Capgemini RESEARCH INSTITUTE

Quantum technologies:

How to prepare your organization for a quantum advantage now

INTRODUCTION

Quantum technologies can manipulate electrons, photons, and atoms to solve problems previously thought insolvable – and to open up exciting new opportunities. Quantum even enables us to work with counterintuitive principles such as superposition (the ability of a particle to be in two or more states simultaneously) and entanglement (the theory that changing the state of one particle can influence the behavior of another, at distance).

Quantum technologies promise exponential speed-up vis-à-vis the best available supercomputers, tap-proof communications, and ultra-precise and fast measurements – a phenomenon commonly known as the 'quantum advantage' – over classical systems that are in use today. Such technologies can bring a huge shift in the way in which businesses solve problems around optimization, mechanical simulation, and machine learning. Quantum can bring greater efficiencies than current technologies in risk management, cybersecurity, logistics, scheduling operations, discovery of lightweight materials or new drugs, and addressing climate change, among other areas.

Quantum technologies are still at an early stage – organizations are still exploring proofs of principle and concept. Most problems solvable using current quantum computers, for example, can also be solved more quickly and cost-effectively using conventional computers. Classical approaches will continue in the foreseeable future, quantum technologies will mostly be used alongside. Nevertheless, in recent years, research advances have accelerated, and the technology has started to move out of lab environments and into real-world applications.

Organizations are creating ecosystems in which they can collaborate and experiment to broaden their understanding of quantum technologies, and how they can be used in their own particular contexts. For example, Airbus has been exploring the applications of quantum technologies for at least five years, such as by identifying complex problems in its aircraft manufacturing processes, developing secure communications for aerospace platforms, or working on space-based gravimeters.[1] In 2018, it set up a quantum technology applications center to work on a set of problems in the field.[2] It collaborated with experts around the world to solve five problems around flight-physics through quantum computing, in a Quantum Challenge in 2019.[3] Two years later, it acquired a stake in quantum sensing startup, Q-Ctrl.[4] Similarly, several large organizations have moved into development of quantum technology use cases in selected areas:

- **JP Morgan** used a hybrid classical-quantum approach to determine the optimum portfolio of financial assets, which it claims can be scaled to work with portfolios of any size.[5]
- **Volkswagen Group** demonstrated the first real-time traffic-routing system based on quantum computing, to minimize wait and travel times. [6]
- Pharma major **GSK** is exploring how quantum optimization approaches would potentially scale in future, in area of drug development.[7]
- **Korea Gas Corp.** is testing a quantum sensing-based gas-safety system. Compared to the widely used infrared system, it promises to detect leaks from significantly further away and identify leaks with a lower concentration of gas.[8]

Although there is a significant hype surrounding quantum technologies, recent breakthroughs suggest that it will reach production stage in the next few years. Some quantum technologies are already being tested/piloted.

This research aims to answer the following questions:

1. Should businesses invest in quantum technologies now?
2. What opportunities are available in quantum computing, communications, and sensing, for organizations?
3. How can organizations identify potential quantum advantage?

To bring an implementation perspective, we surveyed 200 executives at global organizations who are either already working with, or planning to work with, quantum technologies (out of 857 organizations in total). Moreover, we conducted detailed interviews with more than 30 industry executives, researchers, academics, ecosystem experts, and venture capitalists in this field. The research also considers classical technologies that simulate the behavior of quantum particles. Quantum technologies will continue to have a classical component for the next many years.

EXECUTIVE SUMMARY – KEY TAKEAWAYS

A HANDFUL OF ORGANIZATIONS HAVE REACHED EARLY IMPLEMENTATION STAGE

Overall, 23% of organizations stated that they are either working with, or are planning to work with, quantum technologies. However, many are yet to reach testing/piloting stage. Nevertheless, investment is rising and 43% of organizations working on quantum technologies expect them to become available for use in at least one major commercial application within the next 3–5 years.

ORGANIZATIONS CONDUCTING EXPERIMENTS ARE TARGETING HUGE PAYOFFS IN TERMS OF TRANSFORMATIVE IMPACT

Companies moving early into quantum will benefit from greater process efficiencies and enhanced security. Seven in ten organizations in our survey agreed that due to long product-development cycles, they need to integrate quantum technologies into their processes now, to avoid missing out. Early-mover industries include energy, chemicals, automotive, aerospace, life sciences, and banking. The amount of investment needed to gain a foothold in quantum technology is relatively small, for large enterprises (with more than $1 billion of annual revenues).

QUANTUM COMPUTING IS ONLY 5–10 YEARS FROM POWERING COMMERCIAL APPLICATIONS

Organizations that have launched successful proofs of concept (PoCs) are more optimistic about achieving quantum advantage: for quantum computing, 20% of them believe that this goal is less than five years away, compared to 13% overall. The pace of development has accelerated, driven by investor interest, expanding use cases, and breakthroughs in technology frontiers. Improvements in quantum hardware, algorithms, and techniques could provide significant speed-up over classical technology models.

QUANTUM-SECURE INFORMATION SOLUTIONS ARE ALREADY AVAILABLE

Quantum communication provides unbreakable encryption. Quantum-secure information solutions are already commercially available on a limited scale. Infrastructure and software providers, startups, government bodies, standard-setting organizations, and end-user organizations are coming together to form a thriving quantum communications ecosystem.

- 58% of organizations are waiting for standards to emerge before prioritizing quantum-safe security. However, organizations can start with protecting sensitive and critical information using demonstrated techniques of quantum encryption.

43%

of organizations working on quantum technologies expect them to become available for use in at least one major commercial application within the next 3–5 years

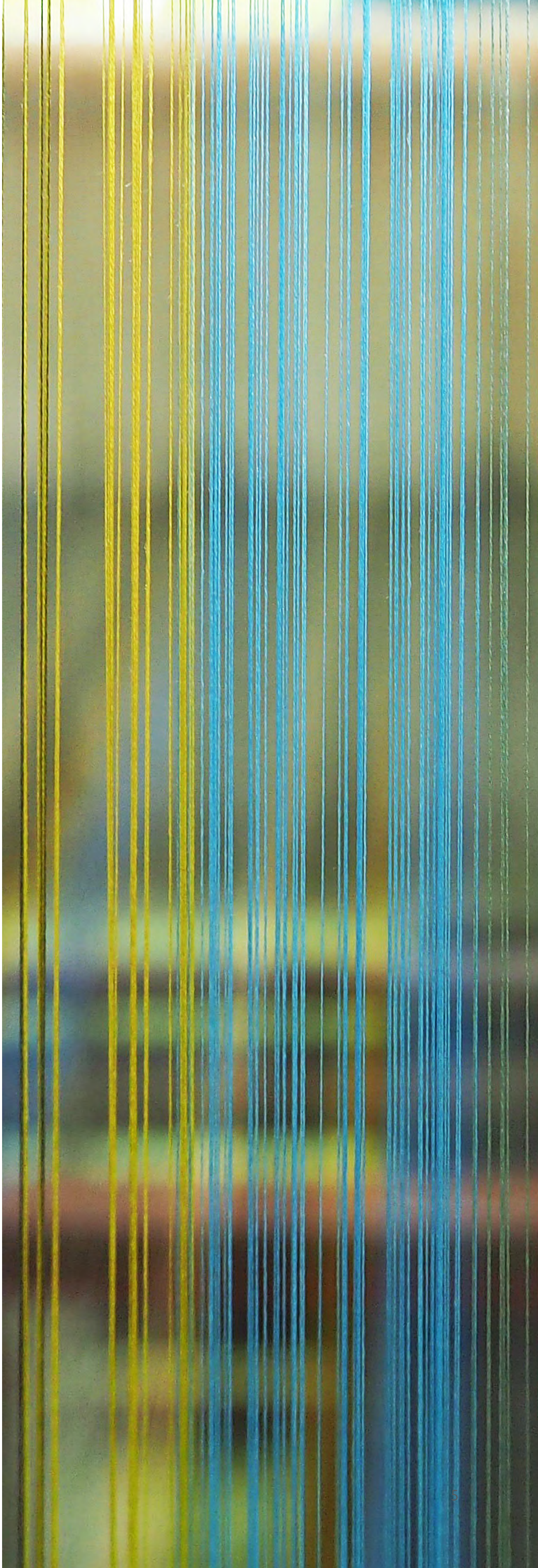
QUANTUM SENSING HAS NOVEL APPLICATIONS WHICH CAN PROVE REVOLUTIONARY FOR SOME INDUSTRIES

Of late, many quantum sensors are emerging from lab environments to industrial applications. Although quantum sensing is niche, quantum sensors can play a transformative role in: 1) prospecting or surveying land or water in mining, construction, telecom, defense; 2) GPS-free navigation in aerospace, automotive, and defense; 3) biomedical imaging; and 4) industrial process control and safety.

HOW CAN YOUR ORGANIZATION PREPARE FOR THE QUANTUM ADVANTAGE?

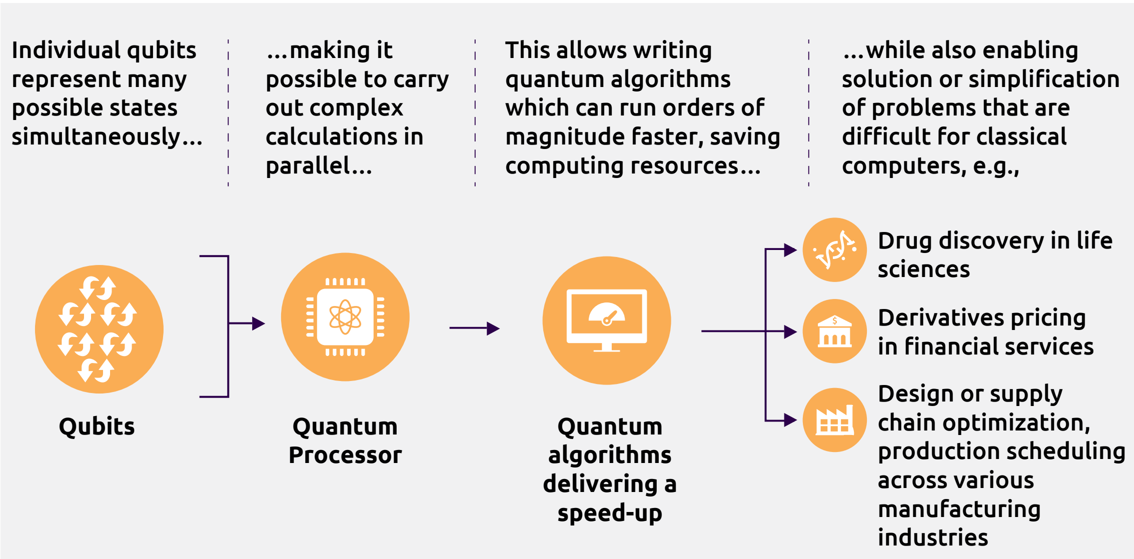
We recommend a five-step approach to harness quantum advantage as soon as it arrives:

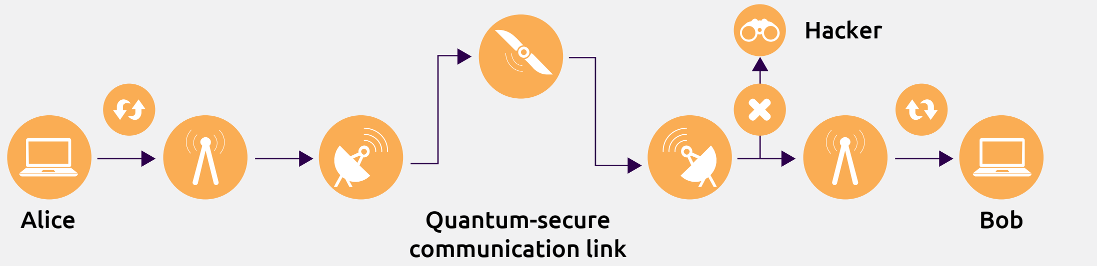
- **Assess** whether investing in quantum technologies makes sense for your business. For example, quantum computing is advantageous for specific categories of problems; it is prudent to explore them only if those problems are part of the organization's business challenges.
- **Build** a small team of experts. Ideally, this team is organized centrally with a lead researcher reporting to the organization's head of R&D or innovation.
- **Translate** the most potent use cases to small-scale quantum experiments. It will help assess whether there is a potential of quantum advantage to be gained, as well as test the capabilities of your teams.
- **Strike long-term partnerships** with technology providers to tide over technical obstacles. Around a third of organizations prefer setting up innovation centers in partnership with IT services/software/hardware companies with expertise in the field.
- **Develop** a long-term strategy to scale up the talent and skill base. As quantum programs with greater scope and scale start to be implemented, plan for developing appropriate skills in-house.

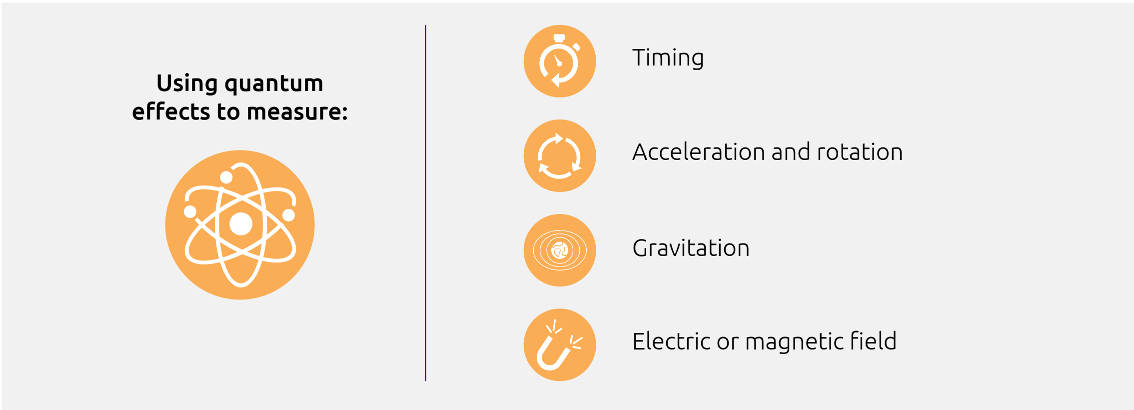


DEFINING QUANTUM TECHNOLOGIES

This research focuses on three broad quantum technologies: **Quantum computing, Quantum communication and security,** and **Quantum sensing**. By 'traditional' or 'classical' computing, we mean computing systems currently in use that do not harness quantum properties.

<table>
<tr><th colspan="2">Quantum computing</th></tr>
<tr><td>What is it and how does it work?</td><td>Use of quantum properties to perform computations. The most basic unit of quantum computation is called a qubit. Qubits can acquire any value between 0 and 1 at the same time. Quantum computing, in some cases, provides an exponential speed-up in computing power.

</td></tr>
<tr><td>Current state</td><td>• Quantum computers solve 'toy' problems that are representative of real-world problems
• Organizations are identifying the right problems to solve with quantum computers and experimenting with potential use cases, which can be scaled up once error-free quantum computers with large-enough number of qubits are available.</td></tr>
<tr><td>Key opportunities</td><td>• Solving problems requiring complex optimization, simulation, or machine learning.</td></tr>
<tr><td>Key challenges</td><td>• Current quantum computers have outputs that are 'noisy' (i.e. have high error rates).
• They require specific conditions (e.g. superconducting qubits require ultra-cold temperatures in which to operate efficiently).
• At-scale applications require thousands of qubits while current quantum computers provide a fraction of that.</td></tr>
</table>

Quantum communication and security	
What is it and how does it work?	Transmitting and controlling information using the laws of quantum mechanics i.e. by using qubits as opposed to bits. Quantum security involves securing information transfer using quantum theory. **Quantum-key distribution** (QKD) is a key distribution protocol to generate "quantum" keys that can be used for secure information exchange over a classical channel with classical cryptography techniques. The keys are distributed using rules of quantum mechanics where any act of listening in leaves a detectable sign of snooping. **1. Alice and Bob generate and share quantum keys using QKD** **2. Alice then encrypts her message using this quantum key and any classical encryption algorithm** **3. Only Bob, who has access to quantum keys, can access this message.** **4. When used in a provably secure encryption like one time pad, the quantum keys guarantee that the message cannot be hacked.** 
Current state	• The quantum communication network, albeit simplistic (mostly point-to-point or requiring non-quantum, lower security interfaces like "trusted nodes"), is already a reality. • Dutch network operator **KPN** recently demonstrated a QKD system, in which multiple users can connect to a central node and securely exchange information.[9]
Key opportunities	• Secure communication and networking. • Secure data transfer that is critical to confidential computing, data storage, and sharing.
Key challenges	• Transmitting quantum information securely over long distances.

	Quantum sensing
What is it and how does it work?	**Use of quantum properties or phenomena to measure a physical quantity with high precision**  Quantum sensors provide unprecedented precision in measurement. These sensors are already deployed in areas such as biomedical imaging, timing synchronization of satellites, and detection of gas leakages.
Current state	• There are many different quantum sensing methods, and they have diverse technology readiness levels and application areas. • Recently, many quantum sensors have emerged from lab environments to be used in industrial applications.
Key opportunities	• Measuring electric and magnetic fields accurately. • Measuring physical quantities against atomic properties. • Areas where current technologies are difficult to deploy, such as navigation in complex terrain (underground/underwater). Over the long term, development in quantum sensing could advance GPS-free navigation for autonomous vehicles and early-warning systems for natural disasters, understanding of neurological diseases, etc.
Key challenges	• Uneconomical trade-offs in cost vs improvements in performance.

Any company that does not start this journey today is a company that is at severe risk of losing any sort of meaningful position within its industry in the next 5–10 years,"

André König
Managing Partner
Entanglement Capital

01 WHY INVEST IN QUANTUM?

ALTHOUGH THE TECHNOLOGY IS NASCENT, ITS IMPACT COULD BE TRANSFORMATIVE

Many key quantum technologies are still in their infancy. Some projects have reached proof-of-concept stage, but tangible, real-world advantages over existing technologies remain elusive. However, quantum's impact can be broad and transformative. Across industries, the use cases abound, ranging from optimization to machine learning, simulation, precision sensing, and security. For businesses, this translates into greater speed, instant results, more precise measurement, and more secure communications.

Gaining a foothold in this transformative technology, then, is important to achieving competitive advantage over peers. Conversely, there is no reward in waiting for the technology to emerge before investing. Organizations, that are at implementation, state that there is a lead time of at least two years in identifying the right problems to solve, learning how to use the technology to solve them, and building a talent base to implement it. Most organizations are already working towards becoming 'quantum-ready' – having the resources and processes in place to test and align quantum technology for use in their unique environments. Additionally they are committing greater resources - as per our research, 20% of all organizations and 85% of the ones working or planning to work with quantum expect to increase investments in the technology in the next year.

According to **Nadia Haider, Lead Applied Electromagnetic Scientist at Netherlands-based QuTech**, an institute for quantum computing and quantum internet, founded by TNO, an applied scientific research organization, and TU Delft University, *"Now we are able to control quantum systems much better, we can use entanglement or superposition. Our ability to really work with this technology has exponentially increased. There is more trust that this is not only useful for fundamental research, but we can bring it to real applications."*

ADVANCES IN QUANTUM TECHNOLOGIES ARE GATHERING PACE AND EARLY APPLICATIONS ARE EXPECTED WITHIN THE NEXT FIVE YEARS

Quantum technologies have gained mainstream industrial attention:

- In China, the world's first integrated quantum communication network was established in 2021, combining ground optical fibers with two ground-to-satellite links to achieve quantum key distribution (QKD) over 4,600 kilometers. It can serve banks, municipal power grids, and e-government websites.[10]
- A Goldman Sachs prediction from 2021 states that quantum computing could begin to yield quantum advantage on practical financial applications within the next five years.[11]

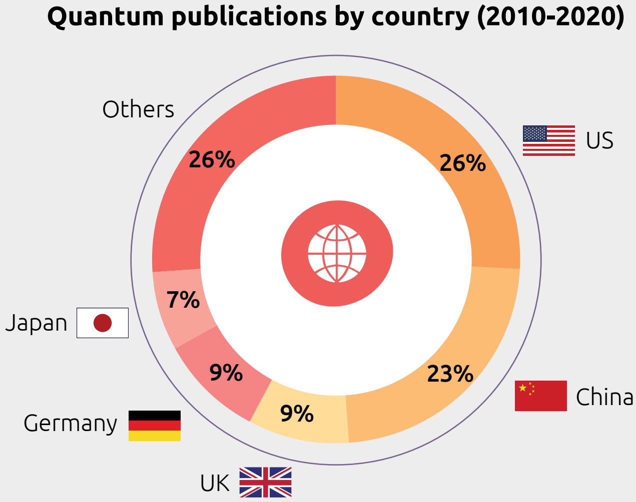
23%

of organizations are either working or planning to work on quantum technologies.

US AND CHINA LEAD IN PUBLICATIONS RELATED TO QUANTUM TECHNOLOGY

The race to advance quantum technologies is heating up. US, China, and European countries have announced significant public funding in the technologies. They also lead in the number of publications in the field. Among the top five countries in publications (from 2010 to 2020) on quantum technologies, US and China lead, while UK and Germany follow each other closely.

Figure 1. US has led in publication of research papers on quantum technologies during 2010-2020



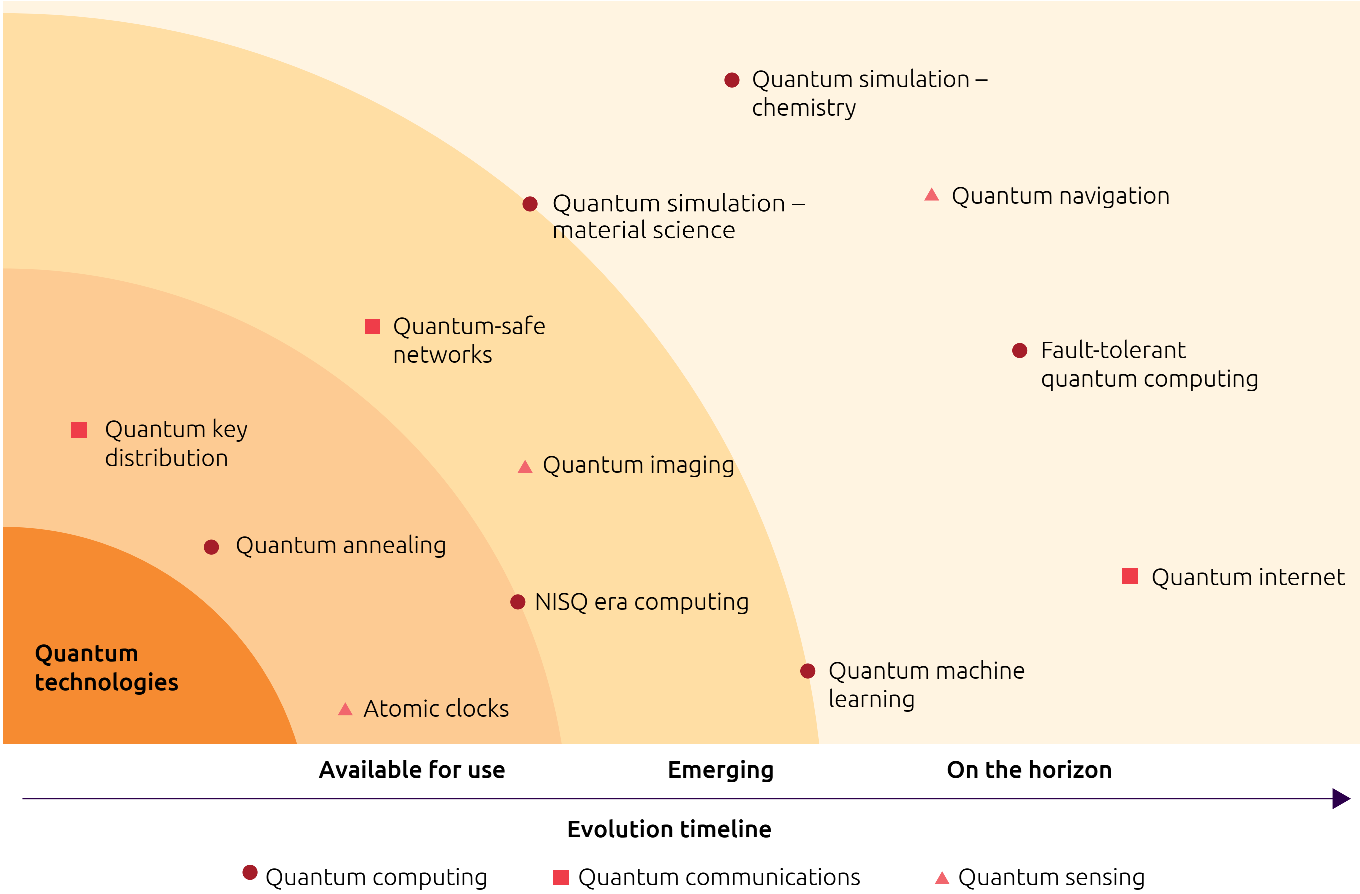
Source: Harvard Kennedy School, Belfer Center for Science and International Affairs, "The Great Tech Rivalry: China vs the U.S.," December 2021. Numbers have been rounded.

The countries also differ in terms of focus: US is strong in quantum computing, while China leads in quantum communications.[12] The UK's quantum technology program has a strong focus on quantum sensing technologies.[13]

Our ability to really work with this technology has exponentially increased. There is more trust that this is not only useful for fundamental research, but we can bring it to real applications."

Nadia Haider
Lead Applied Electromagnetic Scientist
QuTech

Figure 2. Likely evolution of quantum technologies/key use cases



Source: Capgemini Research Institute analysis.

Definitions of stages:
Available for use: Ready to be deployed in a limited way to at least one commercial application.
Emerging: several proofs of concept developed, but not ready for commercial deployment.
On the horizon: At proof-of-principle stage; requires several technical breakthroughs to advance to the next stage.

For definitions of terms used, refer to the Appendix.

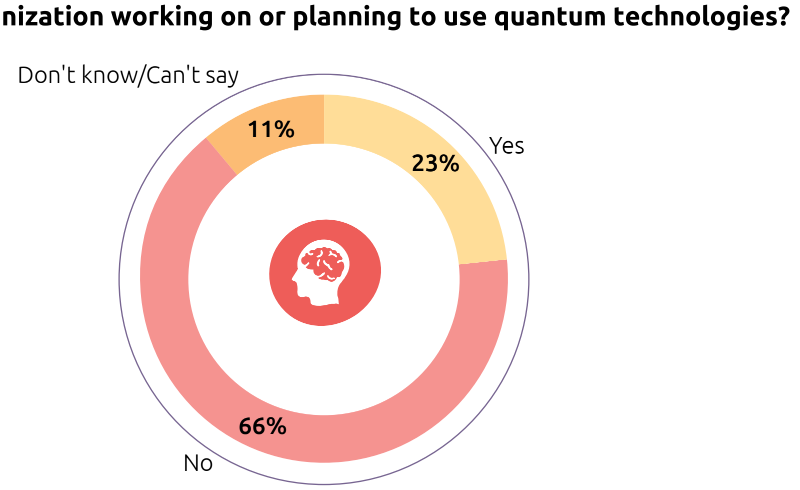
4%

of all surveyed organizations are already early movers in quantum technologies - conducting experiments and pilots, and achieving early results

ORGANIZATIONS REACHING IMPLEMENTATION STAGES HAVE BEEN WORKING ON QUANTUM TECHNOLOGIES FOR MORE THAN TWO YEARS

Overall, 23% of organizations are either working or planning to work on quantum technologies. Of these, many are yet to reach the testing/piloting stage.

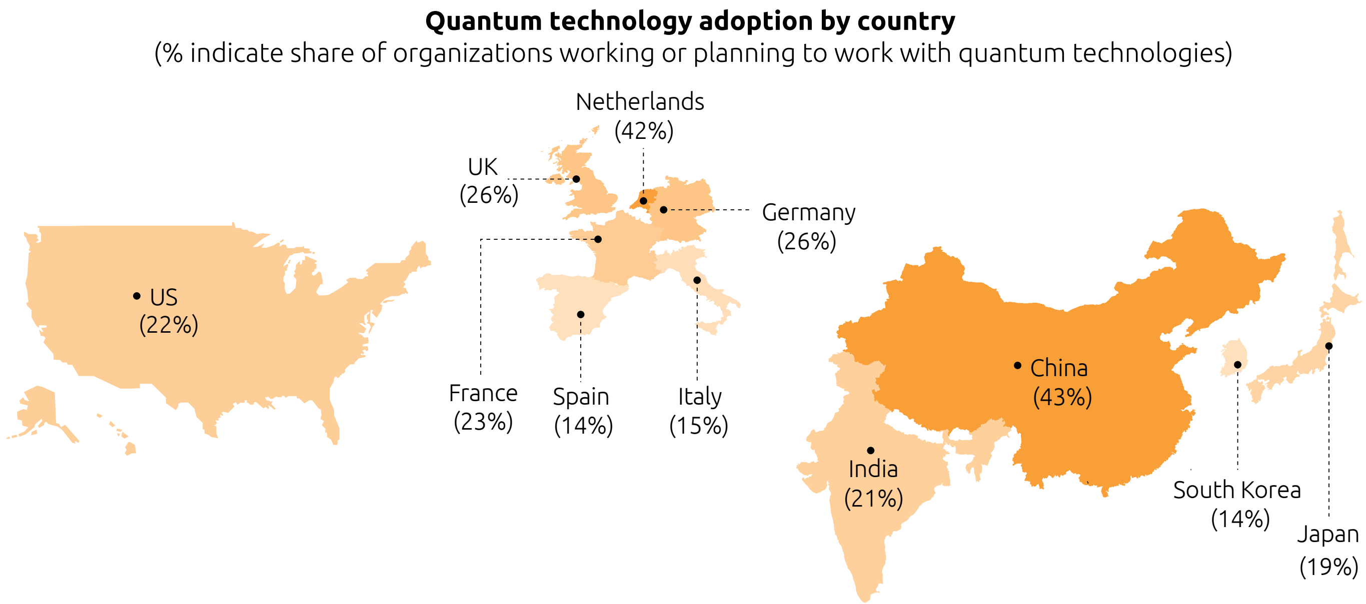
Figure 3. 23% of organizations are experimenting or planning to experiment with quantum technologies



Source: Capgemini Research Institute Quantum Technologies Survey, N=857 organizations, November–December 2021.

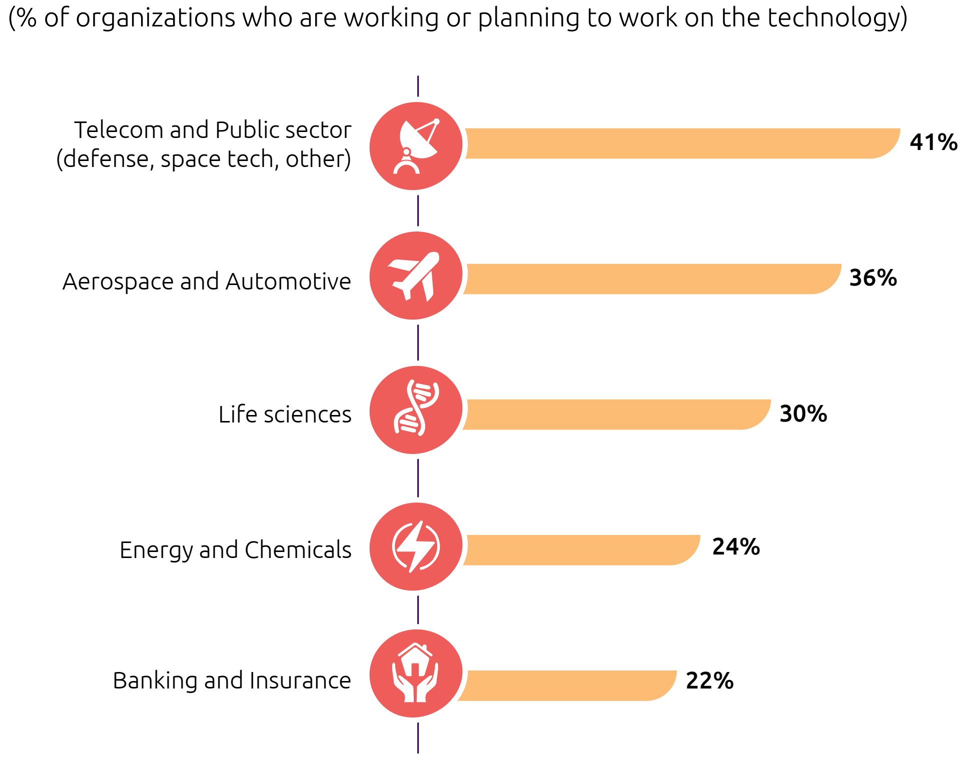
"China and the Netherlands have the largest share of companies working on or planning to work on quantum technologies, well ahead of Germany and the UK"

Figure 4. Most quantum technology adopters come from China and the Netherlands



Source: Capgemini Research Institute Quantum Technologies Survey, N=857 organizations, November–December 2021.

Figure 5. Quantum technology adopters by sector

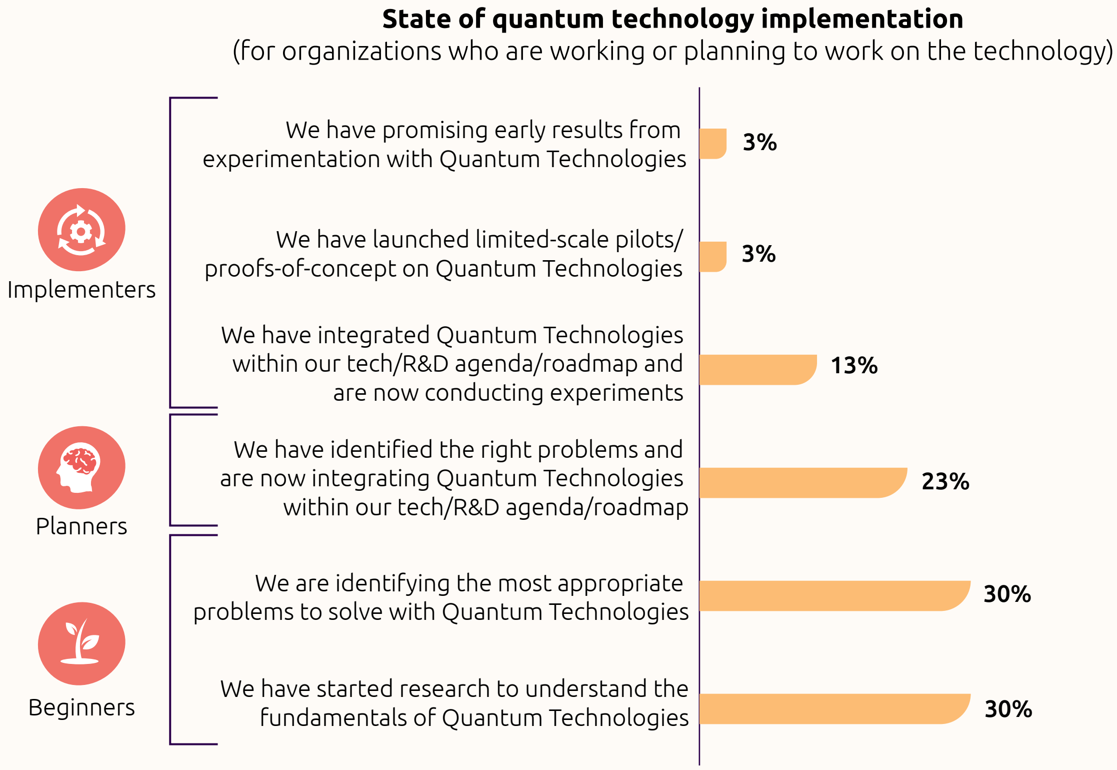


Source: Capgemini Research Institute Quantum Technologies Survey, N=857 organizations, November–December 2021.

As Figure 6 shows, 6% of organizations (within the 23% of organizations who are planning or working on quantum technologies) have reached initial implementation stages. Seventy-two percent of these organizations have been working on this tech for two or more years. This implies that even to reach implementation, companies need to invest time in building a base (the right skills, identifying problems/use cases, conducting lab experiments, or striking partnerships). Once these technologies are mature enough, there is likely to be strong competition for skills or resources. The companies that already have these in place are likely to gain significant advantage over their peers. As **Gopal Karemore, Principal Data Scientist at a Denmark-based multinational pharma company**, suggests, *"Some businesses think that the technology is not mature right now, [so] why should we invest? But what if the technology is successful in the future and all your competitors started the journey long before you? All the low-hanging fruits are gone."*

Additionally, 13% of organizations (within the 23% sample) are conducting experiments with the technology. Taken together, 19% of organizations who are planning or working on quantum technologies are **'early movers'** into quantum technology. Effectively, early movers constitute 4% of the total sample of organizations.

Figure 6. 6% of organizations have launched limited-scale pilots or have early promising results from quantum technologies

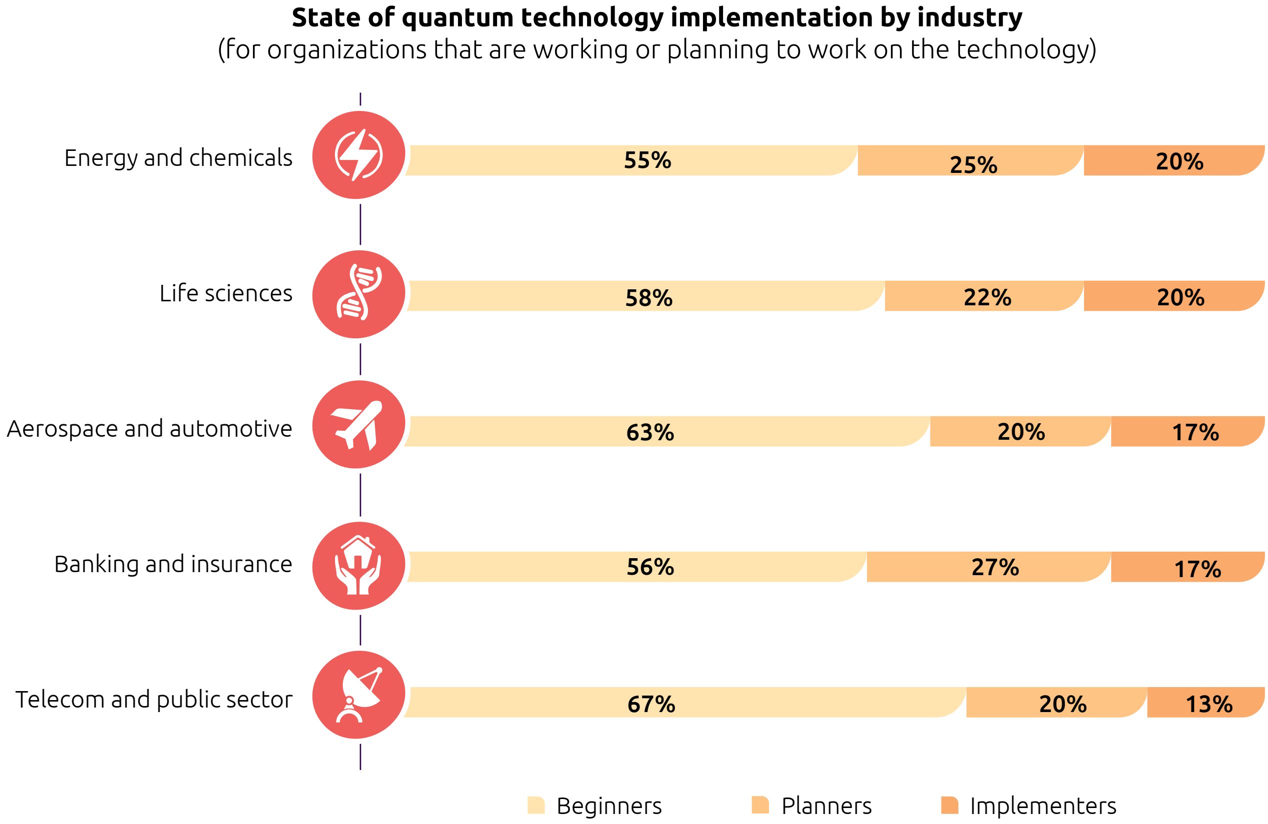


Source: Capgemini Research Institute survey, N=200 organizations working or planning to work on quantum technologies; numbers may not total 100% due to rounding.

ENERGY AND CHEMICALS, AEROSPACE, AND LIFE SCIENCES LEAD IN QUANTUM IMPLEMENTATION

In energy and chemicals, it has become a common cause to improve sustainability. Popular use cases range from discovery of new materials for battery manufacturing, to sensing and mitigating harmful industrial gases. Similarly, life sciences companies are trying to shorten the drug-development cycle using quantum computing.

Figure 7. One in five energy, chemicals, and life sciences organizations are implementers - launching experiments, pilots, and achieving early results



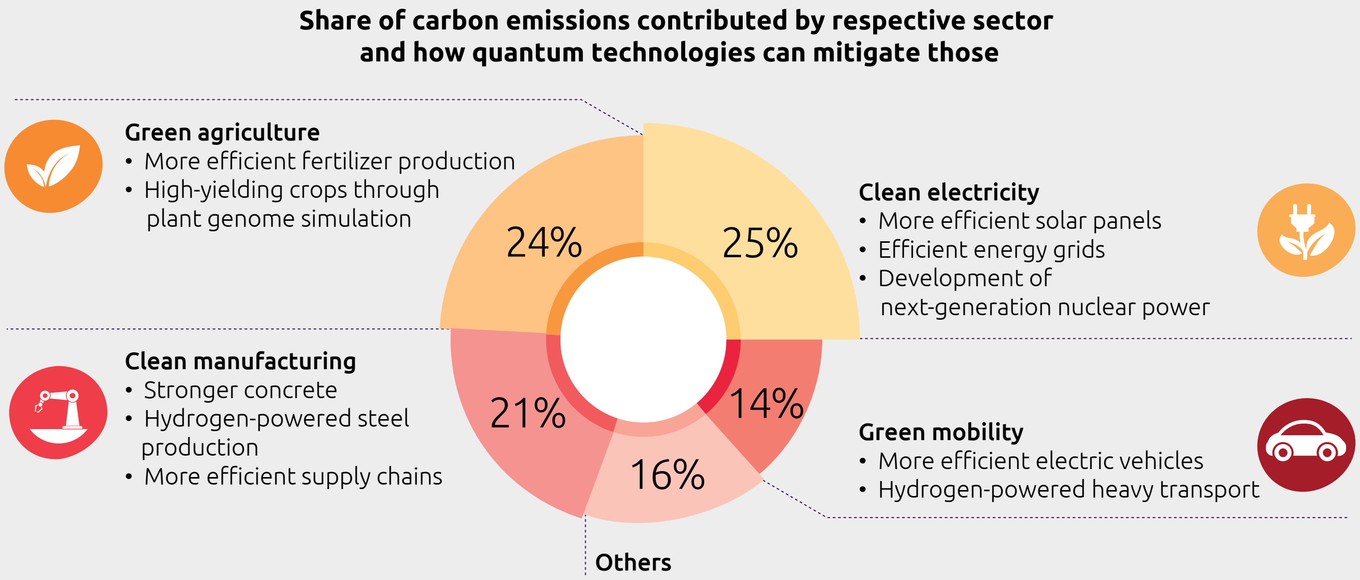
Source: Capgemini Research Institute survey, N=200 organizations working or planning to work on quantum technologies
Note: The data points are directional in nature. The definitions of implementers, planners, and beginners follows from Figure 6.

FOUR AREAS WHERE QUANTUM TECHNOLOGIES CAN BOOST SUSTAINABILITY

Quantum computers can be used to develop and evaluate the technologies that we need to get to net-zero emissions. Figure 8 shows four key areas where quantum technologies can help in improving environmental sustainability. For example, electricity production accounts for 25%[14] of greenhouse gas emissions. Quantum computing can help through simulations of novel photovoltaic materials that either improve the efficiency or reduce the costs of manufacturing solar panels.

Similarly, manufacturing accounts for nearly 21%[15] of total emissions. A way to curb its environmental impact is to make stronger concrete using quantum simulations to find the right combination of polymers.

Figure 8. Four key areas where quantum technologies can help cut carbon emissions.



Source: Capgemini Research Institute analysis; US Environment Protection Agency (EPA).

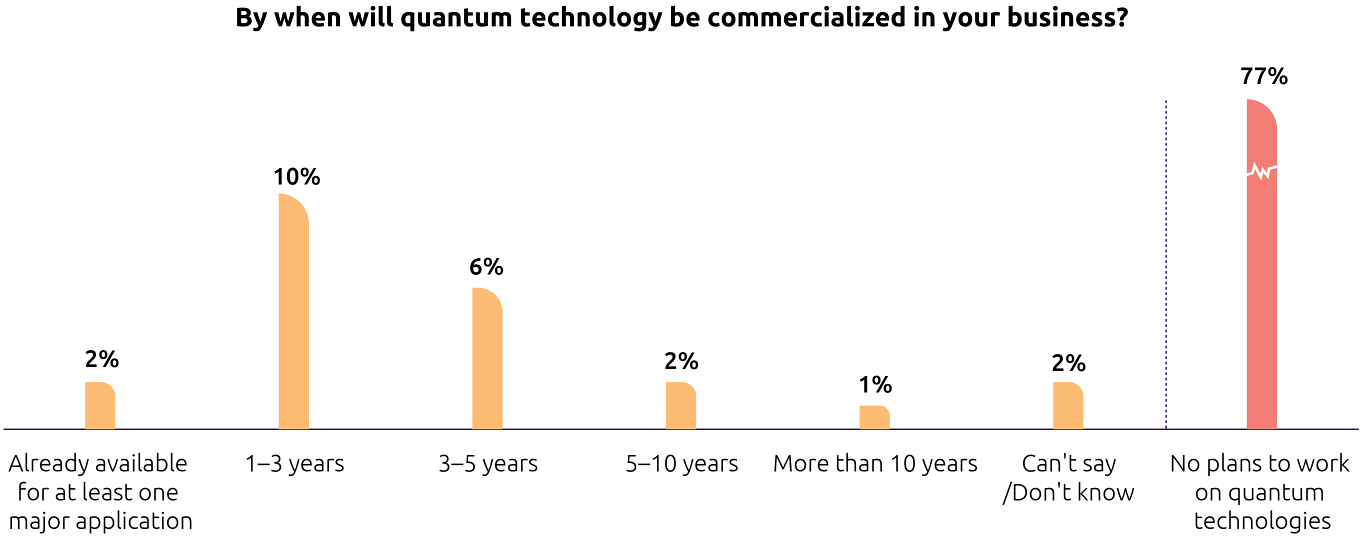
Quantum computing can directly be applied to optimize energy usage within an organization. Although still uncertain, computing on quantum systems can reduce the overall energy consumption compared with getting the same output from classical systems. Quantum computers can process complex computation more easily but, in some cases, it also requires specialized cooling equipment to maintain quantum states. As quantum computing scales, it is expected that the requirement of cooling equipment will not scale linearly, saving energy intensive compute resources.

We also found a step-change in perceptions of quantum technologies. In the last year, organizations working on quantum technologies have observed improved awareness, understanding, and support for the technologies within their entities. Compared to the previous year:

- 60% said they had a more nuanced understanding of quantum technology
- 58% had secured C-level support for quantum initiatives
- 51% stated that they were more aware of the potential of quantum technology.

Companies have also expressed more optimism about quantum technologies reaching implementation stage: around 10% of organizations expect quantum technology to become available for use in at least one major commercial application in their business within the next three years.

Figure 9. 10% of organizations expect quantum technology to become available for use in at least one major commercial application in 1–3 years.



Source: Capgemini Research Institute survey, N=857 organizations, including 77% of those which are neither working nor planning to work on quantum technologies.

IMPLEMENTERS ARE LIKELY TO MAKE CONSIDERABLE GAINS WITH MINIMAL INVESTMENT

For large enterprises, investment needed to build a quantum lab are relatively small. For several of the experts that we spoke to across sectors, the overall set-up cost was less than $5 million. Assuming IT spend to be around 2%[16] of revenue for organizations with revenue over $20 billion, this represents a small proportion. Organizations can dedicate a few members from their existing innovation labs to add new skills (e.g. quantum physicists to set up a lab). Access to quantum hardware can be run like cloud on a pay-per-use or per-unit-of-time basis.

Seven in ten organizations in our survey agreed that, due to long product development cycles in their businesses, they need to integrate quantum technologies into their processes now. Some early mover industries include life sciences, chemicals, energy, automotive, aerospace and defense. Venture capital investments are pouring in too. By November 2021, quantum technologies had attracted $3 billion of private funding, compared with an aggregate of $5 billion since 2002.[17] *"Any company that does not start this journey today is a company that is at severe risk of losing any sort of meaningful position within its industry in the next 5–10 years,"* according to **André König, Managing Partner at Entanglement Capital,** a venture capital firm focused on quantum technologies.

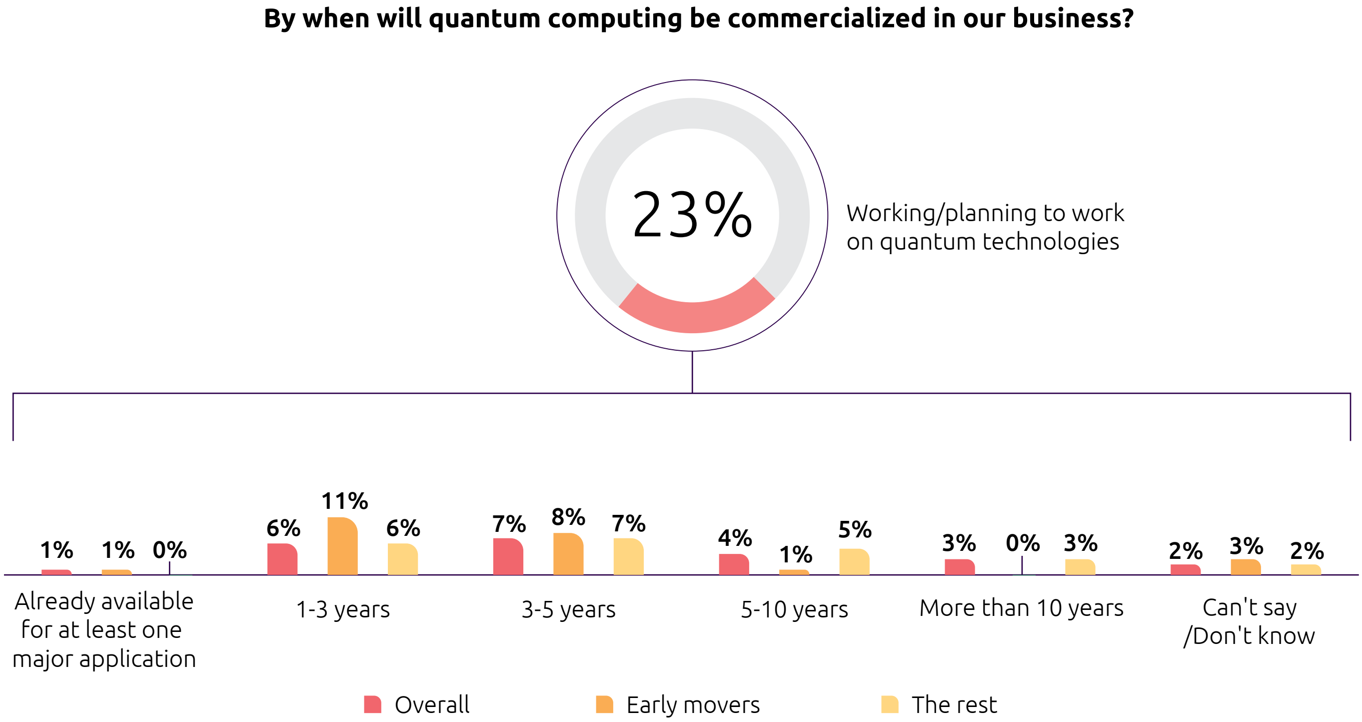
> *Some businesses think that the technology is not mature right now, [so] why should we invest? But what if the technology is successful in the future and all your competitors started the journey long before you? All the low-hanging fruits are gone."*
>
> **Gopal Karemore**
> Principal Data Scientist
> Denmark-based multinational pharma company

02 QUANTUM COMPUTING

THE QUANTUM TECHNOLOGY WITH THE GREATEST POTENTIAL IS LESS THAN 10 YEARS AWAY FROM POWERING COMMERCIAL APPLICATIONS

Quantum computing has the highest potential of all quantum fields but it is also the least mature. On average, respondents to our survey believe that the first commercial quantum computing applications are five years away (see Figure 10). Early-mover organizations are more optimistic about achieving commercialization and quantum advantage: 20% believe that it is less than five years away, compared to 13% overall. In other words, those closest to the action show most conviction.

Figure 10. 20% of early movers and 13% of all organizations expect quantum computing to become available for use in at least one major commercial application in less than five years



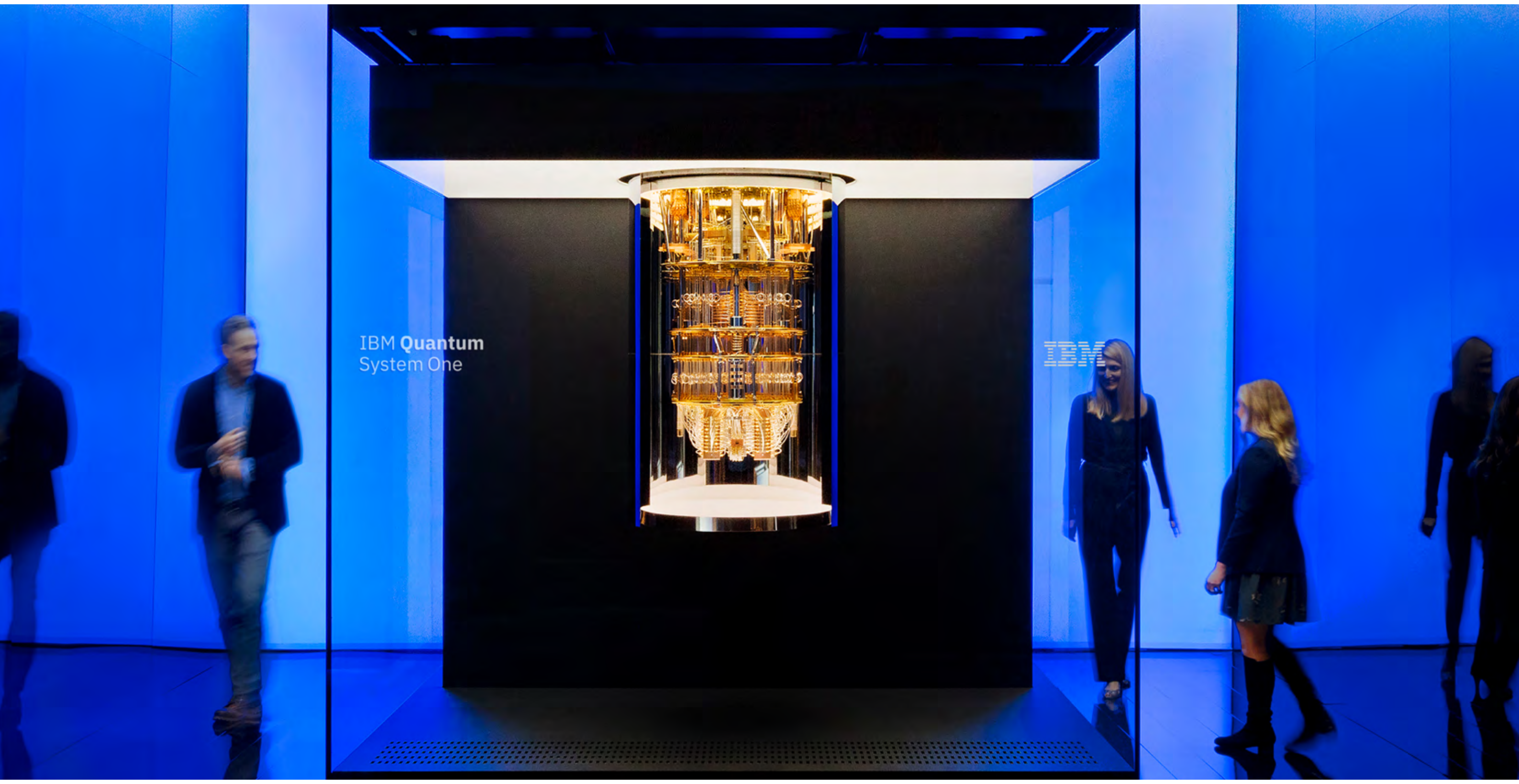
Source: Capgemini Research Institute survey, N=857 organizations, including 77% of those that are neither working nor planning to work on quantum technologies.

Development has accelerated, driven by investor interest, expanding use cases, and technology breakthroughs. Improvement in quantum hardware, algorithms, and techniques is boosting progress.

Peter Bordow, SVP & principal architect for Advanced Technology & head of Quantum and Emerging Technology Research & Development at Wells Fargo says it's appropriate to be cautiously optimistic about developments in quantum computing: *"It can take quite a bit of time for advances and breakthroughs in the laboratory to reach commercialization or production. So, you have to be diligent about your research and what your expectations are. Yet, I'm hopeful that quantum advantage in some use cases, such as modeling complex systems, financial portfolio optimization, and drug development, looks promising in the next three to five years."*

QUANTUM COMPUTING HAS THE POTENTIAL TO SOLVE COMPLEX BUSINESS PROBLEMS

The principal reason for optimism is the broad applicability to problems in business. While quantum has long been used to test 'toy' problems that demonstrate the precision of quantum simulation, these have a lot in common with a range of real-world business problems across industry verticals (see below).



Source: IBM.

WHICH PROBLEMS ARE RIPE FOR A QUANTUM ADVANTAGE?

There are several problem categories that are complex even for today's high performance computers – aggregation of computing power to perform calculations at high speed. These problems have mathematical equivalents more suited for quantum computers, as they can perform multiple calculations in parallel (see Figure 11).

Figure 11. Key high complexity problems suited for quantum computers

Problem type/domain	Business/industrial applications
Travelling salesman problem: Given a list of cities and distance between them, what is the shortest possible route that visits each city once and returns to the origin?	Supply chain optimization, distribution and routing, circuit design, production scheduling, fleet management and insurance, telecom and electrical network optimization
Knapsack problem or bin packing problem: Filling a knapsack in an optimal way with a given set of weights and associated values, so that the total weight is less than or equal to a limit and total value is as large as possible.	Cargo loading optimization for trucks or containers, last-mile delivery, portfolio optimization, lot sizing, design optimization
Molecular simulation and protein folding: How to simulate the behavior and interaction of molecules in chemical reactions? How a protein's amino acid sequence dictates its 3-D structure?	Drug discovery, EV battery development, new material development, carbon capture, studying chemical reactions and behavior of superconducting materials for medical scanners
Integer factoring or prime factorization: How to decompose a large number into a product of smaller integers/primes?	Cryptography, digital signatures, computing Fast Fourier Transforms (FFT) which are used in MRI, music, astronomy, and robotics

Source: Capgemini Research Institute analysis.

Quantum Machine Learning is also a significant area for problems involving classification, convolutional neural networks, generative adversarial networks, etc. and can be used for generating synthetic datasets for training, say, autonomous vehicles.

Computational complexity theory classifies various problem types into the exact boundaries of these various classes of problems are still discussed and debated among mathematicians and computer scientists. As new algorithms to solve complex problems continue to emerge, our understanding of quantum advantage will evolve as well.

We realized that there were, let's say, lower-hanging fruits around quantum simulation for materials – to help us discover materials to capture and convert CO2 efficiently. And, secondly, we looked at optimization problems in our systems, operations, mobility, and offshore wind farms"

Philippe Cordier
Research Program Director, Scientific Computing, Data Science & AI
Total Energies

As the market environment becomes increasingly dynamic, problems will become more computationally intensive (i.e. harder to solve). Consider pricing of complex derivatives. As the market evolves towards more complex products, the estimation of these products is dependent on more criteria and is getting further and further away from the calculation capacities of current high performance computers.

Philippe Cordier, Research Program Director – Scientific Computing, Data Science & AI at Total Energies, explains the problems they're looking to tackle with quantum computing: *"We realized that there were, let's say, lower-hanging fruits around quantum simulation for materials – to help us discover materials to capture and convert CO2 efficiently. And, secondly, we looked at optimization problems in our systems, operations, mobility, and offshore wind farms."*

Joydip Ghosh, Quantum Computing Project Lead at Ford Research & Advanced Engineering told us about the variety of problems they have tried to tackle with quantum computing: *"We have been experimenting with solving optimization problems such as vehicle route optimization and classification using quantum machine learning. Quantum speed-up has big potential in these areas for the automotive industry."*

BANKING AND LIFE SCIENCES ORGANIZATIONS HAVE STARTED PILOTING KEY USE CASES

Solutions to the above problems translate into a wide variety of use cases in business, involving combinatorial optimization (routing, scheduling, etc.) and simulation. As a result, scores of use cases across industries have been identified and many are being tested. (See Figure 12)

Figure 12. Leading quantum computing use cases being tested, by industry

	Automotive	Aerospace	Chemicals	Financial Services	Life Sciences
Leading quantum computing use cases being trialled, by industry	Traffic flow management Car design optimization Crash simulation Battery manufacturing Industrial efficiency Supply chain optimization	Air traffic control Airplane design optimization Optimize fleet, crew, fuel, etc. Cargo loading optimization Supply chain optimization	Modelling and optimization of chemical reactions Battery manufacturing Molecular simulation and discovery	Risk management Dynamic portfolio management Derivatives pricing Fraud detection	Biological target identification Compound lead identification and optimization Drug target interactions Disease diagnosis Clinical trial optimization
Manufacturing use cases across verticals	**New materials discovery**	**Plant scheduling**	**Production process optimization**	**Supply chain optimization**	**Predictive maintenance**
Potential benefits	Efficient car manufacturing and sales, Better materials design, entry into new mobility markets	Efficient aircraft manufacturing and logistics	Entry into new markets through novel materials; efficient production	Better understanding of risk exposures, superior portfolio returns, low risk of fraud	Faster drug launches, efficient drug development, higher return on capital, entry into new markets

Source: Capgemini Research Institute interviews and secondary research.

Naturally, the industries that are likely to generate a transformative impact are also the ones that have been active in the field of quantum computing. We believe the following three industries are best-suited to the high-impact, high-adoption category (see Figure 13):

Financial services – Where a large number of optimization opportunities exist, such as using a Monte Carlo simulation (used in pricing derivatives and evaluating risk that is complex and computationally intensive for risk evaluation, financial planning, derivatives pricing, etc.). Monte Carlo simulation provides a range of possible outcomes and attached probabilities to each outcome for an action.

"Because of the volume of data a quantum computer can manipulate, [a volume] not possible with the classical computer, this could bring better-quality results as we can manipulate more data to get a precise outcome, meaning reduced risk or better pricing to clients. Secondly, we expect faster answers, allowing us to adapt our strategy more quickly," according to **Eric Mely, IT project director and Quantum community leader at Société Générale**.

- **Life Sciences –** Where there is high failure rate of molecules reaching late-stage development.

High-potential use cases include accurate simulation of drug molecules and their interaction with biological targets, optimizing the design and development of new molecules, and optimizing the screening of target molecules for drug development.

"In the case of small molecule therapeutics design, there are 10^{60} chemicals that can be synthesized as a potential drug candidate. Also, in the biologics therapeutics design, there are D to the power of K design solutions, D being amino acid sequence identity, and K being designable sequence position. This computational drug design involves an astronomically large search space beyond traditional classical computers' capacity. Quantum computing can help select contenders for pharma APIs, which is potentially useful in the further stages of drug development. I think the design of experiment (DoE) and lead optimization is going to be the most important beneficiary of quantum computing in the process of drug development,"

suggests **Gopal Karemore from a Denmark-based multinational pharma company.**

- **Manufacturing (across verticals) –** Which offers substantial scope of bringing efficiencies in plant operations, supply chain, and materials research.

Figure 13. Top sectors with high potential applications of quantum computing

	Financial Services **Goldman Sachs**	Life Sciences **Toray Industries**	Manufacturing/ Automotive **Daimler**
Problem statement	Complex calculations needed for Monte Carlo simulation are typically executed only once, which means that, in volatile markets, traders are forced to use outdated results.	During drug discovery, the process of lead identification – which involves identifying the molecule which can mitigate infection – takes almost two years and has a high risk of failure.	Electric vehicles (EVs) face limitations due to the relatively low capacity and charge speed of their batteries
Quantum speed-up or advantage	Quantum algorithms can perform Monte Carlo simulations 1,000x faster than classical methods.	Using combinatorial optimization, quantum computing can help compress the time to identify the lead molecule to about eight weeks	Quantum simulation will help design the next generation of batteries as they have the potential to precisely simulate the fundamental behavior of molecules
Solution approach	Goldman Sachs applied a shallow Monte Carlo algorithm that's 100x faster than classical methods, and could be used on a machine likely to be available in the next 5–10 years	Toray Industries used quantum-inspired digital annealers to more precisely identify drug leads for further development, reducing failure rates.	Daimler used quantum computing to research next-generation lithium sulfur (Li-S) batteries, which are expected to be more powerful, longer lasting, and cheaper than widely used lithium-ion batteries.

Source: Tudor Giurgica-Tiron et al, "Low depth algorithms for quantum amplitude estimation," December 2020. Fujitsu, "Disrupting and accelerating drug discovery for faster and more accurate lead identification," 2021. IBM website, "IBM and Daimler use quantum computer to develop next-gen batteries," January 8, 2020.

Because of the volume of data a quantum computer can manipulate, [a volume] not possible with the classical computer, this could bring better-quality results as we can manipulate more data to get a precise outcome, meaning reduced risk or better pricing to clients. Secondly, we expect faster answers, allowing us to adapt our strategy more quickly"

Eric Mely
IT project director and Quantum community leader Société Générale.

HARDWARE AND ALGORITHMIC LIMITATIONS ARE EASING

Recent advances in relation to the major practical limitations (decoherence, error-correction, or low qubit count) on quantum computing are promising. Below are two examples of recent breakthroughs related to these limitations:

- Decoherence: Due to unwanted interaction of qubits with their environment, the quantum state collapses. To mitigate this, in February 2022, researchers at the Massachusetts Institute of Technology (MIT) were able to maintain qubits in the quantum state for 10 seconds, up from a few microseconds or milliseconds.[18]
- Error-correction: Adding more qubits increases the error rate of output. To tackle this, in July 2021, Honeywell demonstrated the ability to detect and correct the two types of errors found in quantum computers, in real-time.[19]

These limitations are all interrelated. For example, a challenge in error correction is that it requires more qubits, but currently qubit count is also limited. Furthermore, the topology of qubits (how qubits are organized and interact with each other) plays an important role. Quantum volume (QV), a holistic metric that includes not only the qubit count and quality, but also topology, is used to evaluate the capability of quantum computers. In December 2021, Honeywell reported a QV of 2,048 on its quantum computers, a 16-fold increase on the quantum computer it had launched in October 2020.[20]

Another challenge in developing scalable quantum computers is the verification of results produced. Because quantum computers are designed to tackle problems considered intractable for classical computers, the solutions can also be difficult to verify for correctness using conventional computers.

Elham Kashefi, Professor of Quantum Computing at the School of Informatics, University of Edinburgh, who has been researching this area for nearly a decade, told us, *"Quantum verification is going to be a critical enabler to quantum computing. How do you verify whether the output of the quantum computer is correct at all? We have successfully demonstrated a verification protocol to test a quantum computer's ability to perform measurement-based quantum computations."*

Once quantum computers are ready, the ability to access them securely and privately will be of paramount importance. A protocol developed by Professor Kashefi's team called Blind Quantum Computation will play a critical role. Professor Kashefi comments: *"Blind quantum computation allows a user to carry out a quantum computation on a quantum computer with input/output data, with the computation remaining completely private."* The technique can allow for multiple use cases that involve distributed computing. Companies can exchange data securely with other organizations and use the resultant aggregated data for insights, which could be of huge importance for the public services and healthcare sectors.

Quantum verification is going to be a critical enabler to quantum computing. How do you verify whether the output of the quantum computer is correct at all? We have successfully demonstrated a verification protocol to test a quantum computer's ability to perform measurement-based quantum computations."

Elham Kashefi
Professor of Quantum Computing
School of Informatics University of Edinburgh

INTERVIEW WITH PETER BORDOW, SVP & PRINCIPAL ARCHITECT FOR ADVANCED TECHNOLOGY & HEAD OF QUANTUM AND EMERGING TECHNOLOGY RESEARCH & DEVELOPMENT, WELLS FARGO

Q. Please tell us about Wells Fargo's vision and objectives for quantum computing?

A. I categorize our objectives into two broad areas: quantum advantage and quantum resiliency. On the quantum advantage side, we are looking for quantum speedup in ways in which the quantum platforms can provide some level of advantage over traditional compute systems. And on the resiliency side, we're working to develop our skills internally, developing algorithms and broadening the understanding of quantum computing concepts. In addition, we are identifying and mitigating the eventual threats to the security landscape following the introduction of cryptographically-relevant quantum computers.

Q. When do you believe quantum computing applications will be ready for commercialization?

A. You have to be cautiously optimistic about these developments. So, while the technology has yet to mature, there are possibilities of breakthroughs. Quantum technology is in a state where it can take quite a bit of time for advances and breakthroughs in the laboratory to reach commercialization or production. So you have to be diligent about your research and cautious with your expectations. Yet, I'm hopeful that quantum advantage in some use cases such as modeling complex systems, financial portfolio optimization, and drug development looks promising in the next three to five years.

Q. What are the current challenges in the development of quantum-ready applications?

A. I think there's a lot of groundwork to be done in the fundamentals of constructing algorithms and circuits. A lot of work around shoehorning what we would like to run on the quantum systems into the limitations today in terms of not just qubit size, but also the fidelity of the hardware. I think it begins with small-scale experimentation – getting familiar with the gate-based machines, getting familiar with the operators, and then at the same time, expanding the knowledge base within the enterprise, democratizing access to the platforms and the algorithm libraries so that more contributions can be made. I think that leads to a proof of concept where the results can be measured, communicated, and the value quantified.

Q. How is Wells Fargo bolstering cybersecurity resilience to guard against new threats that might emerge as soon as quantum computers are able to break current encryption standards?

A. Transforming the cryptography landscape is an enormous endeavor for any enterprise. I think a quantum cyberattack is not a question of "if," it's a question of "when." But projecting an end date for that is the tricky part. In some circumstances, it can take ten years or more to migrate your cryptography to a more robust model. But frankly, I don't think we have that long. The solution is an aggressive transformation to quantum resiliency while also creating a more agile cryptographic landscape. We need to constantly update our thinking on threats about which we don't know what we don't know. That's the area I'm most concerned about and focused on.

INTERVIEW WITH BHUSHAN BONDE, HEAD OF INNOVATION DEVELOPMENT, IN-SILICO R&D, EVOTEC, A GERMAN DRUG DISCOVERY AND DEVELOPMENT COMPANY (FORMERLY HEAD OF IT - EARLY SOLUTIONS INNOVATION DEVELOPMENT, UCB, A BELGIAN PHARMA MULTINATIONAL)

Q. What was the first trigger to use quantum technologies at UCB?

A. It was costing millions to burn in-house high-performance computing (HPC) capacity. The main cost is electricity to cool HPCs down and to continue and so the budget was exponentially increasing every year. Furthermore, within 3-5 years you have to replace all of your internal infrastructure too and quantum computing is emerging as an alternative to this. It might not solve all the problems, but it might complement classical technologies in solving a lot of problems

Q. Apart from hardware cost reduction, where can pharma companies generate quantum advantage?

A. Most promising is obviously drug development. The speedup from quantum computing can help us save 2-3 years out of the 10-14 that it typically takes a drug from R&D to production. Even if you remove certain phases using the right computing in this time period, that will be a big advantage. Another advantage is in lowering attrition – the time required to identify projects to be discontinued. Quantum computing can help the pharma industry to focus efforts on right compounds thereby reducing the likelihood of failure of large scale investments at a later stage, resulting in big cost savings.

Over time, the biggest benefit of quantum computing will be to augment its processing ability much beyond the limit of current computing capacity. In biology, we do a lot of experiments to identify where the distribution of the fluxes in the body are. Here we put some radio labeled substances, feed it to the cells or our organs and then identify how much is coming out of the thing to understand if the body is at steady state. I spent three years in trying to identify using classical computer and there is so much approximation. It gives you wrong answers every time you run it or it may be just misleading you and it's not reaching to the global minima (smallest value in a function). It's getting trapped always somewhere into local minima (appears to be the smallest value in a function but is not actually the lowest point).

With quantum computing, you really get a robust answer, and it is robust because you can then dilute the instrument and verify the output.

Q. In the absence of more capable quantum computers, how can organizations gain quantum advantage in the NISQ era?

A. Rather than waiting for a higher qubit computer to emerge, we can take, let's say, 2D structure problems at an abstract level and do some smart algorithm development. Let's say, Benzene ring. There are six carbons which are symmetric in the Benzene ring. So, you don't have to solve for each bond angle (the angle formed between three atoms across at least two bonds) separately. Can we use one qubit to solve it for the bond angle and then replicate for six bond angles? So, these are the smart algorithms that we are building instead of using six qubits where we can use just one qubit. We could replicate this approach to the other problems in the organizations, such as in finance.

Q. How to identify the right problems to tackle using quantum computing?

A. Companies can start with use cases where they are burning high performance computing (HPC) today. What are the problems that are challenging on HPCs? We take a problem from HPCs to a quantum computer and if we can show that there is a possibility of a better answer and benchmark it, then that is what you can develop further. That is where you start.

Importantly, there should be ambassadors inside the organization which promote the idea of quantum computing even to finance or operations people. They then start to think about optimizations challenges within their processes which are currently unsolvable or provide sub-optimal outputs.

QUANTUM COMPUTING CAN ENHANCE MACHINE LEARNING MODELS AND EVEN GO BEYOND

Machine learning has created strong impact across industries but require huge computational resources, are energy intensive, and can be time-consuming. Quantum machine learning (QML) techniques aim to enhance the performance of classical ML algorithms. such as through faster algorithms, or better model representations which yield superior performance for a given amount of training data. Other applications being researched include neural network verification, or improving model explainability using quantum ML techniques.

According to **Davide Venturelli, Associate Director at Universities Space Research Association, working at NASA Ames Research Center,** *"One of the problems I'm working on, with collaborators at Stanford, is neural network verification. Suppose that in a neural network to direct a drone flight, we need to ensure that certain choices are blacklisted. Like, the aircraft will never be told to U-turn at a certain speed. So you will want to mathematically verify that your neural network will never violate those safety rules. So you can cast this problem into an optimization problem which turns out to be very hard. We are looking at the performance to solve these kind of problems with quantum inspired hardware or QML techniques."*

Figure 14. QML can potentially enhance ML performance and thus, applications across sectors

ML models are energy intensive, time-consuming, and lead to high computational power consumption.

QML can improve the accuracy of output, reduces computation costs, and is faster.

Example use cases by sector

Financial services	• Market forecasting • Fraud detection • Financial synthetic data generation • Portfolio optimization • Risk simulation • Asset pricing
Pharma/ healthcare	• Clinical trials data generation • NLP* for literature search • Drug development • Compound screening • Imaging analysis for accurate diagnosis
Manufacturing	• New materials discovery through simulation • Anomaly detection for quality control
Mobility	• Autonomous vehicles (generating training datasets) • Crash simulation

*NLP – Natural-language processing

Source: Capgemini Research Institute analysis.

Like quantum computing, QML is at a nascent stage. Many of the above advantages are theoretical and require significant research, such as how to efficiently load classical data onto quantum computers.[21]

03 QUANTUM COMMUNICATIONS AND SECURITY TECHNOLOGIES ARE ALREADY AT IMPLEMENTATION

Quantum communications refers to the use of quantum mechanics to transmit data in a provably secure way, or even 'teleporting' quantum information (transferring information without traversing physical space between nodes).

Over 7.9 billion data records are compromised every year. A combination of the growing incidence of cyberattacks, rising demand of next-gen security solutions for cloud and IoT technologies; and stricter data-privacy legislations necessitates secure ways to transmit information. Security is the single-most important feature of quantum communications. Often, such systems involve quantum key distribution (QKD) – an unhackable technique to share encryption 'keys' between locations using a stream of single photons.

Furthermore, current security standards are based on factorization of large composite numbers, which although impossible to break with the available classical computers, a sufficiently large quantum computer will be able to do so. There are rising threats to information that needs to be protected or stored for longer periods of time, from 'harvest now, decrypt later' attacks, too.

According to **Reena Dayal, Board Chair of the Quantum Ecosystems and Technology Council of India,** *"Once we have a scalability breakthrough in quantum computing, it can suddenly threaten organizations' information security, assuming that the commercialization of the scalable quantum computer takes six months to a year after the breakthrough. This means organizations get only that much time to quantum-proof their systems. Thus, they need to start post-quantum security work today, because the efforts (to secure their data and networks) will be extensive and long drawn."*

There is ongoing debate on when and in what form the quantum computers can break the current encryption standards, and on how to make information quantum-resistant. Information security can be achieved in one of two ways: using quantum mechanics in information transfer or altering current encryption standards on classical networks to make them quantum-safe, which is called post-quantum cryptography (PQC).

Quantum cryptographic solutions are already being implemented, especially point-to-point networks for secure data exchange between two parties. Doing so over very long distances is a challenge; once successfully scaled, however, quantum has the potential to emerge as the standard for all secure communications.

A QUANTUM CRYPTOGRAPHY ECOSYSTEM EMERGES

QKD systems have already reached PoC stage, with demonstrations on point-to-point connectivity and security. Similarly, developments are under way to set the standards for PQC. No one organization can provide or manage every aspect of quantum communications because of the cost and required skills. So it is necessary to look outside the organisation. Building up or being part of an ecosystem is essential.

Of late, a large ecosystem of players is developing, from device vendors to research institutions, standard-setting bodies (such as NIST (National Institute of Standards and Technology) in the US and ETSI (European Telecommunications Standards Institute, or IEEE, OpenQKD, etc.) in Europe, or VCs, and importantly, end users (primarily those working with sensitive data such as banking, defense, healthcare, public sector, and cloud data center providers). Organizations creating or protecting IP, such as product designs in automotive, molecular formulations in life sciences, or locations of strategic assets in oil and gas, are also early end users. (see Figure 15)

Once we have a scalability breakthrough in quantum computing, it can suddenly threaten organizations' information security, assuming that the commercialization of the scalable quantum computer takes six months to a year after the breakthrough. This means organizations get only that much time to quantum-proof their systems. Thus, they need to start post-quantum security work today, because the efforts (to secure their data and networks) will be extensive and long drawn."

Reena Dayal
Board Chair of the Quantum Ecosystems and Technology Council of India

Figure 15. The quantum communications ecosystem is thriving

Source: Capgemini Research Institute analysis.

Several PoCs have been implemented successfully in the recent past:

- **BT** and **Toshiba** have collaborated to deploy a quantum-secure network, based on the QKD system. The system was deployed to generate thousands of quantum-secure cryptographic keys per minute over 6 km of fiber-optic cable, with a range extending up to 120 km.[23] This can help secure point-to-point communications links between two locations.
- **Netherlands-based KPN** ran test traffic between Delft and the Hague using QKD from a central node in Rijswijk. The central node can't learn the secrets transmitted between the end nodes. Current range between the nodes is 150 km, but KPN is aiming to upgrade the system to reach 250 km.[24] For organizations, extending the range of QKD links will help broaden the set of use cases to include IoT, identity, and access management over long distances, securing data in motion from remote servers, secure messaging, etc.

Similarly, PQC, which aims to develop systems that are secure against both quantum and classical computers, and can interoperate with existing communications protocols and networks, is developing fast. In October 2021, The US Department of Homeland Security (DHS), in partnership with NIST, released a roadmap to help organizations protect their data and systems and to reduce risks related to the advancement of Quantum Computing technology. DHS's new guidance will help organizations prepare for the transition to post-quantum cryptography by identifying, prioritizing, and protecting potentially vulnerable data, algorithms, protocols, and systems.[25]

ORGANIZATIONS ARE ALREADY SECURING THEIR CRITICAL INFRASTRUCTURE AND INFORMATION USING QUANTUM

Of the survey respondents working on quantum communications, the top three (out of seven) ranked promising applications are:

1. Secure information exchange with external parties
2. Protection of critical infrastructure (IoT and cloud-enabled technologies) within the organization
3. Security of cloud data centers.

Others included "removing vulnerabilities to quantum-enabled cyber attacks;" "network security in general;" "implementing privacy-by-design;" and "secure data migration."

- **Babcock**, a security solutions provider, partnered with **Arqit,** a UK-based quantum encryption services startup, to secure manned and unmanned aerial vehicles, maritime connectivity, etc.[26]
- **Toshiba Corp.** backed up around 80 GB of genome analysis data from universities and hospitals to multiple sites using QKD. Genome analysis data is directly linked to individuals and therefore requires strict processes to protect against data leaks. To use it in genomic medicine, this data will also require back-ups across multiple sites to protect data from system failures or natural disasters. This is a step change over physically transporting genome analysis data using tape or other media from a remote storage location.[27]
- **SK Telecom** partnered with **ID Quantique** to trial QKD at its clients, including to secure an emergency broadcasting network at a nuclear plant; protect administrative data at public institutions; a hydrogen car-design technology center; a cloud-based medical system; or personal information used by autonomous robots.[28]

PQC and QKD are not opposing solutions. We can create a link that is secured with QKD physically, then, on top of that, there can be a layer that uses PQC and the quantum-derived key in order to secure the communication between two ends. So, if one thing fails, there is still the other to protect it."

Victoria Lipinska
Quantum Advisor
KPN

BOTH POST-QUANTUM CRYPTOGRAPHY AND QKD APPROACHES WILL CREATE A BACKBONE OF QUANTUM-SAFE COMMUNICATION

Both Post-Quantum Cryptography and Quantum Key Distribution are likely to emerge as dominant techniques in securing information in the post-quantum future. Our research indicated notes that both technologies have their own advantages and will be needed for developing robust and cost-effective security solutions. Using both approaches for different layers (such as application or physical), timescales and data types, can provide a secure quantum link. Organizations can implement PQC-based solutions now and then use QKD to guarantee the security of the transition from classical computing to quantum computing.

According to **Victoria Lipinska, Quantum Advisor at KPN,** *"PQC and QKD are not opposing solutions. We can create a link that is secured with QKD physically, then, on top of that, there can be a layer that uses PQC and the quantum-derived key in order to secure the communication between two ends. So, if one thing fails, there is still the other to protect it."* She adds, *"However, there are specialized applications where the lifespan of data is really important, such as government, military, police, etc., and where it really makes sense to consider securing the communication for as long as possible. And, for this, QKD could be a good choice."*

Figure 16. A comparison of PQC and QKD

	Post-Quantum Cryptography	Quantum Key Distribution
Technology	Adds a software-based encryption layer on existing networks/applications	Hardware-based encryption using quantum channel. Requires specialized equipment
Cost	Relatively low cost	Relatively high
Complexity of implementation	Low – existing protocols available for use	High – point-to-point links required
Security level	Security cannot be 100% guaranteed	Ultra-secure and tamper-proof
Distance	Not limited by distance	Only a few hundred kilometers
Recommended for	Information which needs to be protected for shorter duration or data at rest	Information which needs to be fully protected for long duration or data in motion

Source: Capgemini Research Institute analysis.

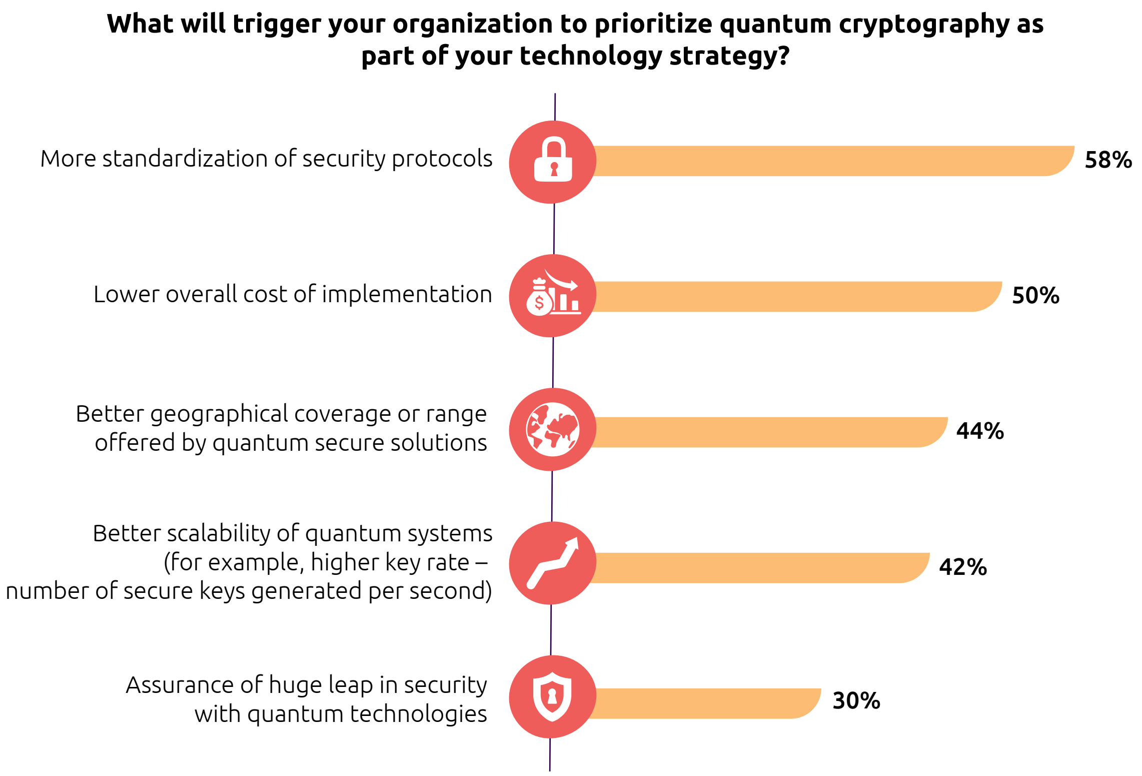
Organizations need to create a comprehensive roadmap for the migration of their data, to address post-quantum risks. Effecting the change across an organization will take years and a different set of security skills than those currently available to organizations. Security experts at organizations need to tap into the quantum communications ecosystem to stay up to date with recent developments in encryptions approaches, or hardware/software suppliers. Based on currently available encryption technologies, organizations need to take the following steps to secure their data:

- Start with identifying critical information, which needs to be protected, both for 'data at rest' and 'data in motion'; grade this data based on high to low priority for secure encryption.
- For datasets/networks requiring the highest level of security, establish QKD-based point-to-point connectivity.
- Implement a PQC layer for all high-priority data.
- Assess the readiness of systems and software to adopt the additional PQC layer for all other information. Continuously monitor the crypto-agility (ability of organizations to quickly change their quantum-safe encryption standards without rewriting applications or deploying new hardware) of existing systems. Embed crypto-agility into the design of all future applications.

LACK OF STANDARDS SHOULD NOT BE A BARRIER TO IMPLEMENTING QUANTUM-SAFE SOLUTIONS

As indicated in our survey, many organizations are waiting for greater standardization of security protocols before prioritizing quantum cryptography. However, companies need to start thinking now about transitioning their network security to quantum. NIST is expected to publish PQC standards by 2024. But it will also announce standardization of PQC algorithms in early 2022. Similarly, as of March 2021, there were 22 published QKD standards and 20 documents under development.[29] Based on these, organizations can start migrating their critical datasets, such as legally protected information, IP-related data, etc., from classical cryptographic solutions to PQC algorithms.

Figure 17. Most organizations are waiting for standards to emerge before prioritizing quantum security



Source: Capgemini Research Institute survey, N=200 organizations working or planning to work on quantum technologies.

Current limitations of such solutions are already being addressed. For scalability issues in QKD, KPN built a measurement-device independent (MDI) QKD system, which overcomes the problem of scaling in a typical QKD system. Multiple users can be connected via a central node, which need not be trusted. It leads to the creation of a star-type network.

Given such developments, organizations working on sensitive information such as financial services, defense, etc., need to start using quantum networks to transmit and receive highly confidential information.

INTERVIEW WITH ANDREW LORD, SENIOR MANAGER, OPTICAL NETWORKS AND QUANTUM RESEARCH, BT

Q. Could you elaborate on BT's quantum communication initiatives?

A. We are partnering with Toshiba to build the world's first commercially available quantum-secured metro network in London. The project will use QKD technology to provide quantum-secured network services to our customers. This will be an expansion to an earlier trial of the technology. The objective of these trials have been twofold – firstly, to expand from point-to-point quantum links to create a large-scale quantum network, and secondly to bring customers into the trials, starting with some of our enterprise customers, to understand what services we can create from our quantum network.

Q. Which quantum communication services have you experimented with? Which ones will be commercialized first?

A. The service with the biggest potential is to provide a trusted, robust, and secure data transfer. It is going to be highly beneficial for organizations requiring a very high level of security and consumer data privacy – for instance, defense, financial services, healthcare, and cloud data center providers, among others. On top of this, we can potentially build quantum-encrypted links, and quantum keys-as-a-service. We're assessing what our customers would want – a fully encrypted link for a defined period of time, or quantum keys charged on the basis of their usage. All of these services will be key to quantum networks of the future. In the future, we might also be able to provide organizations connection and access to quantum computers in a quantum computing-as-a-service model.

Q. By when do you anticipate the first commercial quantum-secure network services to be available in the market?

A. It is a bit hard to estimate the time to market at this point of time as that's contingent on the success of the trials. If our customers are happy and we can develop a business case, we can bring the service to market within a year. Of course, assuming there are no further hurdles. I'm quite hopeful that we can move very fast to provide a quantum-secure network to our clients soon while also monetizing our fiber network assets.

Q. How are you working with the senior leaders and collaborating across various departments within BT on quantum initiatives?

A. I started quantum initiatives at BT about eight years ago, and over time grew the team around me. We now have quantum tech experts – some of them with a deep physics research experience, commercialization experts, partnership managers to liaise with our partners including the government. The team has developed some very exciting intellectual property, filed patents, and published papers in the last few years. Our work is very well known right up to the top of BT. We engage quite seamlessly across BT networks, customer-facing units, as well as security. It's a total team effort.

"I'm hopeful that we can provide a quantum-secure network to our clients soon."

We are now pushing for the second generation of quantum sensors, where we use really exotic quantum properties like entanglement and superposition to go beyond the standard quantum limit."

Nadia Haider
Lead Applied Electromagnetic Scientist,
QuTech

04 QUANTUM SENSING: NOVEL APPLICATIONS WITH REVOLUTIONARY POTENTIAL

Quantum effects are already used in precision measurement (of time, gravity, magnetism, and temperature) and are considered far more precise than conventional measurement techniques. Standard clocks and watches have an accuracy margin of around one second per day. In comparison, an atomic clock based on quantum effects has an accuracy margin of one second in millions of years. Quantum sensing and its applications are fairly niche, as well as more mature, compared to quantum computing and quantum communications. Currently envisaged applications of quantum sensors are in the healthcare/diagnostics, defense, automotive, civil engineering, construction, oil & gas, space exploration, and telecom sectors. There are certain application areas, such as medical, where it is clear that technology needs to go beyond what is possible conventionally.

There are many different quantum sensing methods, and they have diverse technology readiness levels and application areas. For example, in 2019, a US-based defense agency collaborated with industry and academia to create a commercially available chip-scale atomic clock achieving a hundredfold size reduction, while consuming 50 times less power than traditional atomic clocks.[30]

Researchers are currently working on the next generation of quantum sensors, which will be more energy-efficient, portable, and cheaper. Recently, many quantum sensors have emerged from lab environments to be used in industrial applications. For example, gas cell magnetometers are revolutionizing brain imaging to manage chronic neurological diseases. According to **Jörg Wrachtrup, Professor at the University of Stuttgart**, *"Such examinations have only been possible in a few European centers but, suddenly, we are on the way to making them available to practically every family doctor."*[31]

Figure 18. Most common types of quantum sensors and their applications

Quantum sensor type	Applications
Atomic clocks	Electricity and telecom networks management, navigation, space technologies
Gravimeters/ accelerometers	Prospecting, land surveys, construction, civil engineering
Magnetometers	Navigation for fully/semi-autonomous vehicles, process controls, medical diagnostics

Source: Capgemini Research Institute analysis.

SEVERAL INDUSTRIES STAND TO BE REVOLUTIONIZED WITH THE NEXT GENERATION OF QUANTUM SENSORS

Experts in our study indicated that, while fields, such as computing and communications are revolutionary, quantum sensing is evolutionary. As the overall quantum space gains attention, companies are trying to speed up the applications related to quantum sensing. Nevertheless, there are use cases where quantum sensors can play a transformative role to accelerate precision of measurement, notably in four areas highlighted in the figure below.

"Within five years, quantum sensors in particular will lead to groundbreaking innovations in fields as diverse as transportation, energy, security, medical technology and seismography." **Dr. Thierry Debuisschert, Head of applied quantum physics, Thales Research & Technology**.[32] Sivers Photonics is developing range-finding and 3D-imaging systems for driver-assisted and autonomous vehicles, in collaboration with Toshiba and Thales UK, among others. *"The photon detector delivers sub-nanosecond precision, detecting single photons from the faintest possible reflections. This technology enables a far greater detection range for 3D cameras than is currently available, enhancing both safety and effectiveness when deployed in real-life applications such as vehicle safety,"* according to **Billy McLaughlin, Managing Director at Sivers Photonics.**[33] Reduced equipment costs, better performance in terms of operational ease, and sensitivity will help in broadening their use.

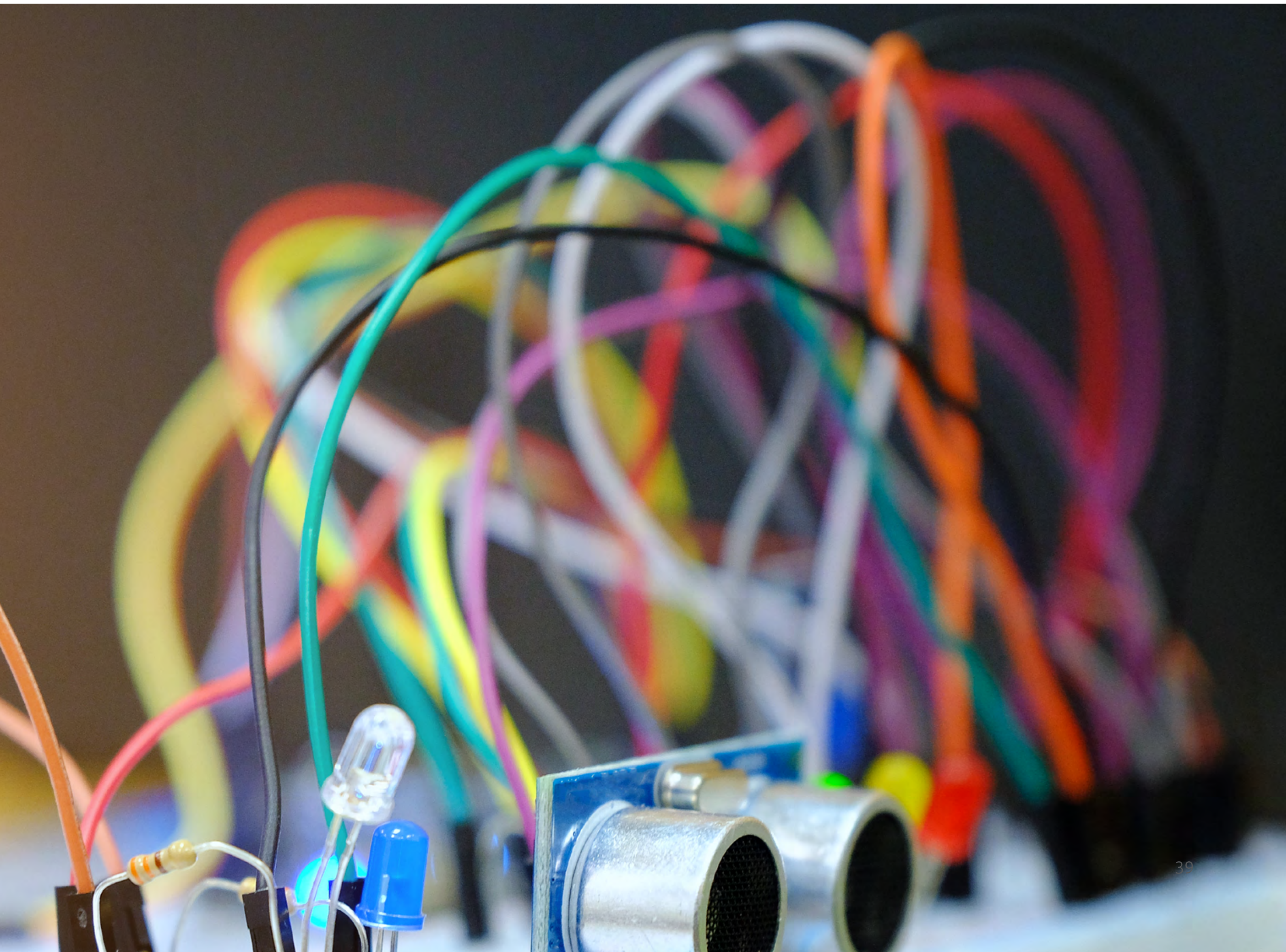


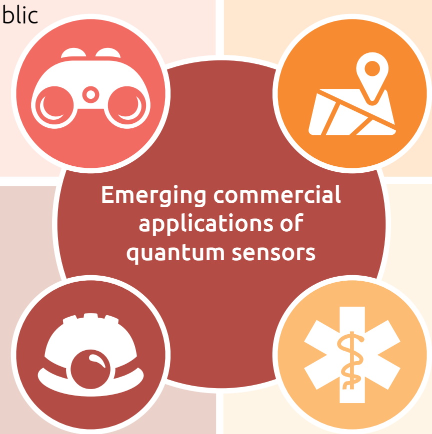
Figure 19. The next generation of quantum sensors is enabling a number of cross-sector applications

Quantum Gravimeters for prospecting or surveying land or water

- Can help find buried or submerged elements such as pipes, fiber, mines, cavities, or tunnels
- Applied in mining, construction, telecom, and defense sectors
- Can also monitor natural disasters and feed into climate models for insurance and public sector organizations

Sensors and Oscillators for GPS-free navigation

- Can be used in difficult terrains such as mountains, underwater, underground, space etc. where GPS is not available
- Quantum-enabled radars can detect small, slow-moving, and distant objects
- Find application in aerospace, automotive, and defense
- The Australian Army has trialed a cryogenic sapphire oscillator which improved the timing precision of its radar network by **1000x**



Quantum sensors for process control and safety

- Can detect leakages or spillages during industrial processes
- UK startup QLM trialed a gas sensor to detect methane emissions
- Could potentially replace manual sniffer tests for about USD 1,500 per unit

Magnetometers for biomedical imaging

- UK Quantum Technology Hub developed optically pumped magnetometers that allow free movement of patients under scan and are more accurate
- Can enable detailed research into brain conditions such as dementia and Parkinson's

Source: Capgemini Research Institute Analysis, "Quantum Sensing for Energy Applications: Review and Perspective," Scott E. Crawford, Roman A. Shugayev, et al. 2021. UK Quantum Tech Hub, sensors and timing. Novus Light, "Sivers Photonics to Develop Quantum-Based, Lidar for Safety Applications," December 9, 2020. ZdNet, "Quantum technologies are now part of the military's future roadmap," November 1, 2021. QLM website, December 2021.

BULKINESS, ENERGY CONSUMPTION, AND COST OF QUANTUM SENSORS TO COME DOWN WITH MINIATURIZATION

Most quantum sensors on the market are obliged to compete heavily with conventional sensors in terms of cost, size, and availability. Organizations that might benefit from quantum sensors but are currently discouraged by their large size or cost constraints should watch this space. Within a decade, many widely available sensors are expected to be miniaturized, with improved functionality.

Bosch, for example, has been working on the miniaturization of quantum sensors used in neurological diagnostics. Currently, superconducting magnetometers, which have to be cooled to minus 269 degrees Celsius, are used for diagnostics. The scanners are huge, yet cramped for patients, and expensive, and consequently rarely found in hospitals. Bosch developed an apparatus that is only slightly bigger than a laptop. Bosch expects further miniaturization, developing a sensor that works at room temperature and costs a fraction of the price of existing equipment.[34]

Meanwhile, organizations that invest in early quantum sensors need to develop a clear and comprehensive business case. For example, to mitigate gas leakages, traditional oil and gas companies need to account for financial benefits, as well as non-financial metrics, such as reduced probability of accidents, improved overall sustainability, etc.

Among other key monitorables is the development of enabling technologies, including nano-fabrication techniques, which help in building miniaturized sensors at scale. Another is cryogenic technology, which needs to evolve to make cooling cheaper and more energy-efficient.

INTERVIEW WITH NADIA HAIDER, LEAD APPLIED ELECTROMAGNETIC SCIENTIST, QUTECH, A COLLABORATION BETWEEN TECHNICAL UNIVERSITY OF DELFT AND TNO, AN APPLIED SCIENTIFIC RESEARCH ORGANIZATION IN THE NETHERLANDS

Q. What is the state of quantum sensor technologies today?

A. Unlike quantum computing and quantum internet, quantum sensors are already a mature technology. First generation quantum sensors are available commercially. One of the interesting example is the SQUID (superconducting quantum interference device). They can be used as really sensitive magnetic field sensors to unearth minerals, detect mines, submarines, etc. Similarly, atomic clocks have high technology readiness levels. But we are now pushing for the second generation of quantum sensors, where we use really exotic quantum properties like entanglement and superposition to go beyond the standard quantum limit.

The challenge is twofold. One is technology breakthrough to demonstrate the usefulness of quantum sensing, and the other is to find the right application for them. Adoption has to come from application pull and technology push; we need to find the match there.

Q. Which real-world applications of quantum sensing have the biggest potential?

A. High-potential applications include military, medical microscopy, and navigation, but it also depends on the level of nuance needed. Take navigation; for different navigation platforms, you need different quantum sensors, depending on whether the platforms are large or small. Aircrafts require very different quantum sensors for navigation than sensors that can help navigate drones. It also depends on what is the timeline of this technological development. Some second-generation quantum sensors are very close to being a commercial product. Then others are maybe 10-20 years ahead.

Q. How can developing ecosystems accelerate the adoption of quantum sensors?

A. I think ecosystem development is the key. That's also why we have been making these test facilities for quantum sensors. The aim is to foster an ecosystem where universities, research organizations, spin-off companies, and end users can come together and explore how we can use quantum sensors. Without a healthy ecosystem it is almost impossible to push a technology.

"Ecosystem development is the key to accelerating the adoption of quantum sensors"

05 HOW CAN YOUR ORGANIZATION PREPARE FOR THE QUANTUM ADVANTAGE?

Our research and experience in working with early-mover organizations in quantum technologies leads us to believe that this is the right moment to prepare for the quantum advantage – the ability to drive significantly higher performance that what is possible with the current state-of-the-art technology. Quantum technologies are at a nascent stage; however, that does not rule out the possibility of breakthrough advances and sudden acceleration in the pace of development.

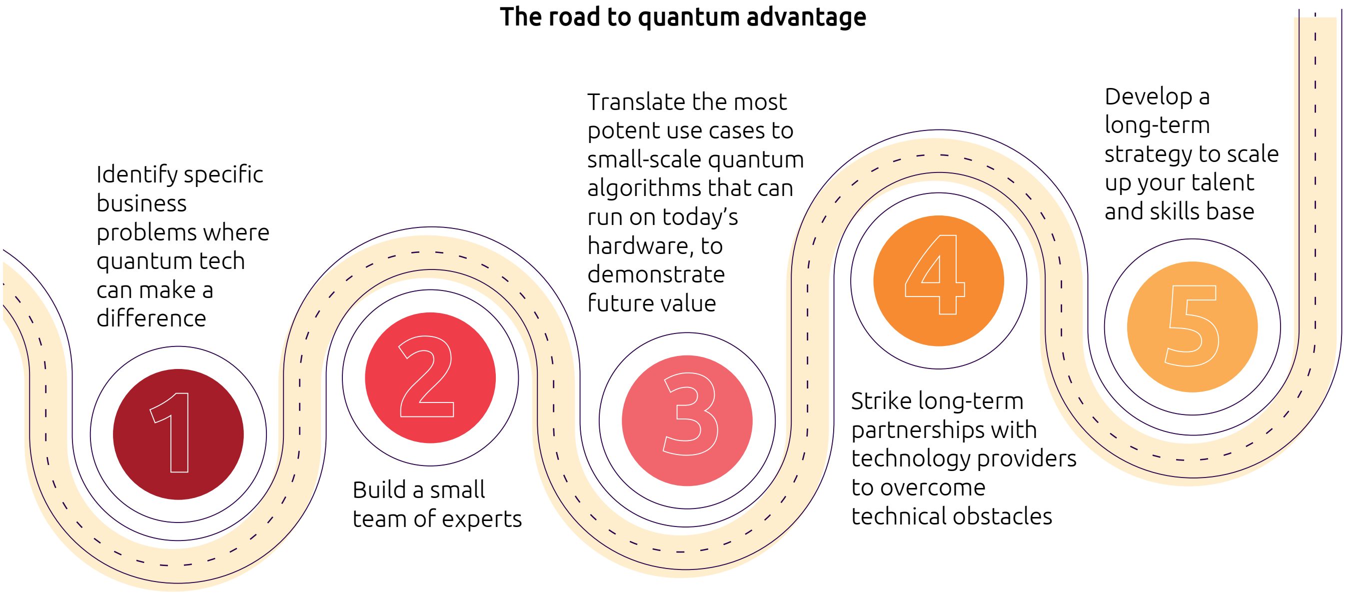
Breakthroughs are, by nature, unpredictable and organizations preparing for a quantum future will be much better placed than those who are not. Here's how to prepare your organization to harness quantum advantage as soon as the right commercial context and technological maturity are in place (see Figure 20).

Organizations starting on their journey to be quantum-ready may find it difficult to assess their current state and logical next steps. At first it is important to assess whether it makes sense for your business to invest in quantum technologies before committing to a full blown investment. Being a quantum-ready enterprise is going to be a long journey and a structured approach to it will be helpful. See vignette on "How does the journey to a quantum-ready enterprise look like?" Quantum technologies will likely co-exist with the classical technologies in use currently. So it would be prudent to prepare organizations to work with, for instance, a hybrid computing approach where quantum computers work in tandem with classical ones and not fully replace them.

In a top-down approach, you should start with some of the biggest challenges or opportunities that senior management wants you to tackle and then shortlist ones where quantum computing can make a difference. In a bottom-up approach, you look at various quantum technologies and see where possibilities exist to address specific industry problems."

Joydip Ghosh
Ford Research & Advanced Engineering

Figure 20. How to prepare your organization to harness a quantum advantage



Source: Capgemini Research Institute analysis.

IDENTIFY SPECIFIC BUSINESS PROBLEMS WHERE QUANTUM TECH CAN MAKE A DIFFERENCE

In the initial stages of the journey when identifying problems and use cases to tackle with quantum technologies, Joydip Ghosh of Ford Research & Advanced Engineering advises that organizations must find a balance between a top-down (business-pull) and bottom-up (technology-push) approach: *"In a top-down approach, you should start with some of the biggest challenges or opportunities that senior management wants you to tackle and then shortlist ones where quantum computing can make a difference."*

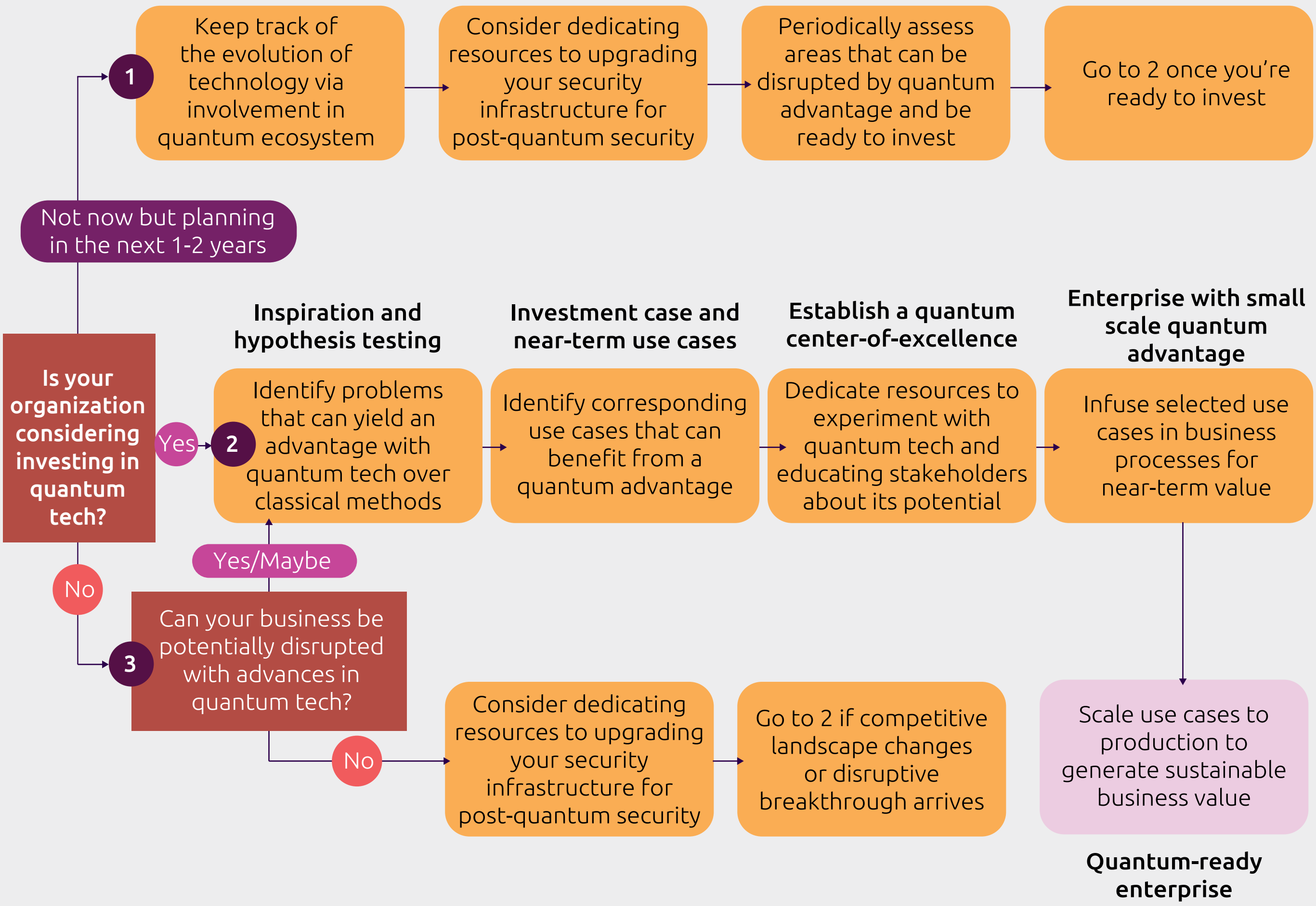
He adds, *"In a bottom-up approach, you look at various quantum technologies and see where possibilities exist to address specific industry problems. Speak with relevant stakeholders and select the right areas. In the end, you have to maintain a balance between the two approaches."*

- **For quantum computing:** A careful assessment is needed before embarking on a full-fledged exploration of use cases in this field As detailed in previous sections, quantum computing is advantageous for certain, very specific categories of problems. It is prudent to explore use cases only if those problems form part of your structural business challenges. Every sector has specific use cases where deploying quantum computing has shown some early positive signs – these can be seen as low-hanging fruit for the deployment of quantum computing. See earlier vignette "Which problems are ripe for a quantum advantage?"

HOW DOES THE JOURNEY TO BECOME A QUANTUM-READY ENTERPRISE LOOK LIKE?

Even though quantum technologies have some way to go before yielding their full potential and advantage to organizations at commercial scale, we believe that organizations can start today and position themselves at the forefront of harnessing this advantage as soon as it arrives on scene.

Figure 21. An example of a business' journey to becoming a quantum-ready enterprise



Source: Capgemini Research Institute analysis.

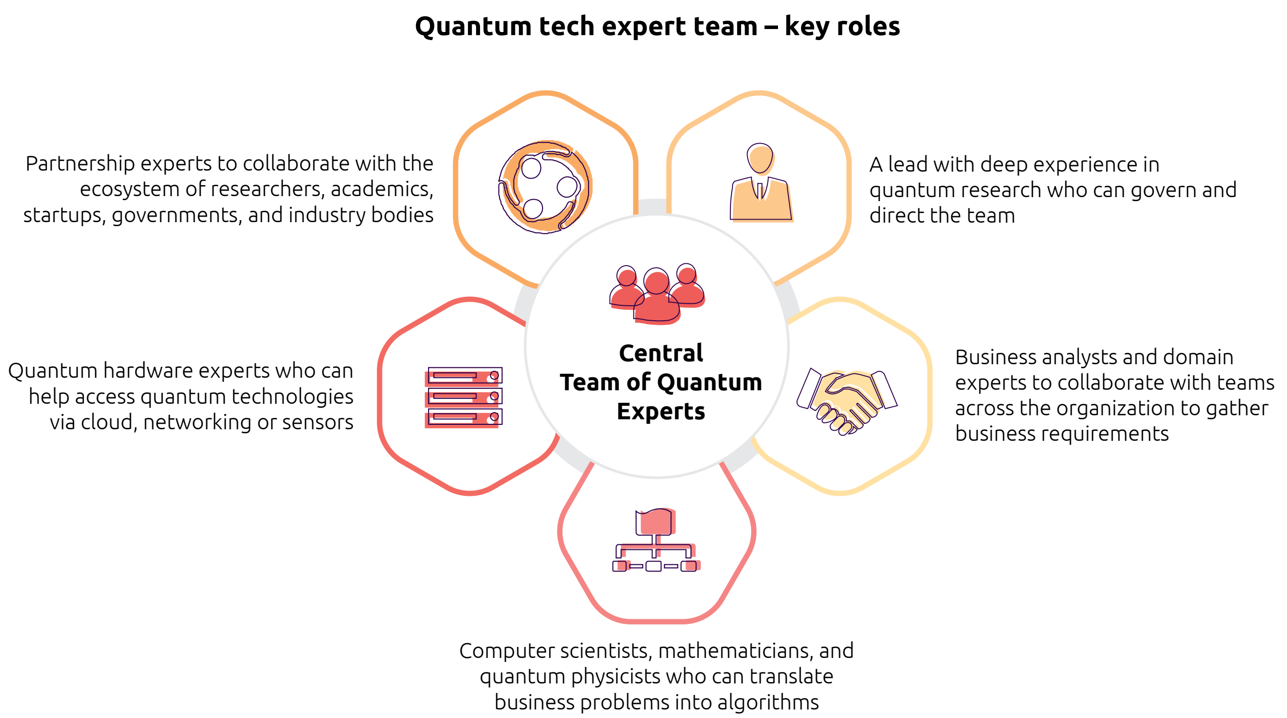
- **For quantum communication & security:** Organizations must work on the assumption that quantum attacks are a question of "when," rather than "if". As we saw in Section 3, methods are available to achieve quantum-safe security even today. Yet, organizations' current cybersecurity landscape involving dozens of cryptographic standards spread across multiple systems will require a massive upgrade effort spanning multiple years. It is therefore prudent to get started with quantum security as soon as possible.
- **For quantum sensing:** For organizations in mining, construction, aerospace & defense, manufacturing, and healthcare, the second generation of quantum sensors hold a lot of potential. There are several fundamental opportunities for sensing things that were not possible with conventional sensors. Keep track of areas where sensing modalities failed in the past to solve critical problems due to not having enough accuracy or resolution. Keep abreast with the latest developments in quantum sensors and understand when quantum sensors could achieve parity in terms of cost or energy consumption or bulkiness, for your specific sensor application. Keep in tune with the vendors of quantum sensors to quickly get access to the best-in-class sensors.

BUILD A SMALL TEAM OF QUANTUM EXPERTS

Organizations can kick-off use-case evaluation and algorithm development with a small team with multi-disciplinary experience in quantum tech, business analysis, and partnership building. Ideally, this team must be organized centrally with a lead researcher reporting to the organization's head of R&D or Innovation. When the commercial adoption of AI was in its early days, our research found that organizations with a central AI team drove up to 18% higher customer satisfaction and reduced operational cost vs. a much lower 12% improvement with no such central team.[35]

The team can include quantum physicists, computer scientists, mathematicians, and domain experts (microbiologists in life sciences or quantitative finance experts in banks, for example) (see Figure 22)

Figure 22. Key roles in a central quantum tech team



Source: Capgemini Research Institute Analysis.

The central quantum team should play a leading role in infusing quantum technologies within the organization and collaborate with the external ecosystem as well (see section on partnerships below). Some of the key actions that the team can take in the first few months of its conception are:

1. Building C-level awareness and explaining basics in an easy to understand way
2. Ideating with business teams on the most impactful problems that quantum tech can tackle
3. Conducting impact studies to determine how quantum will affect your field, where the competition stands, and how you can gain an edge
4. Prioritizing key use cases or initiatives and determine the target operating model

TRANSLATE THE MOST POTENT USE CASES TO SMALL-SCALE QUANTUM EXPERIMENTS THAT CAN RUN ON TODAY'S HARDWARE

Quantum computers solve 'toy' problems that are representative of real-world problems but are not directly scalable to them, yet. Hence, translating real-world problems to smaller-scale simulations that can be adequately tested on quantum computers is key. This serves two purposes. First, it allows researchers to assess whether there is a potential quantum advantage over and above traditional computers in pursuing a quantum solution. Second, with a PoC, organizations can gauge the capabilities of their quantum teams and identify skills gaps that will need to be filled when the solution is scaled up.

Upon shortlisting a potential use case, organizations are advised to encourage the involvement of outside experts to develop solutions. **Airbus**, for instance, launched a quantum computing challenge in 2019 to call upon quantum experts globally to find solutions to five specific problems in aircraft design and in-service optimization using quantum computing.[36] Similarly, **BMW** identified over fifty business problems which could be benefit from quantum technologies and then launched a hackathon in 2021 to invite solutions to four specific problems in vehicle configuration, material deformation, sensor placement, and the automated quality assessment of vehicles.[37]

A senior executive in R&D at a leading US-based investment bank, told us, *"Once you have identified use cases that you need to tackle with quantum computing, you need to understand how to run it on a quantum computer. For that, you need people who are technical experts, who can translate abstract algorithms written in a mathematical form into a more programmatic form suited for quantum computers"*

This step is also essential in testing the applicability of your business problem on quantum machines, since large-scale solutions are simply not testable due to the limitations of the hardware. **Peter Bordow from Wells Fargo** told us, *"Running small-scale versions of algorithms, adjusting them to the limitations of the hardware platform is probably one of the best ways to test and learn, while dealing with the challenges of working with the limitations of today's quantum hardware."*

To overcome this challenge, a senior R&D executive at a leading US investment bank says, *"Take a really toy example and ensure that you understand the math that's going on and see if you can simulate the quantum circuit."* He adds, *"For example, running (smaller scale) Monte Carlo simulation by modifying its algorithms to use fewer qubits and slightly shallower circuits. You can run many small circuits, take the results from all of them, and put them together. Although we still don't have good enough quantum computers to run even the shallow-circuit version, we were able to run some toy examples of the shallow-circuit algorithm."*

The takeaways and lessons learned from these smaller-scale experiments can help organizations scale their algorithms as quantum computers with bigger qubit counts become available.

Running small-scale versions of algorithms, adjusting them to the limitations of the hardware platform is probably one of the best ways to test and learn"

Peter Bordow,
SVP & principal architect for Advanced Technology & Head of Quantum and Emerging Technology R&D Wells Fargo

STRIKE UP LONG-TERM PARTNERSHIPS WITH TECHNOLOGY PROVIDERS IN THE QUANTUM ECOSYSTEM TO OVERCOME TECHNICAL OBSTACLES

As research continues into overcoming the limitations of quantum computing, large companies are not holding back from partnering externally to run experiments. As Peter from Wells Fargo told us, *"We formally announced a partnership with IBM in 2019. We work with several of our partners directly to get the latest information on how the hardware is evolving and what their road maps look like, and fine-tune our strategy around it."*

No one business can provide or manage every aspect of quantum exploration because of the cost, complexity, skills, and knowledge. It is therefore necessary to look outside the organization to experts who can help. Building up or being part of an ecosystem is essential to success.

Figure 23. Most common partnership approaches to exploring quantum technologies

33% Set up innovation/research labs with service providers (IT services companies/hardware/-software companies/system integrators)

25% Work with big tech players (such as IBM, Amazon, Microsoft) to implement solutions around quantum technologies

25% Buy stakes in startups on quantum technologies

Source: Capgemini Research Institute Quantum Technologies Survey, N=200 organizations working or planning to work on quantum technologies.

The quantum ecosystem consists of a number of technology providers who can help with specific areas:

- Hardware: Access to quantum computers and infrastructure, usually via cloud (for instance, IBM and Google), and sensors
- Software: Development of quantum algorithms, applications, and software platforms
- Start-ups: Dealing with niche aspects of quantum technologies
- Consultants and service providers: Access to technical and operational support from strategy to implementation
- Research institutes and Academia: Technical institutes (e.g. Fraunhofer), and Universities (Cambridge UK, Lisbon, MIT); providing cutting-edge research in both theory and practice. Like other deep tech, quantum is heavily rooted in scientific breakthroughs, so there is an inherent need to work with academia.
- Standards bodies: Follow the output of technical bodies such as NIST in the US and ETSI or IEEE, OpenQKD, etc. in Europe
- Industry associations or consortia: Bring various ecosystem players together and spur innovation, such as European Quantum Industry Consortium (QuIC) and QED-C in the US. QuIC has around 150 members and associate members from small, medium, and large-scale organizations, research institutes, and venture capital firms.

A few ways early movers adopt to get to a usable output faster:

- **Use hybrid computing:** Break the problem into parts and solve the one that is computationally more intensive using a quantum computer. Then, apply traditional computing to arrive at a more satisfactory answer than could be arrived at using a classical approach.

  This principle has given rise to iterative classical algorithms for solving problems, where a crude guess at the solution is the input, and a somewhat-improved approximation is the output. This output is then used as the guess for the next iteration, and, with each cycle, the output gets closer and closer to the true solution.

  This approach can be split between a classical and a quantum algorithm, with the optimization step performed by the quantum processor, and a classical control unit updates parameters in the quantum circuit to try to get closer to the optimum with each iteration.

- **Use digital annealers:** A digital annealer is a 'quantum-inspired' digital technology architecture capable of performing precise, parallel, real-time optimization calculations at speed, and on a scale conventional classical computers cannot.

  Joydip Ghosh of Ford told us, *"We partnered with NASA's Quantum Artificial Intelligence Lab (QuAIL) in the Ames Research Center. They had one of the quantum annealers from D-Wave. The use case was about a fleet of diesel trucks and certain conditions that must be satisfied while the trucks are en route The complexity of the problem rises exponentially once there are n trucks. It soon becomes an optimization problem that can be tested out on annealers."*

- **Develop confidence in quantum output using validation approaches:** It is important to build confidence in quantum output, especially for problems that cannot be classically solved. This involves, among other things, testing the consistency of the solution by using one quantum computer multiple times or using different quantum computers. There also exist a number of proven tests to validate the output. For problems currently solvable with classical computing, classical output can be used to validate the quantum output.

DEVELOP A LONG-TERM STRATEGY TO SCALE UP YOUR TALENT AND SKILLS BASE

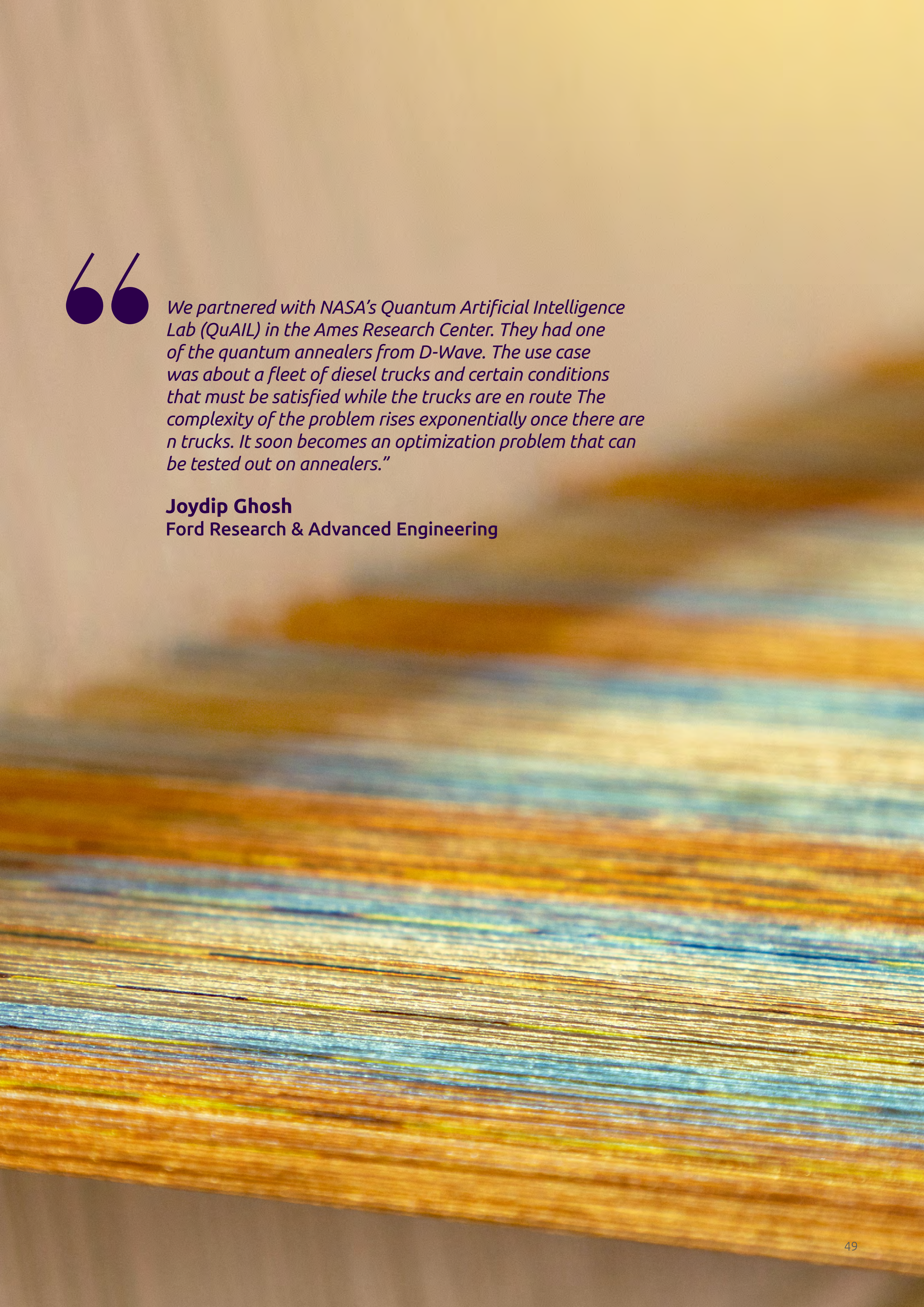
Quantum technologies are always going to be complex, requiring multidisciplinary teams to develop successful products and services. While a quantum physicist will still be an essential member of the team, so will engineers and developers with backgrounds in optics, electronics, software, networking, design, mathematics, data science, etc., to develop complete systems. As problems of greater scope and scale start to be implemented on quantum computers, the size of teams developing quantum algorithms and looking after their implementation will need to grow in parallel – creating greater demand for quantum talent. Having a proactive strategy in place to deal with this stage will help.

One way to manage the need for specialist skills is that today's quantum hardware providers are creating abstraction layers on top of their hardware as the infrastructure for an easy-to-use interface, so that users do not need to be physicists to start doing meaningful work in the field.

From a people perspective, organizations must also look into:

- Upskilling some of their workforce working on data and AI initiatives with quantum skills, as there is a lot of overlap between the two fields in terms of necessary skills, for example, data management and preparation, and algorithm and model development, among others.
- Reskill users of data and AI applications to work with quantum applications as soon as there are working proofs-of-concept.

Some of the users and developers of the existing/legacy technologies may have apprehensions about the transition to quantum applications. They need to be reassured that early applications of quantum will likely have quantum tech working in a 'hybrid' setting with existing solutions.



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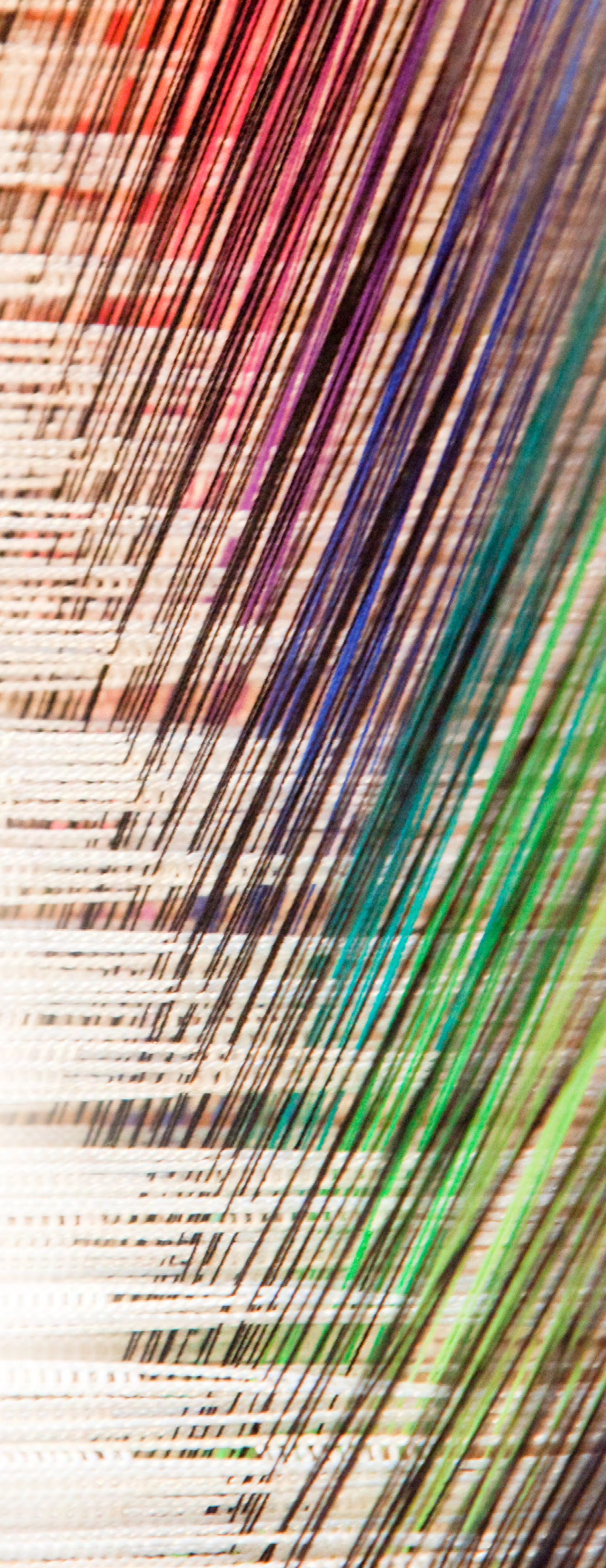
Joydip Ghosh
Ford Research & Advanced Engineering

CONCLUSION

Even though quantum technologies have been in existence for a few decades, the technology is still in its infancy as far as commercial applications are concerned; much like the Internet of the 1980s and computing soon after the inventions of the transistor. That is not to say that mass adoption is decades away. Far from it – recent breakthroughs in quantum technologies seek to herald a new era for computing and the internet as early as this decade itself. High-speed calculations, innovative materials and drugs, and ultra-secure communications, are much closer to reality than ever.

Each of the quantum technologies has specific applications with potential to bring about a paradigm shift, once prevailing hardware and software challenges are overcome. This is now only a question of “when” and not “if”. And leading firms are already organizing teams to harness the power of this transformative technology. If your industry can be impacted by quantum tech, waiting till the technology matures is not an option. It is important to start discovering use cases now, exploring potential quantum solutions, forming partnerships, and assessing ways to bridge the skills gap.



APPENDIX

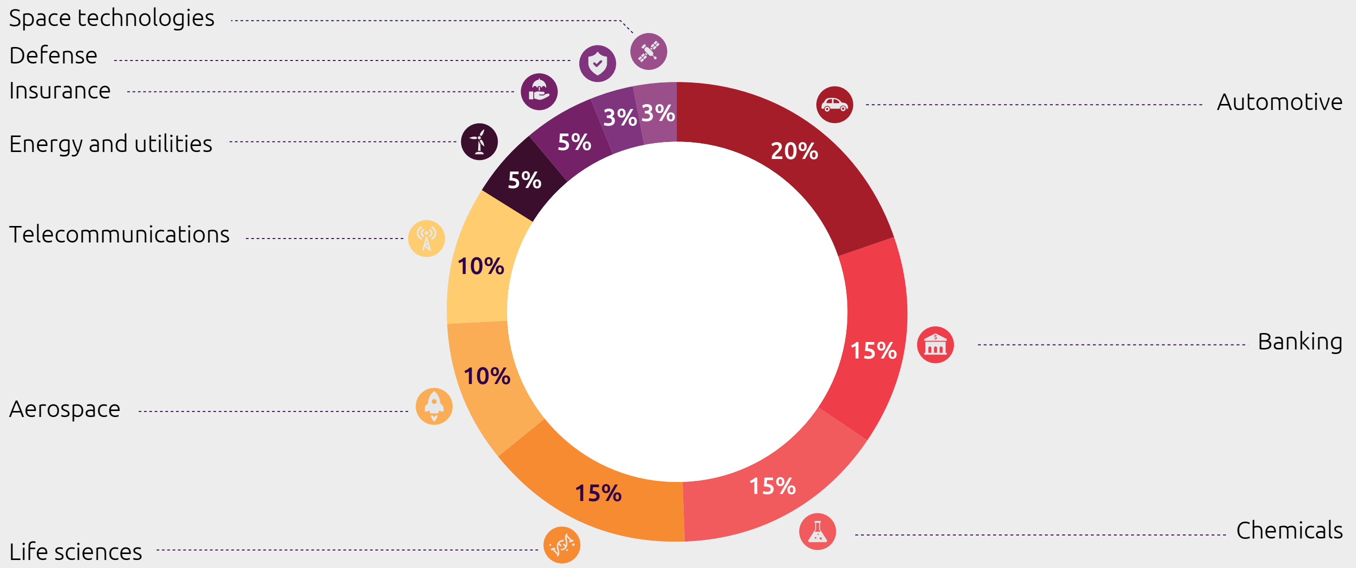
1. GLOSSARY

Term	Definition
Qubits	The most fundamental unit of quantum information, analogous to “bits” in classical computers.
Quantum entanglement	A quantum-physical phenomenon in which the quantum states of two particles (e.g., electrons, photons) are linked together regardless of their physical separation.
Quantum superposition	A property of a quantum system to exist in multiple states until measured. For instance, a qubit can exhibit two quantum states at the same time.
Available for use	Ready to be deployed in a limited way to at least one commercial application.
Emerging	Several proofs of concept developed, but not ready for commercial deployment.
On the horizon	At proof-of-principle stage; requires several technical breakthroughs to advance to the next stage.
Quantum decoherence	The phenomenon by which quantum particles lose their quantum behavior, for instance, when exposed to an environment
NISQ or Noisy Intermediate-Scale Quantum Era	The current state of quantum processors in which the qubits are ‘noisy’ – very sensitive to environment and lose their quantum state easily. Due to this the quantum processor is impacted by decoherence and requires ‘error correction’ in its output.
PQC or Post-Quantum Cryptography	NIST defines PQC systems as cryptographic systems that are secure against both quantum and classical computers, and can interoperate with existing communications protocols and networks.
QKD or Quantum Key Distribution	A key distribution protocol to generate “quantum” keys that can be used for secure information exchange over a classical channel with classical cryptography techniques. The keys are distributed using rules of quantum mechanics where any act of listening in leaves a detectable sign of snooping.

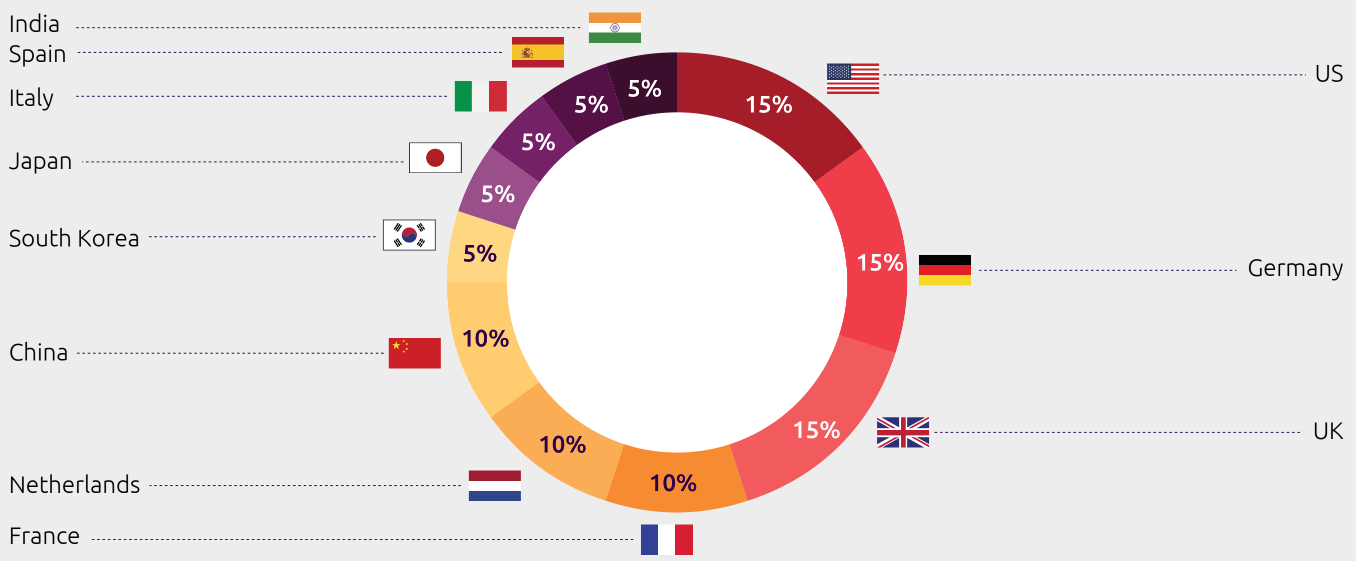
Research methodology

In November–December 2021, we gathered input from 857 organizations asking whether they were working on or planning to use quantum technologies, and surveyed 200 executives working or planning to work on quantum technologies. We also supplemented the survey with more than 30 in-depth interviews of practitioners of quantum technology at large organizations, startups, academics working on quantum technology, VCs in the field, as well as communities around quantum technology.

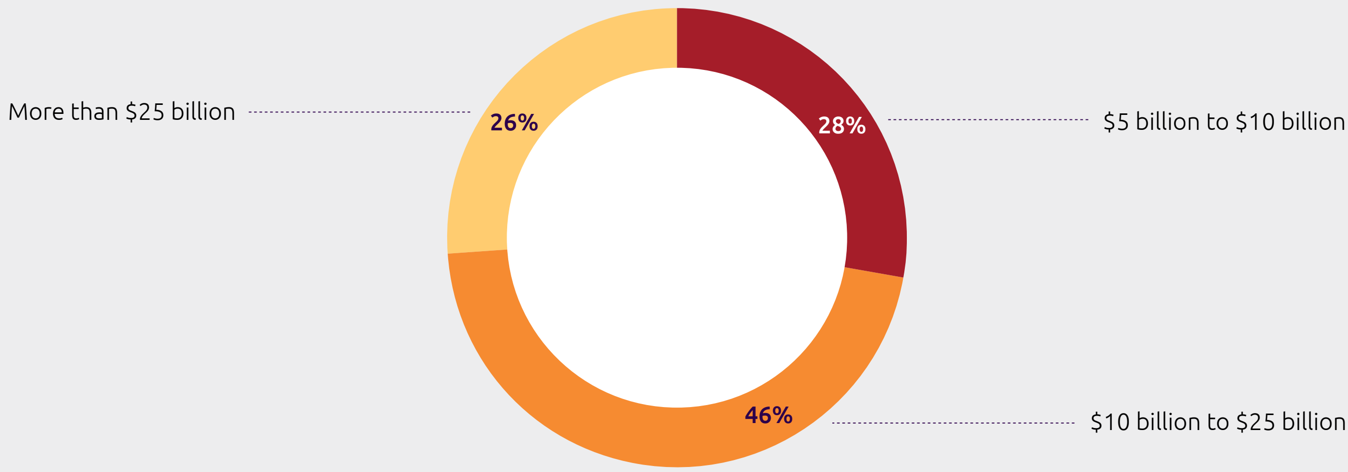
Organizations by sector



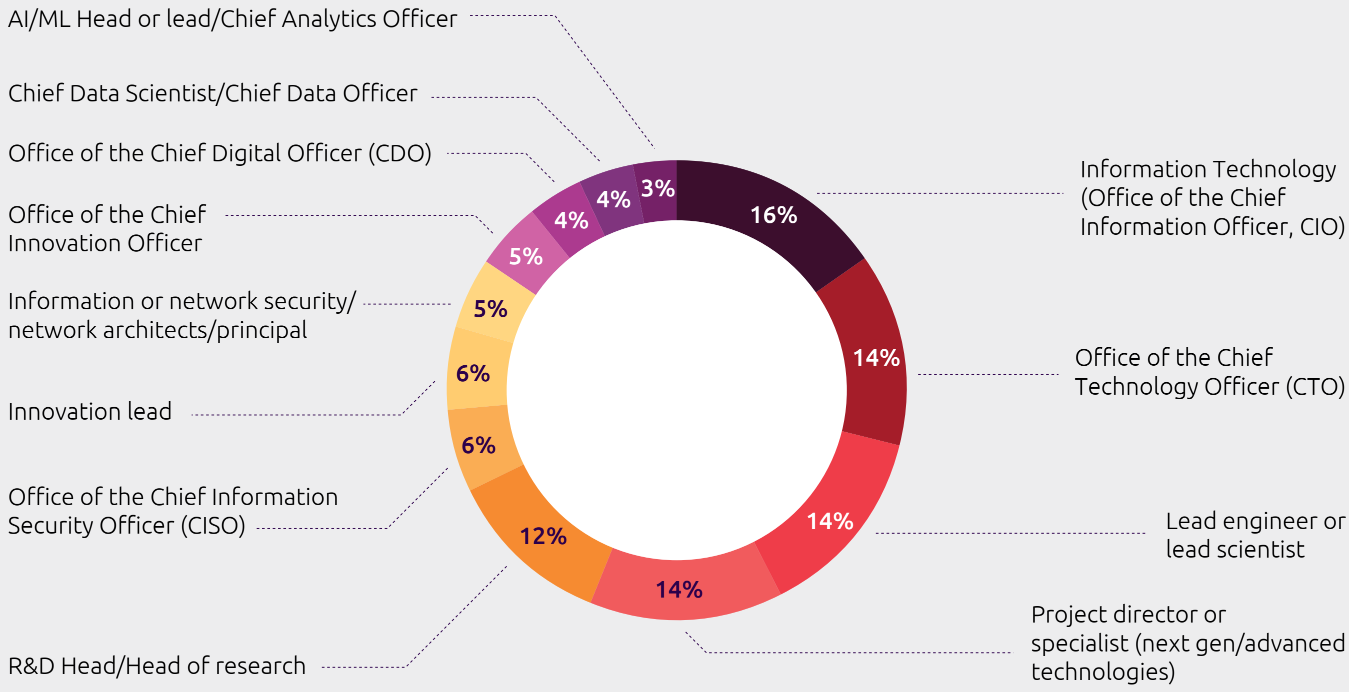
Organizations by country



Organizations by annual revenue (budget for public-sector organizations)



Executives by role



The study findings reflect the views of the people who responded to our online questionnaire for this research and are aimed at providing directional guidance. Please refer to the methodology for details of respondents and get in touch with a Capgemini expert to understand specific implications. The quotes from experts in the report represent their views in a personal capacity and not necessarily views of their current or past employer.

List of select interviewees

We extend our special thanks to the organizations, executives, and academics who took part in the in-depth interviews for this research. Following is a list of select interviewees who agreed to be named in the report:

Name	Role and Organization
André König	Managing Partner**, Entanglement Capital,** quantum technologies VC firm
Andrew Lord	Senior Manager, Optical Networks and Quantum Research, **BT**
Bhushan Bonde	Head of Innovation Development, In-silico R&D, **Evotec**, a German drug maker (Formerly Head of IT - Early Solutions Innovation Development, UCB, a Belgian pharma MNC)
Brian Lenahan	Founder & Chair, **Quantum Strategy Institute**
Davide Venturelli	Associate Director, Universities Space Research Association, working at **NASA Ames Research Center**
Diego R. Lopez	Senior Technology Expert, **Telefonica**
Dr. Erling Riis	Professor, Department of Physics, **University of Strathclyde**, Scotland
Dr Elham Kashefi	Professor of Quantum Computing at the School of Informatics, **University of Edinburgh**, UK, Director of Research at **CNRS**, LIP6, Sorbonne University France, and Co-founder **VeriQloud** Ltd
Eric Mely	IT project director and Quantum community leader, **Société Générale**
Emanuele Colonnella	Innovation Activation Manager, **Generali**
Frank Wilhelm-Mauch	Professor of Physics, **Saarland University**, Germany
Gopal Karemore	Principal Data Scientist, Denmark-based pharmaceutical firm

Joydip Ghosh	Quantum Computing Project Lead, **Ford Research & Advanced Engineering**
Laurent de Forges de Parny	Quantum telecom system engineer, **Thales Alenia Space**
Marten Teitsma	Professor of Applied Quantum Computing, **Amsterdam University of Applied Sciences**, Netherlands
Matthew R. Versaggi	Senior Director of AI + Distinguished Engineer - Optum Technology, **UnitedHealth Group**
Mischa Vos	Lead, QuantumLab, Strategy & Innovation, **Rabobank**
Nadia Haider	Lead Applied Electromagnetic Scientist, **QuTech**
Peter Bordow	SVP & principal architect for Advanced Technology & head of Quantum and Emerging Technology Research & Development, **Wells Fargo**
Philippe Cordier	Research Program Director – Scientific Computing, Data Science & AI, **Total Energies**
Reena Dayal	Board Chair, **Quantum Ecosystems and Technology Council of India**
Ross C. Walker	Global Head of Scientific Computing, **GSK (GlaxoSmithKline)**
Sebastian Luber	Senior Director Technology & Innovation, **Infineon Technologies AG**
Sergio Gago	Managing Director Media Solutions, **Moody's Analytics Group**
Victoria Lipinska	Quantum Advisor, **KPN**

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About the Capgemini Research Institute

The Capgemini Research Institute is Capgemini's in-house think-tank on all things digital. The Institute publishes research on the impact of digital technologies on large traditional businesses. The team draws on the worldwide network of Capgemini experts and works closely with academic and technology partners. The Institute has dedicated research centers in India, Singapore, the UK, and the US. It was recently ranked number one in the world by independent analysts for the quality of its research.

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Capgemini's Q Lab: Start preparing your organization for a quantum advantage now

Capgemini is a leading expert in the application of quantum technologies, helping clients to solve previously intractable business and societal problems and to explore the potential of three Quantum fields: computing, communications and sensing.

Although much of the potential of quantum is still to be realized, we expect benefits of the Quantum Advantage will include:

- Tackle business problems previously unimaginable, and process complex data with incredible speed through carefully designed quantum algorithms and computing power
- Transform sensing, detection and imaging – from autonomous transport to brain imaging – through superior accuracy in critical measurements
- Advance cybersecurity to new levels unobtainable with traditional techniques - greater communication security in a post quantum world.

We believe that now is the time for forward-looking businesses to recognize the practical applications of quantum and invest in creating their quantum advantage.

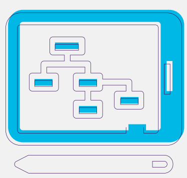
Our Quantum Lab is a global network of quantum experts, partners and specialist research facilities, in the UK, Portugal and India, running research programs and developing capabilities aimed at the advancement of quantum technologies.

Capgemini's Quantum Lab's approach is to:

- Partner with our clients in targeted quantum research to identify priority use cases, showcase quantum applications, and carry out early exploration, experimentation and incubation
- Support clients on their quantum journey, developing a roadmap for timely and calibrated investments to achieve industry leadership
- Accelerate their quantum readiness internally through building capabilities and preparing for the future
- Help them develop business-driven propositions that address their needs, ensuring that quantum solutions can be integrated seamlessly into their processes
- Provide access to an ever-growing ecosystem of specialist partners bringing IP, expertise and skills.

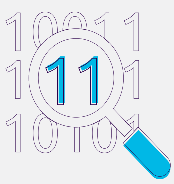
CAPGEMINI QUANTUM LAB CLIENT SERVICES

Capgemini supports organizations along the various stages of a quantum journey:



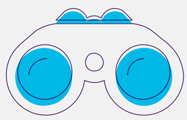
Plan:

from building awareness of the potential of quantum technologies, to framing a roadmap



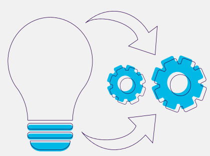
Discover:

identify use cases with real future business value and prioritize



Explore:

build proofs of concept and examine the scalability of the approach in a business context



Industrialize:

define the next steps to future quantum value – people, process and technology.

Capgemini's Quantum Lab provides the following services:

Quantum Technology consulting

- Consultancy and advisory, strategy and roadmap development, business case preparation, CoE setup
- Quantum Discover Assessment: Identify, prioritize and define use cases relevant to the industry and organization

Quantum Computing

- Solution areas: Optimization, Simulation and Quantum Machine Learning
- Use case exploration, definition and implementation
- PoCs, demos, solutions, algorithm design, exploration for business applications
- A key member of the IBM Quantum Hub, providing access to IBM's quantum computing systems and professional services for end-to-end implementation
- Core engineering services for the development of quantum hardware, equipment and related devices

Quantum Communication & security

- PQC assessment and migration
- QKD, Communication assessment and protocols implementation

Quantum Sensing

- Prototype/develop new sensors, including software capabilities
- Develop new sensing applications

SELECTED CLIENT PROJECTS AND ENGAGEMENTS

- **Life Sciences: In silico experiments via quantum simulation for drug discovery**

  The client wanted to leverage quantum simulation to pre-filter candidate molecules at the start of the drug discovery process. Work included analysis of past molecules and processes to gather data, development of a hybrid model of classical ML algorithms and quantum simulations, and a range of models to predict the properties of new molecules. Using these models, the solution could better predict the properties of new molecules and allow rapid filtering of candidate molecules.

- **Financial Services: Portfolio optimization algorithms**

  The client wanted to understand how it could optimize its portfolio using quantum algorithms. We identified use cases and translated business logic in mathematical formula with different levels of difficulty. Using cleaned data, we used a quantum simulator to verify that the use case is possible and to benchmark solutions.

- **Public Sector: Quantum Machine Learning (QML) for IT security**

  A Federal Office for Information Security has commissioned a study to identify the threats and potential of QML and to use the findings to shape digitization actively and securely in the country. It is examining the vulnerability of QML methods and their applications to new forms of cyberattack.

- **Aerospace: Quantum algorithms for structural analysis research**

  The client wanted to leverage the power of quantum to create a more efficient wingbox, by simulating more precisely the behavior of air around an airplane. Starting with two specific parts of the problem of wingbox optimization process, we replaced them with quantum algorithms for better exploration of the parameter space and more wingbox designs than currently classically possible.

- **Automotive: Quantum ML for automating quality assessment**

  The client wanted to optimize and automate its quality assessment of manufactured parts via image recognition and an automated feature extraction system, capable of classifying and localizing defects. We created an algorithm that maps classical data into a more dense quantum tensor that can be input to a classical Convolutional Neural Networks (CNN). The algorithm allows us to use near-term quantum technologies in a current business use case. As a result we expect to be able to get better results using fewer inputs with our hybrid QCNN compared to a fully classical CNN.

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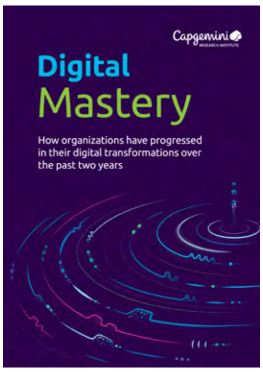

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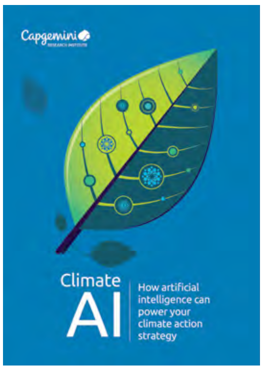
How organizations have progressed in their digital transformations over the past two years



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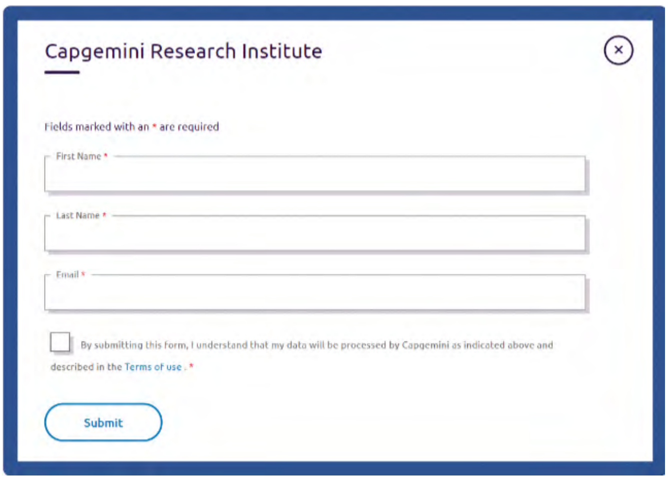
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Capgemini is a global leader in partnering with companies to transform and manage their business by harnessing the power of technology. The Group is guided everyday by its purpose of unleashing human energy through technology for an inclusive and sustainable future. It is a responsible and diverse organization of 325,000 team members in more than 50 countries. With its strong 55-year heritage and deep industry expertise, Capgemini is trusted by its clients to address the entire breadth of their business needs, from strategy and design to operations, fuelled by the fast evolving and innovative world of cloud, data, AI, connectivity, software, digital engineering and platforms. The Group reported in 2021 global revenues of €18 billion.

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