or supplement the current radio-based WiFi (Wireless Fidelity) indoors, whereby secure high-performance communication with data transmission takes place via light (e.g., through micro-LEDs)[32], which is picked up by light-sensitive receivers (photosensors) and then processed electronically. Li-Fi enables novel applications such as indoor positioning where GPS cannot be received, or wireless data transmission at close range under water.[33] Communication by light (Li-Fi), in combination with the Internet of Things (IoT) and new radio bandwidths (5G and 6G), offers numerous application possibilities in areas such as education and business (wireless high-speed data transmission indoors by Li-Fi), aviation (communication by micro-LEDs in aircraft without electromagnetic effects), healthcare (monitoring and positioning of patients indoors) and retail (positioning of customers and wayfinding to offers). The market volume for VLC and Li-Fi is estimated[34] at USD 1,582.66 billion by 2026 (2020: USD 24.01 billion) (CAGR 101% over the forecast period 2021 – 2026).

D. Quantum computing: An open-ended global race

Current activities to produce working laboratory devices and commercial quantum computers are taking place in a fiercely competitive environment involving research laboratories, large technology companies and a growing number of start-ups worldwide. As quantum computing research is currently developing very dynamically and new breakthroughs and announcements are being reported all the time, hype and excited reporting has emerged. A scientifically sceptical view will both acknowledge the enormous achievements and the reaching of important milestones, but also keep an eye on the continuing large series of technical breakthroughs. Various competitors with different hardware strategies are participating in this race, and it is still uncertain who will prevail.

Quantum hardware strategies

The ideas for how to build quantum computers emerged in the early 1980s. In 1980, Paul Benioff first proposed building a quantum computer as a Turing machine.[35] The work of David Deutsch on the realisation of quantum computers

[29] Hunsperger, Robert G. (2009). Integrated Optics: Theory and Technology. Springer Science + Business Media, New York. 6th edition.
[30] Rehman, Saeed Ur et al. (2019). Visible Light Communication: A System Perspective—Overview and Challenges. Systems, Vol. 19 (1153).
[31] The term Li-Fi was first introduced by Harald Haas in a TED Global Talk in 2011. URL: https://web.archive.org/web/20170608024336/https://www.ted.com/talks/harald_haas_wireless_data_from_every_light_bulb
[32] Singh, James et al. (2020). Micro-LED as a Promising Candidate for High-Speed Visible Light Communication. Applied Science, Vol. 10, 7384.
[33] Schirripa Spagnolo, Giuseppe et al. (2020). Underwater Optical Wireless Communications: Overview. Sensors, Vol. 20, 2261.
[34] https://www.mordorintelligence.com/industry-reports/visible-light-communication-market
[35] Benioff, Paul (1980). The Computer as a Physical System: A Microscopic Quantum Mechanical Hamiltonian Model of Computers as Represented by Turing Machines. Journal of Statistical Physics, Vol. 22, No. 5, p. 563-591.

based on quantum gates[36] was another important milestone. Richard Feynman postulated in 1982 that only quantum computers could simulate quantum systems.[37] In 2000, David DiVincenzo formulated a catalogue of five criteria for fault-tolerant and scalable quantum computers (DiVincenzo criteria[38]) and described various approaches for their construction. Today, the relevant concepts pursued by companies in the development of quantum hardware are very diverse and highly variable.

Each approach involves trade-offs and the acceptance of certain advantages and disadvantages. A practical comparison of quantum computer architectures is very difficult, as the advantages and disadvantages of the respective approaches are hard to compare. For example, with regard to the parameter coherence time (i.e., the duration of the stable position of a quantum computer), ion traps are ahead by about a few seconds, while superconducting quantum computers currently achieve a coherence time of only a few microseconds. In terms of quantum gate times (i.e., the speed of computing operations), a superconducting computer has values in the nanosecond range, while ion traps only achieve microseconds. Architectures based on ion traps are therefore better able to process longer and more complex algorithms at the current stage of development, while superconducting quantum computers achieve higher speeds, which, however, only last for a very short time so far. The technical environment of quantum computers is also an important factor. Superconducting quantum computers have to be cooled down to almost absolute zero and require vacuum. The construction of the first superconducting quantum computer by IBM outside the USA in Ehingen near Tübingen and thus the first quantum computer in Germany, which was inaugurated in June 2021 by German Chancellor Angela Merkel and others[39], took two years, with many parts having to be manufactured by hand due to the high quality requirements. IBM and Google use the superconducting quantum computer approach, while Honeywell and IonQ, for example, use ion traps as the basis for their quantum computers.

There are also other approaches such as the so-called quantum annealers, which are based on Qbits in superconducting circuits. The quantum annealer approach cannot implement the same quantum algorithms as superconducting quantum computers, but certain optimisations (e.g., machine learning or combinatorics) can be solved more effectively with it. D-Wave and Fujitsu are companies that produce quantum computers based on quantum annealing. A completely different concept, on the other hand, is used by the US start-up Rigetti Computing, for example, which has quantum processor chips designed and built.

A final verdict on which concept will come out on top is not yet possible. Quantum physicist John Preskill has coined the term Noisy Intermediate-Scale Quantum (NISQ)[40] for the current state of research on quantum computers, whereby it will take at least a decade before new quantum systems are discovered or existing Qbit systems are decisively improved. The further development of the various approaches must therefore be followed closely.

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[36] Deutsch, David (1985). Quantum theory, the Church-Turing principle and the universal Quantum computer. Proceedings of The Royal Society London, A 400, p. 97-117.
[37] Feynman, Richard P. (1982). Simulating Physics with Computers. International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, p. 467-488.
[38] DiVincenzo, David P. (2000). The Physical Implementation of Quantum Computation. Fortschritte der Physik, Vol. 9-11, p. 771-783.
[39] https://www.fraunhofer.de/en/events/inauguration-Quantum-computing-research-platform.html
[40] Preskill, John (2018). Quantum Computing in the NISQ era and beyond. Quantum, Vol. 2, 79. pp. 1-20.

Quantum computers: Overcoming digital-binary limits

A quantum computer is a computing machine based on quantum mechanics that uses single photons in quantum systems to generate energy states of quantum bits (Qbits) and uses them through manipulation to encode and process the information. Qbits have the strange-seeming property that they take on a number of values simultaneously ("superposition"). Digital computers, on the other hand, which operate according to the laws of classical physics, are limited in the number of states and work with a strict binary code ("0" or "1")

What is a quantum computer? 4

A quantum computer is a complex piece of technology that needs to function on many levels. Its basic components – Qbits – are intricate physical objects based on pushing some experimental modality to its extremes. On the other hand, while obviously not as huge as some modern classical applications due to the power of quantum computing, algorithms running on it are already complex pieces of code. These elements are connected by a stack with intermediate level of detail. The challenge of evaluating where construction of a quantum computer stands is essentially an exercise in evaluating the machine on all of these levels and connecting them.

Source: BSI (2020). Status of Quantum computer development. Berlin. p. 37

Since the end of the 1990s, various experimental prototypes have been presented. For superconducting quantum computers, this development can be divided into a development period from 1999-2015 and, since spring 2016, the era of cloud quantum processors.[41]

Development of quantum computers from 1998 -2023 5

	Company	Country	Number of Qbits	Quantum Volume
1998	IBM, Oxford, Berkeley, Stanford, MIT	USA	2 Qbits	
2001	Technical University of Munich	Germany	5 Qbits	
2000	Los Alamos National Laboratory	USA	7 Qbits	
2006	MIT	USA	12 QBits	
2008	D-Wave System TWO	Canada	28 Qbits	
2017	IBM Q Experience	USA	50 Qbits	
2019	Intel	USA	49 Qbits	
	Google Sycamore	USA	54 Qbits	
	IBM Raleigh	USA	28 Qbits	32
	Honeywell H0	USA	6 Qbits	64
2020	D-Wave “Advantage” (only via cloud)	Canada	5,000 Qbits	
	Rigetti Aspen-8 on AWS	USA	31 Qbits	
	IBM Falcon	USA	27 Qbits	128
	Jiuzhang Photonic Quantum System	China	76 Qbits (Peak)	
	Honeywell H1*	USA	10 Qbits	512
2021	Rigetti Aspen-9	USA	32 Qbits	
	IBM “Eagle”**	USA	127 QBits	
2022	IBM “Osprey”***	USA	433 Qbits	
2023	IBM “Condor“****	USA	1,121 Qbits	

* Honeywell Quantum Computer System Model H1. URL: https://www.honeywell.com/us/en/news/2020/10/get-to-know-honeywell-s-latest-Quantum-computer-system-model-h1
** IBM Quantum Roadmap. https://research.ibm.com/blog/ibm-Quantum-roadmap
*** dto.
**** dto.

Source: Deutsche Bank Research

[41] BSI (2020). Status of Quantum computer development. Berlin. p. 20.

Quantum advantage: Has a spectacular milestone been achieved?

A race is currently underway to build the first robust quantum computer that would offer a true quantum advantage and be usable for scientific and commercial applications, i.e., such a system would be dimensions faster than the most powerful existing digital supercomputer.

In 2019, Google CEO Sundar Pichai announced that the Google Sycamore quantum computer had achieved "quantum supremacy" for the first time, i.e., a computing power that is dimensions higher than a conventional digital supercomputer. The underlying experiment was subsequently published[42] and triggered worldwide reporting. The Google experiment used a task specially designed for quantum computers called 'random circuit sampling'[43], which consists of calculating random numbers that must be subject to a certain distribution from quantum physics. Google's quantum computer needed about 200 seconds to solve it.

In the technical discussion that ensued, criticism was voiced both from a methodological point of view and with regards to the interpretation of the existence of quantum superiority. The Google experiment and the underlying method of benchmarking as well as a verification of error correction have been described and analysed by the BSI[44], for example. In response to Google's announcement, researchers at IBM pointed out[45] that digital supercomputers took about 2.5 days to solve instead of the 10,000 years mentioned by Google that a classical supercomputer would need.

In December 2020, a team of Chinese researchers led by Jianwei Pan announced that they had achieved quantum superiority with a photonic Jiuzhang quantum system[46]. In parallel, the researchers calculated that solving the experiment, which took the photonic system just over three minutes, would have taken more than 2 billion years using China's most powerful supercomputer, Sunway TaihuLight. However, the Jiuzhang quantum system has a completely different design than superconducting quantum computers and was only fitted for this one specific experiment.

So, whether quantum superiority has already been achieved is judged differently.

When will a powerful commercially usable quantum computer be available?

Physicist Robert Schoelkopf, who founded a quantum start-up with colleagues at Yale University in 2015, is quoted in an article in Nature[47] saying that estimates of how long it will take to build a universal quantum computer are too pessimistic. "If you had projected forward from where we were ten years ago, you would never have predicted how far we are today," he said. Innovative hardware combined with software that picks out the most tractable problems means "we're going to be reaching useful quantum computations faster than people think".

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42 Arute, Frank et al. (2019). Quantum supremacy using a programmable superconducting processor. Nature, Vol. 574, pp. 505-511.
43 Bouland, Adam et al. (2019). On the complexity and verification of Quantum random circuit sampling. Nature Physics, Vol. 15, p. 159–163.
44 BSI (2020). Status of Quantum computer development. Entwicklungsstand Quantencomputer. Bundesamt für Sicherheit in der Informationstechnik (BSI), Berlin. pp. 21, 57, 60-61, 215-217.
45 IBM Research Blog, URL: https://www.ibm.com/blogs/research/2019/10/on-Quantum-supremacy/
46 Zhong, Han-Sen et al. (2020). Quantum computational advantage using photons. Science (Vol. Dec.) URL: https://www.science.org/doi/10.1126/science.abe8770
47 Gibney, Elizabeth (2019). The Quantum gold rush. Nature, Vol. 574, p. 22-24.

Hartmut Neven, the director of Google's Quantum AI Laboratory argued in 2017[48], that a conservative view of quantum computing gave the impression that investors would only benefit in the long term, but that short-term returns were possible with small devices coming to market in the following five years to 2022, even if they would not yet have full error correction. In the meantime, the growth in the performance of quantum computers is referred to as "Neven's Law"[49], which states that the performance of quantum computers grows twice exponentially[50] as that of digital computers ("Moore's Law").

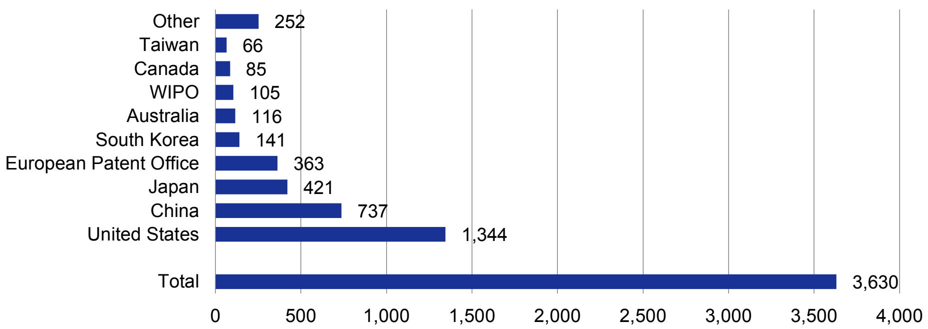
If one takes the IBM roadmap[51] as a benchmark, according to which the performance of superconducting quantum computers roughly doubles every year, and extrapolates this, then the threshold of one million Qbits could be reached in about 2033, with which robust quantum computing with sufficient error correction would be achieved. However, this is only on the condition that the necessary breakthroughs and technical milestones are actually achieved.

One such breakthrough could be qutrits[52], which also play an important role in quantum teleportation. This would increase the capacity of quantum computers by one dimension or, with further progress, by several dimensions.

Quantum patents

The number of patent applications in the field of quantum computing has risen sharply in recent years (2020: 1,787 compared to 2015: 667 and 2012: 557). In addition to large companies, patents are increasingly being filed by start-up companies.

Quantum patent applications worldwide (2021) 6



Sources: Statista, Deutsche Bank Research

[48] https://www.nature.com/articles/543171a
[49] Named after Hartmut Neven, Director of the Google Quantum Artificial Intelligence Lab.
[50] Yoshida, Hubert (2019). Moore's Law is Replaced by Neven's Law for Quantum Computing. Hitachi Vantara, June 24, 2019. Available at: https://community.hitachivantara.com/s/article/moores-law-is-replaced-by-nevens-law-for-Quantum-computing
[51] https://www.ibm.com/blogs/research/2020/09/ibm-Quantum-roadmap/
[52] Erhard, Manuel et al. (2020). Advances in high-dimensional Quantum entanglement. Nature Reviews - Physics, Vol.2, pp. 365-381.

Patent analysis as indicator 7

Patent analysis is a well-established way to gauge economic potential of new technologies. Several studies have been done on patenting trends in quantum technologies. All these studies rely on search tools based on key words and International Patent Classification (IPC) or Cooperative Patent Classification (CPC) codes, and there is no indication that they have been made by people with a background in quantum physics. In these conditions, they carry the risk of attributing to the field being investigated a consistent number of patents belonging to other technological areas ("false positives"), therefore inducing the reader into the perception of a higher technology readiness level than the one actually reached, and of a larger interest by industrial players. This risk is compounded by the fact that the main aim of most of these reports is to raise the interest of potential customers and investors in the area. Such an aim is particularly evident in the market analyses which have been prepared and are sold by several tech consultancies. As a general rule, we have found that they tend to present a much rosier picture of the technological readiness and market potential of these technologies than it is reasonable to expect.

Source: Travagnin, Martino (2019). Patent analysis of selected Quantum technologies. European Commission, Joint Research Centre (JRC), Ispra/Italy. Publications Office of the European Union, Luxembourg. p. 2

E. Quantum software

Quantum computers offer the possibility to test quantum software. Quantum software is a dynamic field that develops independently of quantum hardware architectures.

— In software development for quantum computers, Python[53] dominates as an open-source programming language.

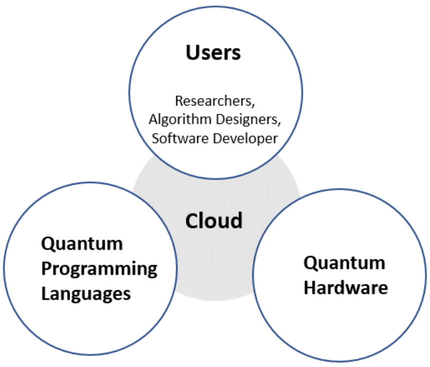
— IBM's development environment Qiskit[54] supports Python.

— Silq[55] is a new high-level programming language for quantum computers that was developed at ETH Zurich and first published in 2020.[56]

— Microsoft has introduced its own open-source programming language for quantum computing, Q#[57], as part of the Microsoft Quantum Development Kit (QDK).

— Quantum software company Cambridge Quantum Computing (CQC) offers a quantum software development kit (SDK) "tket" (pronounced "ticket"), with all licensing restrictions removed for using tket's Python module (known as "pytket"). It is architecture independent.

Quantum Computing-as-a-Service (QCaaS) 8



Source: Deutsche Bank Research

The development of quantum software is currently being driven forward in many projects worldwide. Analogous to the classical software architecture, quantum compilers, quantum assemblers, special software, and libraries (quantum full stack) are being created. Compared to conventional software, quantum software has some special features that are giving rise to a new field of computer science. In particular, quantum software is based on a completely different logic (see below).

Users from science and industry can already gain access to high-performance quantum computers via the cloud, which is used by tens of thousands of researchers and companies. The demand for offers to be able to carry out one's own quantum software projects is increasing worldwide due to both a rise in use cases and user numbers.

User preference will be one of the decisive factors in deciding which software and hardware will prevail in quantum computing. Many large technology

53 https://www.python.org/
54 https://qiskit.org/
55 https://silq.ethz.ch/
56 https://files.sri.inf.ethz.ch/website/papers/pldi20-silq.pdf
57 https://docs.microsoft.com/en-us/azure/Quantum/overview-what-is-qsharp-and-qdk

companies have positioned themselves with cloud-based development environments, as the exemplary overview of existing offerings shows. Access via the cloud drastically lowers the technical entry barriers and costs for users.

The Quantum Open Source Foundation (QOSF) provides access to the following open source quantum software projects on GitHub:

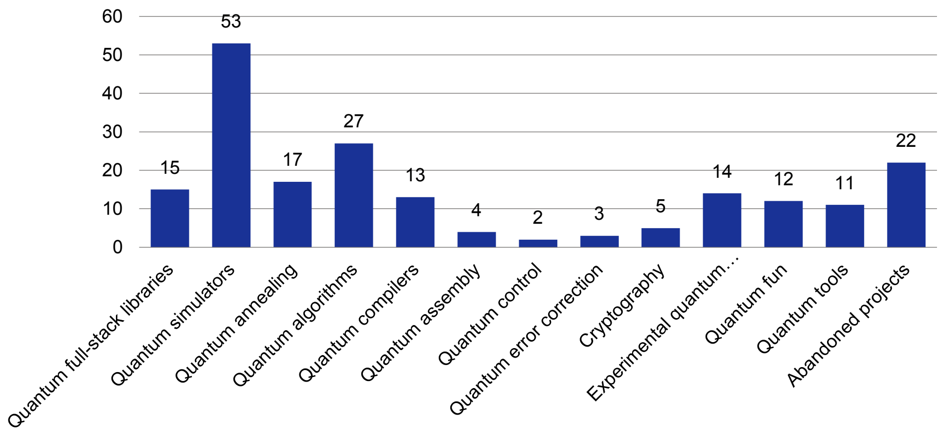
Selected quantum software environments of technology companies 9

	Quantum software platform	URL
IBM	IBM Quantum Experience; IBM Qiskit	https://www.ibm.com/quantum-computing/ https://www.ibm.com/quantum-computing/tools/
Microsoft	Microsoft Azure Quantum; Microsoft QDK, Q#	https://azure.microsoft.com/en-us/services/quantum/
Google	Google Quantum AI; Cirq	https://quantumai.google
AWS	Amazon Web Services (AWS); AWS Braket	https://aws.amazon.com/de/braket/
Alibaba	Alibaba Quantum Lab	https://damo.alibaba.com/labs/quantum
CAS	CAS (Chinese Academy of Sciences) Key Laboratory of Quantum Information	http://lqcc.ustc.edu.cn/index/info/826 [in Chinese]

Source: Deutsche Bank Research

Comparison of digital computing and quantum computing

Quantum software projects 10



Sources: GitHub.com, Deutsche Bank Research

The use cases for quantum computing overlap only partially from those for conventional digital computing. At the same time, each method has its specific strengths and weaknesses, which means that we could enter a new era in which digital computers and quantum computers coexist or combine digital and quantum-based co-processors. In the case of complex computational problems, quantum computers should theoretically be dimensions more powerful than classical digital supercomputers or be able to solve problems that were previously considered unsolvable.

Difference between digital and quantum-based computing methods

Differences between digital and quantum computing 11

	Digital computing	Quantum computing
Description	Digital computers use binary code in the integer range and the states of "0" and "1".	Quantum computing is based on quantum mechanics. An array of Qbits can use superposition to represent all 2^{64} possible values at once, allowing a quantum computer to solve problems that are practically impossible for standard computers.
State-of-the-art	High-performance computing through digital computer chips and special processors in a wide range of devices from smartphones to notebooks and PCs to servers, grid computing and supercomputers.	Not yet commercially applicable. Currently in research or testing; various hardware strategies in competition; quantum software in development; devices for teleportation and future quantum information networks in development.
	Established technology with billions of users and millions of programmers worldwide.	Computing at near light speed, massively parallel computing. Future technology requiring new thinking; only a few tens of thousands of users and a developing programmer community.
Weakness	Certain computing problems are not solvable or not solvable in acceptable or finite time.	Future technology that requires new thinking; only a few tens of thousands of users and an evolving programmer community.

Source: Deutsche Bank Research

Prime number calculation and encryption methods

The analysis of computational problems as a subfield of theoretical computer science deals with the algorithmic solvability of computational problems, which are divided into several levels of complexity and whose complexity can vary dramatically. Here, the difference between problems that can be solved with conventional digital computing methods and those that are predestined for quantum computers is described as follows:

Digital computing vs. quantum computing 12

	Digital computing	Quantum computing
Class of solvable decision problems	BPP (Bounded-Error Probabilistic Polynomial Time)	BQP (Bounded-Error Quantum Polynomial Time)
Error probability	Established automated techniques to handle malfunction problems and machine errors	Error correction resp. Error suppression to be developed
Time needed	O (n log n)	O (n^2)

Source: Deutsche Bank Research

An example of the different behaviour of digital computers and quantum computers is the mathematical determination of prime numbers (factorisation)[58], [59] which are of central importance for data security when exchanging data with encryption, among other things.

[58] Kobler, Johannes and Olaf Beyersdorff (2006). Von der Turingmaschine zum Quantencomputer – ein Gang durch die Geschichte der Komplexitätstheorie. In: Reisig, Wolfgang and Johann-Christoph Freytag (Hrsg.) Informatik. Aktuelle Themen im historischen Kontext. Springer-Verlag Berlin/ Heidelberg. pp. 165-195.

[59] Montanaro, Ashley (2016). Quantum algorithms: an overview. npj Quantum Information, Macmillan Publishers.

The following table gives an idea of the exponentially developing advantages in computing time of quantum computers over digital computers.

Comparison of calculating processes and calculating time 13

	Digital computer	Quantum computer
n	n^n	2^n
15	437,893,890,380,859,000	32,768
13	302,875,106,592,253	8,192
11	285,311,670,611	2,048
10	10,000,000,000	1,024
9	387,420,489	512
7	823,543	128
5	3,125	32
3	27	8
1	1	2
0	1	1

Source: Deutsche Bank Research

For more complex calculations, the time advantage of fewer computing operations has an even greater exponential effect with quantum computers. For example, encryption with the RSA method uses up to 600-digit numbers. While encryption with private and public keys in one direction is easy to calculate, the reverse direction (inverse function) is very complex with digital high-performance computers and thus does not pose a direct threat with suitable key lengths for cryptographic methods commonly used today. According to the statement of the German Federal Government[60] quantum algorithms do not pose a threat to symmetric encryption methods according to the current state of research. However, quantum algorithms (such as Grover search and the Simon problem) have implications for symmetric cryptography, especially for key lengths and modes of operation.

However, quantum computers would endanger the public-key cryptography used today, since asymmetric procedures such as the RSA algorithm, among others, are based on the factorisation problem. The Federal Office for Information Security (BSI) explains this as follows:

> ‘It is common knowledge that a sufficiently scalable quantum computer would break the currently used asymmetric cryptosystems based on RSA and elliptic curves. Indeed, since the publication of Shor's algorithm (1994), polynomial-time quantum algorithms exist for factorising RSA modules and calculating the discrete logarithm on elliptic curves.’

Currently, research is being conducted on a new level of encryption standards, e.g., by organisations such as the US National Institute of Standards and Technology (NIST), the European Technical Standards Institute (ETSI) and the German Federal Office for Information Security (BSI). NIST is conducting a competition to achieve Post-Quantum Cryptography (PGC)[61]. As soon as appropriate standards have been established, these will form the next generation of encryption methods up to a robust post-quantum cryptography.

[60] Deutscher Bundestag (2021). Die Verschlüsselungspolitik der Bundesregierung. Antwort der Bundesregierung. Drucksache 19/26340.
[61] https://csrc.nist.gov/projects/post-Quantum-cryptography

Quantum logistics

Quantum logistics deals with complex routing problems, e.g. for planning and controlling fleets of vehicles or calculating routes, which is also relevant for self-driving autonomous systems. A classic theoretical problem is the "travelling salesman problem" (TSP), which sounds deceptively simple but has puzzled scientists and practitioners for centuries. It involves, for example, the question of how to determine the shortest route for a delivery vehicle to deliver packages to one address in each of several cities. The goal is to find the shortest route that passes through each city exactly once and then returns to the starting point in the first city. Several factors play a role here, which together result in a computational problem that grows exponentially with an increasing number of waypoints: the vectorisation of the network (graph theory), the order of the routes (combinatorics) and the selection of the shortest route in total (optimisation).

In 2020, a team of researchers led by Takayuki Kawahara in Tokyo succeeded in solving the TSP in a network with 22 cities (i.e., network nodes) using a special design for an AI chip[62]. Before that, the maximum solvability with digital circuits had been 16 nodes. A survey study[63] from 2020 provides an insight into the practice of optimisation problems with quantum software. As soon as more powerful quantum computers are available, quantum-based computing methods will enable a drastic increase in this threshold and more complex routing problems will become solvable.

F. Quantum communication: High-performance networks and the vision of a quantum internet

Research for a next generation of quantum information networks (Quantum 2.0) has already begun. This requires technical breakthroughs in the construction of quantum computers or quantum chips as well as in a range of optical network and switching elements for a future quantum-based network infrastructure. The long-term vision is that networks for the transmission of quantum information will become a new internet that achieves a dimensionally higher performance and speed through the increased computing power of quantum computers and optical or quantum-based data transmission. Various related fields such as quantum mechanics, quantum information theory, quantum channel coding, quantum error correction and quantum cryptography contribute to this[64].

A fundamental phenomenon of quantum information science is teleportation. Quantum communication and a future quantum internet are based on the transmission of quantum information from a sender to a receiver. To do this, entangled photons are manipulated in such a way that they can transmit binary information. The range for quantum-based information transmission via optical fibres or lasers within the Earth's atmosphere is limited by interference effects, since only a few photons arrive at the destination in an entangled state. In recent years, a series of experiments by scientific teams from Austria and China, led by the teleportation pioneer Prof. Zeilinger from Vienna, have transmitted quantum-based information in the Earth's atmosphere through

[62] https://www.eurekalert.org/news-releases/840425
[63] Warren, Richard H. (2020). Solving the traveling salesman problem on a Quantum annealer. SN Applied Sciences, Vol. 2 (7). URL: https://link.springer.com/content/pdf/10.1007/s42452-019-1829-x.pdf
[64] Hayashi, Masahito et al. (2015). Introduction to Quantum Information Science. Graduate Texts in Physics. Springer-Verlag, Berlin/ Heidelberg.

teleportation. In 2012, for example, a transmission over 143 km was achieved between two Canary Islands.[65]

Satellites with certain quantum devices can transmit entangled photons through the vacuum in space largely undisturbed. In August 2016, quantum information was transmitted by the Chinese research satellite ‘Micius’ to two ground stations in China over a distance of up to 1,203 km.[66] However, this has so far only been possible at night, as otherwise the photons are deflected by daylight. A quantum-based transmission between two satellites in space was announced by India in 2021.[67]

Another key milestone was achieved in 2019 at the Institute of Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences led by Anton Zeilinger – in collaboration with a Chinese team from the University of Science and Technology of China (USTC) (Hefei/ Anhui Province) led by JianWei Pan. For the first time, three-dimensional states (qutrits) of photons were transferred successfully[68]. In further development, this could enable the quantum teleportation of very large amounts of data, as not only two-digit quantum states (qubits) would be available for information transmission, but these could theoretically be extended to n-digits with advancing quantum technology. In Germany, the Fraunhofer Gesellschaft has launched a research project to create innovative hardware for quantum communication[69].

The high strategic importance of a quantum internet as a super technology and its many advantages with a dimensionally higher transmission speed and bandwidth and thus an overcoming of the capacity bottlenecks of the current internet as well as a previously unattainable eavesdropping security drives intensive research activities, which makes a realisation of this still long-term vision more likely. For example, Fermilab[70] as a national US research institution is also involved in research on quantum teleportation in cooperation with AT&T[71] and several universities with regard to a future quantum internet.

In July 2020, the US Department of Energy presented a blueprint for a quantum Internet[72], which already contains a proposal for a future quantum internet network architecture.

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65 Erhard, Manuel et al. (2019). Advances in High Dimensional Quantum Entanglement. arXiv:1911.10006v2 [quant-ph].
66 https://www.science.org/doi/full/10.1126/science.aan3211
67 https://www.isro.gov.in/update/22-mar-2021/isro-makes-breakthrough-demonstration-of-free-space-Quantum-key-distribution-qkd
68 https://www.iqoqi-vienna.at/detail/news/qutrit-complex-Quantum-teleportation-achieved-for-the-first-time
69 https://www.laserfocusworld.com/optics/article/14075356/european-intequant-project-launched-to-create-nextgen-Quantum-photonic-hardware
70 https://Quantum.fnal.gov
71 Valivarthi, Raju (2020). Teleportation Systems Toward a Quantum Internet. American Physical Society, PRX Quantum 1, 020317, S. 1-16. Available at: https://journals.aps.org/prxQuantum/pdf/10.1103/PRXQuantum.1.020317
72 https://www.energy.gov/articles/us-department-energy-unveils-blueprint-Quantum-internet-launch-future-Quantum-internet

Comparison between TCP/IP 5 reference model and the blueprint for a Quantum Internet Network Architecture 14

Layers	Quantum Internet Network Architecture	
Application Layer	Distributed Quantum Algorithms	
Transport Layer	Coexistence with Classical Networks	Control Plane
Network Layer	Entanglement Generation and Memory-assisted Distribution	
Data Link	Transduction Superconducting/Photonic	
Physical	Quantum Processor/Quantum Computer	
TCP/IP Network Stack	Entanglement Distribution Network Stack	

Source: Deutsche Bank Research

In summary, although a quantum internet is still a long-term vision, first significant milestones have already been reached regarding the conception (network stack), the production of necessary components and the testing of the transmission of quantum information (quantum teleportation).

G. Global approaches to support quantum technologies

National quantum strategies and initiatives

Worldwide, more than 60 countries have launched quantum technology initiatives, and some have defined national quantum strategies. These initiatives and funding from international organisations and governmental actors are helping to overcome the high technical barriers by providing public funding in the range of hundreds of millions to billions of USD and financing a research infrastructure. Apart from the hoped-for improvements for productivity and competitiveness, Quantum 2.0 technologies also have security policy relevance, for example for encryption and message transmission.

Quantum ecosystem

A global quantum ecosystem has evolved in recent years, linking research institutions and technology companies and both public and private investors.

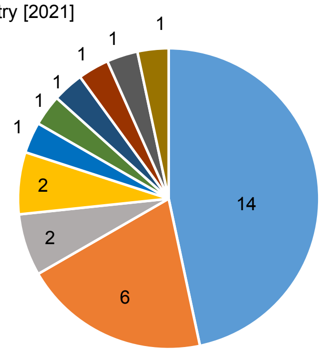
Quantum 2.0 – ecosystem 16

Producers	§ Research institutions (Academies of Science, technology hubs, innovation and research agencies) § Technology companies § Start-ups
Users	§ Corporates § Researchers and research organisations § Software developers
Investors	§ Government agencies and regional authorities § Private investors

Source: Deutsche Bank Research

Listed quantum technology producers 15

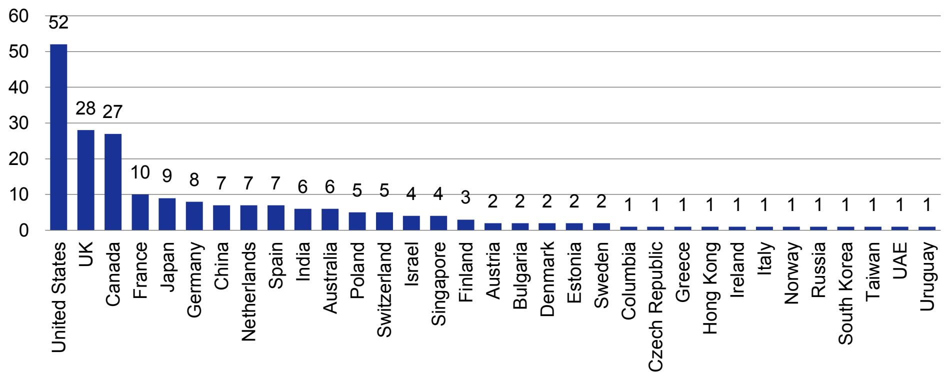
per country [2021]



Source: Deutsche Bank Research

Quantum start-ups 17

per country [2020]



Source: Deutsche Bank Research

Of the 210 quantum start-ups selected for this evaluation, 64 quantum start-ups (30.4%) are from EU-27 countries, about a quarter (24.8%) are from the US, and about an eighth (12.9%) each are from the UK and Canada. A total of 184 (or 88%) of the quantum start-ups are spread across 15 of the 33 countries. Most of these countries have national quantum strategies, each with a budget of several hundred million USD. For China, however, the number of start-ups could be much higher, as no information is available on these companies and state research institutions sometimes operate their own quantum research laboratories, which are equivalent to start-ups.

The three leading countries or regions in the field of quantum technologies[73] are the United States (quantum computers), Europe (quantum mechanics and laser technologies) and China (quantum communication and cryptography).

The United States

The US National Quantum Initiative (NQI)[74], adopted by the US Congress in December 2018, empowers the US President to determine, among other things, the goals and priorities of a 10-year plan to advance the development of quantum information science and quantum technology applications. The NQI,

[73] OECD-Outlook of the Digital Economy 2020.
[74] The US National Quantum Initiative Act. Public Law No: 115-368 (12/21/2018)

launched by the Trump administration, is being continued under the Biden administration[75]. It is an umbrella under which a number of government agencies develop and implement programmes for quantum science and technology in the US. Government, academic and private sector organisations work together under the NQI, for example, the NASA Ames – Quantum AI Laboratory (QuAIL)[76], Fermilab[77], Los Alamos National Laboratory[78] and Lawrence Livermore National Laboratory[79]. As a US agency, the National Institute of Standards and Technology (NIST) is leading a global initiative to achieve Post-Quantum Cryptography (PGC)[80]. The National Science Foundation (NSF)[81] and the Department of Energy (DOE) are also represented with their own research centres and programmes[82] being involved in advancing quantum technologies. In addition, the big tech companies are also active players driving quantum computing, e.g., IBM, Google, Microsoft, Intel, Honeywell, but also start-ups such as Rigetti Computing and IonQ, and many others.

PR China

The People's Republic of China has set growth targets in five strategic areas of science and technology in its current five-year plan (2021 - 2026), with breakthroughs expected in quantum information technology, artificial intelligence, semiconductors, and space, among others. In this context, China has increased the state budget and stepped-up investment in research and development of quantum technologies, including research into a long-range and high-speed quantum communication system. The Chinese Academy of Sciences (CAS) is taking a leading role in this and has pooled resources with the University of Science and Technology of China (USTC) in Hefei (Anhui Province). The Chinese quantum physicist Jianwei Pan, who received his doctorate from Anton Zeilinger in Vienna in 1999 and is involved with his team in breakthroughs in the field of teleportation (including the quantum satellite 'Micius'), is a professor there. The first Quantum Computing Industrial Park for 60 quantum companies is also to be opened in Hefei.[83] As part of CAS Quantum Net, ZTE is working on quantum security applications. In recent years, the technology companies Alibaba (since 2015) and the search engine Baidu (since 2018) have also opened their own quantum research labs. The number of Chinese start-ups in the field of quantum technology is difficult to estimate, as little information is available on this. In addition, there are state-funded spin-offs or departments of research centres and universities which act as start-ups.

The Digital Silk Road (DSR) was launched in 2013 as part of the overarching Belt and Road Initiative (BRI) to achieve the sub-goal of "connectivity". Through agreements under China's Belt and Road Initiative, China provides other countries with access to mobile technologies, including 5G, advanced AI-based monitoring capabilities and, in the future, access to Chinese quantum technologies and quantum information networks.

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75 https://www.whitehouse.gov/ostp/news-updates/2021/10/07/readout-of-white-house-summit-on-Quantum-industry-and-society/
76 https://ti.arc.nasa.gov/tech/dash/groups/quail/
77 https://Quantum.fnal.gov/
78 https://Quantum.lanl.gov/q_computing.shtml
79 https://Quantum.llnl.gov/
80 https://csrc.nist.gov/projects/post-Quantum-cryptography
81 https://www.nsf.gov/mps/Quantum/Quantum_research_at_nsf.jsp
82 https://www.energy.gov/articles/us-department-energy-announces-61-million-advance-breakthroughs-Quantum-information
83 https://theQuantumdaily.com/2021/09/05/Quantum-china-weekly-volume-21-2021-08-28-2021-09-03/

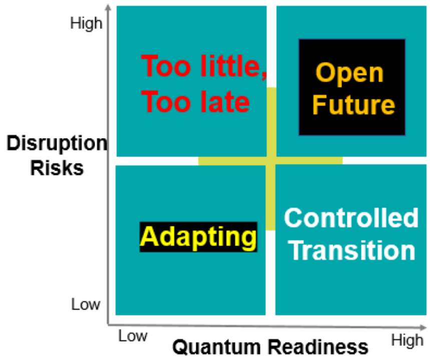
The European Union (EU–27)

In 2017, the EU launched an innovation offensive[84] to promote research and application development of Quantum 2.0. Launched in October 2018, the EU Quantum Technologies Flagship programme[85] is a long-term research and innovation initiative. The Quantum Technologies Flagship will support 24 projects with EUR 152 million in an initial phase (ramp-up) and a total of EUR 1 billion in research over a 10-year period. The EU Quantum Innovation Initiative also uses funds from the EU's Horizon 2020 research framework.[86]

Europe's research and technology organisations (RTOs) are one of the cornerstones of the EU quantum strategy to build a competitive quantum industry by supporting the private sector. Driven by public spending, RTOs aim to bridge the gap between academic knowledge and industrial capacity. After consultation with more than 2,000 quantum experts across Europe, the EU Strategic Research Agenda for quantum Research (SRA)[87] was developed, with goals for a three-year period and a vision for six to ten years. In Europe, the EU-27 countries, the UK, Switzerland, Russia and some other countries, a large number of internationally renowned research institutions and universities exists, which are involved in quantum research. Also, the high number of about 64 relevant quantum start-ups in the EU-27 countries is an important indicator of the importance of the quantum ecosystem in Europe. It is a challenge whether these start-ups achieve sufficient growth – and whether they then also keep their headquarters in Europe. Among the large European companies that are working on quantum computers respectively quantum chips are Infineon and Bosch.

H. Quantum readiness: Scenario analysis and new thinking

Four scenarios of quantum readiness 18



Source: Deutsche Bank Research

Quantum technologies can have a potentially disruptive impact on any industry with new business models and value chains emerging. This requires a specific analysis that takes into account the peculiarities of different industry sectors, company and product profiles, and the flexibility of business models in order to work towards a favourable scenario.

- Companies should start looking at Quantum 2.0 today, whereby the testing or implementation of quantum technologies should always take place in connection with a business question (business case).
- Within the quantum ecosystem, engagement of industrial companies and collaboration with research institutions is needed at this stage to initiate, finance, and drive the development of future quantum technologies to market maturity in the face of long development times.
- Access to a quantum technology knowledge base in specific projects or as needed is a challenge to be considered in talent management and education/training. Priority should be given to experts from different disciplines and skilled workers to develop and apply quantum technologies to market.

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[84] MIT Technology Review (2017). Europe Unveils Its Vision for a Quantum Future. The race to develop the next generation of Quantum technology just got hotter. URL: https://www.technologyreview.com/2017/12/20/146704/europe-unveils-its-vision-for-a-Quantum-future/
[85] https://digital-strategy.ec.europa.eu/en/policies/Quantum-technologies-flagship
[86] https://ec.europa.eu/programmes/horizon2020/en/news/eu-funds-Quantum-technology-projects
[87] https://qt.eu/app/uploads/2020/04/Strategic_Research-_Agenda_d_FINAL.pdf

— Understanding quantum technologies requires knowledge and expertise from various scientific disciplines such as mathematics, quantum physics, chemistry, computer science and engineering. In cooperation with research institutions and universities, a transfer of knowledge or the development of products can succeed.

— Quantum 2.0 technologies are, with few exceptions, not yet ready for industrial use in scientifically or economically relevant use cases today. However, this will change in the next few years and new markets related to specific quantum technologies can develop rapidly and quickly reach a high market volume.

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