SUOMALAINEN TIEDEAKATEMIA
FINNISH ACADEMY OF SCIENCE AND LETTERS

SCIENCE BRIEFS

A snapshot of a phenomenon and its societal significance.

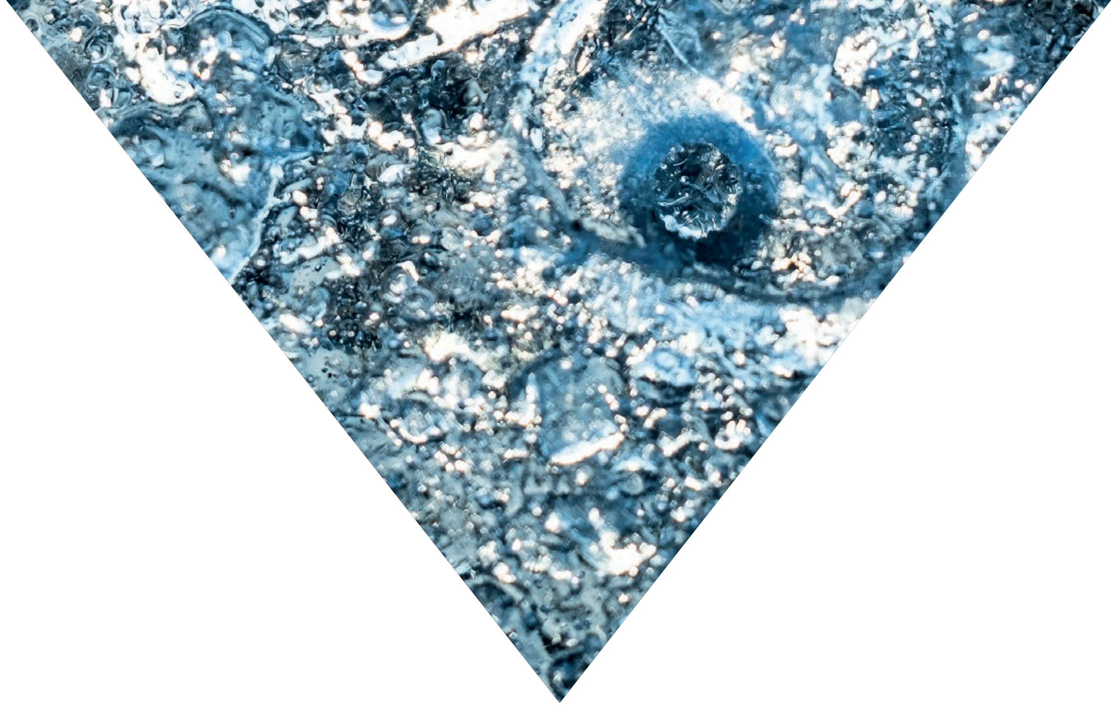
QUANTUM TECHNOLOGY

Where is the development going? What are the opportunities and risks of the field for Finland?

SUOMALAINEN TIEDEAKATEMIA
FINNISH ACADEMY OF SCIENCE AND LETTERS

JANE JA AATOS ERKON SÄÄTIÖ

This Science Briefs publication was prepared by the Finnish Academy of Science and Letters as a part of the Phenomenon Maps project funded by the Jane and Aatos Erkko Foundation. The work was led by Academician **Risto Nieminen**. **Nanna Särkkä** was responsible for editing. | The content is based on discussions with the following researchers: **Nina Granqvist** (Aalto University), **Teiko Heinosaari** (University of Turku and VTT), **Jukka Jouhki** (Tampere University), **Sabrina Maniscalco** (University of Helsinki), **Elsa Mannila** (VTT), **Juha Muhonen** (University of Jyväskylä), **Mikko Möttönen** (Aalto University, VTT and IQM), **Jukka Pekola** (Aalto University), **Matti Silveri** (University of Oulu), **Antti Vasara** (VTT) and **Visa Vesterinen** (VTT). A warm thank you to you all! Thematic publications and websites were also used in compiling this publication. | The Science Briefs publication was completed in January 2023, and its content reflects the situation at that time. | Translation: Elisa Wulff | Layout: Marika Eerola | Printing house: Picaset | Graphic, pages 18–19: Nanna Särkkä. Photos: VTT, Aleksi Kylmälahti, DKosig/iStockphoto, Benjamin Lehman/Pexels, Justin Kauffman/Pexels, Joyce McCown/Pexels, Bryan Rodriguez/Pexels.



IN THE COMING YEARS, we will see the first examples of the practical applications of quantum technology. We are not yet sure where its biggest value lies. The solutions may be related to cyber security, energy or drug development. Quantum technology will probably have a major impact on key European industrial sectors.

THERE ARE GREAT EXPECTATIONS for the industry. Development is rapid and there are growing investments around the world. The strategic significance of quantum technology has been recognised globally. Competition between the United States, China and Europe is intense. Finland has excellent opportunities for success.

Finland's First quantum computer HELMI is located in Otaniemi, Espoo.

WHAT DOES QUANTUM TECHNOLOGY INCLUDE?

Quantum technology utilises quantum phenomena, which occur at the level of atoms and smaller particles and photons. The following applications can be distinguished:

Quantum computing i.e. quantum computers

- The computers' processing power exceeds today's supercomputers by several thousands of times.
- Help optimising extensive and complex processes, e.g. designing delivery chains. Finland already has many internationally successful companies in this area.

Quantum simulation

- Modelling the characteristics and behaviour of molecules and materials, starting from the atomic level.
- Can improve the efficiency of materials processing and drug development.

Quantum communication

- Securely programmed encrypted communication.
- Large projects are already underway in the United States and the Netherlands. For instance, a fibre-optic network supporting quantum communication is under construction in the Netherlands. Finland is also committed to developing related infrastructure in Europe.

Quantum observation and quantum sensors

- Precise measurement of molecular phenomena.
- Potential applications include medicine (imaging), environmental research and metrology (determination of measurement units).

WHAT IS A QUANTUM COMPUTER?

A quantum computer is an extremely powerful computer that exploits the *superposition* property of quantum mechanics, in which the qubit is simultaneously in two different states. While a bit of a classic computer is always either 1 or 0, the qubit of a quantum computer is calculating both options at the same time. The number of qubits increases the computer's capacity exponentially: a two-qubit computer can calculate four, a three-qubit computer eight and a four-qubit computer sixteen values at the same time and so on. In theory, a twenty-qubit computer could exist in over a million states at the same time.

However, we should not be too focused on the number of qubits as their quality is what really matters. They are very fragile, and even minor interaction with the environment is prone to cause *decoherence*, making the quantum state of the qubit collapse. This, in turn, can cause an error in the calculation. As a result, error correction algorithms and extra qubits are necessary.

! The mass of the kilogram was originally defined based on a weight located in Paris. Today, the unit of weight is determined using quantum technology based on atom-sized phenomena. The VTT Centre for Metrology participated in redefining the kilogram.

Quantum computers can achieve certain tasks significantly more quickly compared to the computers used today. Quantum computers are unlikely to fully replace classical computers, but will instead be used alongside them. Best results can probably be often achieved by exploiting a combination of a classical supercomputer and a quantum computer.

! So far, there are only a few dozen quantum computers in the world. One of them is located in Finland.

The qubits required by quantum computers can be implemented in various ways. So far, the greatest leaps in development have been achieved with *superconducting technology,* and most of the research conducted in Finland and Europe is focused on this area. Other significant areas of progress include *silicon-based applications* and so-called *ion traps*.

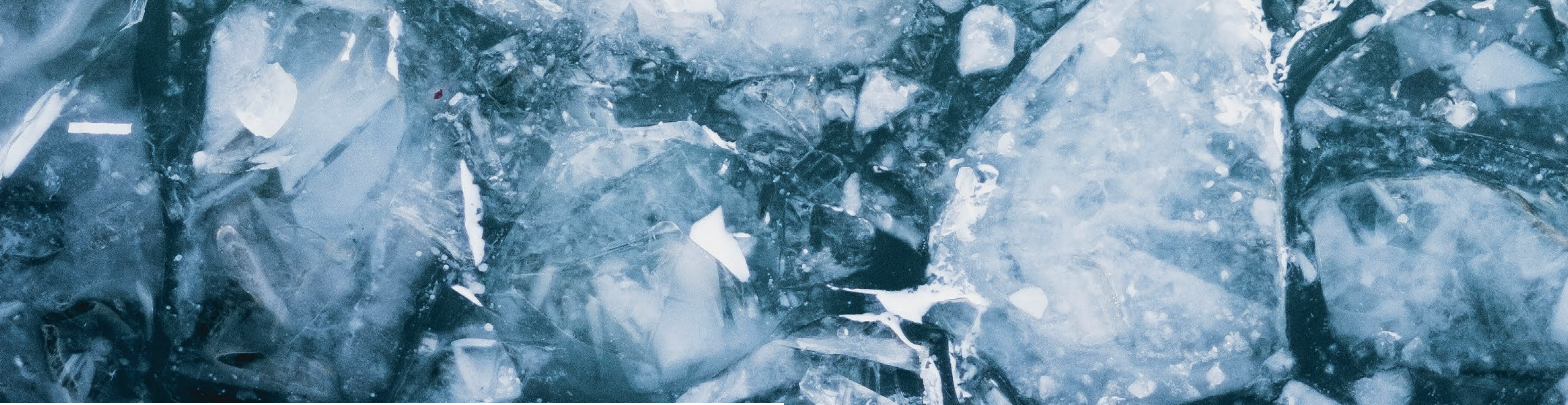
WHAT IS THE CURRENT STATE OF DEVELOPMENT IN THE FIELD?

We are currently living in an era of the second quantum revolution. Quantum physics emerged at the turn of the 19th and 20th centuries, and this so-called **first quantum revolution** around 100 years ago taught us to understand and manipulate single atoms and the interactions between them. This served as the basis for many innovations that are based on quantum mechanics, including transistors, lasers and LEDs.

The second quantum revolution has taught us to manage and utilise quantum phenomena. Basic research has evolved into applied research and commercial applications, and startup companies and commercial players are emerging. Currently, the emphasis in business is on research instrument manufacturers and operators involved in the infrastructure required by quantum technology. Companies in different industries are starting to consider increasingly broadly what quantum technology could mean to their operations.

As of early 2023, there have been around a few dozen successful attempts to build quantum computers around the world. One of these computers is located in Finland, at VTT. The five-qubit quantum computer was built in collaboration with IQM, a Finnish quantum computer company. The goal of VTT and IQM is to build an even more powerful 50-qubit quantum computer by 2024.

So far (late 2022), the largest quantum computer in operation is IBM's 127-qubit computer. Future breakthrough applications will probably require a computer with at least hundreds if not thousands of qubits.



WHAT APPLICATIONS CAN WE EXPECT TO EMERGE…

…in the 2020s or at the latest in the 2030s?

- **Quantum cryptography:** Enables secure data transfer. Is already used.
- **Optimization:** Quantum computing can help with tasks such as the planning of more cost-effective logistics routes. The increase in the speed and power of computing may also have major impacts on the financing sector.
- **Modelling materials and chemistry:** Predicting the characteristics and effects of different substances may speed up the development of new materials, fertilizers, drugs and energy solutions, among other things.
- **Imaging:** Unparalleled accuracy may be achieved in imaging in medicine and the materials sector, for instance.
- **Artificial intelligence applications:** Quantum computing can enable the effective processing of massive datasets in machine learning.

Quantum computing can enable the effective processing of massive datasets in machine learning.

…only after several decades?

- **Reliable general-purpose quantum computers** (that combine the best features of classical and quantum computers)
- **Most ambitious quantum physics simulations**
- **Full-scale simulation of biological and chemical reactions**
- **Decryption**
- **Utilisation in consumer electronics** (at best, this is likely to be achieved by connecting a consumer device to a cloud that exploits quantum computing)

It is also possible some areas of quantum technology evolve considerably faster than expected.

WHAT ARE THE KEY QUESTIONS?

? So far, quantum computers are highly prone to errors. It is essential to find solutions that succeed in error correction.

? How to identify problems that can be solved with quantum technology – both with today's smaller quantum computers as well as with the more effective and reliable computers of the future?

? Which technology should be utilised in building quantum computers and producing qubits in the future?

? How to develop algorithms, software and applications that serve more extensive user groups?

How to identify problems that can be solved with quantum technology?

WHAT ARE FINLAND'S STRENGTHS...

+ Considering its size, Finland is a strong and competitive player.
+ Finland has a long research tradition and internationally high-quality competence and research in areas with key importance to quantum technology, such as low-temperature and superconducting technology.
+ An effective innovation ecosystem for basic research, applied research and industry has emerged in Finland, which also serves as a breeding ground for startups.
+ Close collaboration related to research and innovation is realised in various areas of application.
+ Finland has a high-quality research infrastructure. For instance, the biggest cleanroom in the Nordic countries used for research and development purposes is located in Otaniemi.
+ Finland has great potential for gaining a significant position in building quantum equipment. VTT is already manufacturing high-quality components for which there is international demand.
+ Other fields with potential for Finland to succeed include optical data buses, which are set to replace traditional interfaces, as well as silicon-based quantum computing and photonics, and quantum sensors.
+ Finland is a country with great potential for introducing new technologies, as its citizens are highly educated and trust public administration.

...AND CURRENT WEAKNESSES?

– Lack of scope: research and competence are largely focused on superconducting technology and only one company (IQM) has been able to obtain over EUR 200 million in funding.
– There is a lack of experts in the field and international recruitment is a difficult and laborious process.
– More investments related to quantum computer algorithms and programming are needed.

- The applied research related to quantum sensors and efforts to bring these solutions to the commercial market are still at an early stage.
- International cooperation and coordination in education and research is insufficient.
- There are not enough degree programmes specialised in the field (incl. master's and doctoral programmes).
- Clearly less research funding has been allocated to the field compared to Sweden and the Netherlands, the countries set as controls.

BEWARE OF THESE STATEMENTS

"Quantum computing will solve climate change" and other overly optimistic promises. – Quantum technology solutions will not emerge in time to solve the imminent climate crisis. Nevertheless, they may help us discover more sustainable solutions, such as reducing our energy needs (faster and more effective computing and optimization) and developing more sustainable materials.

"Quantum computers will replace classical computers." – Quantum computers are not good at the same general tasks as the computers we use today, but rather work in highly-specialised applications. Quantum computers also need to be guided by classical computers. Indeed, quantum computers are rather the next supercomputers or their peripheral devices.

"The computer with the most qubits will win the race." – Ultimately, the size of the quantum processors, i.e. the number of qubits, is not the deciding factor. Instead, key issues include the stability of the computer, reducing the number of errors, and the success of the efforts to make use of qubits.

> The size of the quantum processors, i.e. the number of qubits, is not the deciding factor.

"There is an imminent threat to cryptographic systems." –We can combat the threats to cybersecurity by developing quantum-resistant algorithms. *Post-quantum cryptography* research is already carried out, also in Finland, with the aim to develop cryptographic algorithms that cannot be broken with the means of quantum.

"Quantum technology equals quantum computers." – Quantum computers are only one area of quantum technology, and practical applications may be quicker to emerge in areas other than quantum computing. While investments in quantum technology will produce significant results, these may also be something other than quantum computers.

WHAT ARE THE RISKS?

- **It is easy to get carried away by the hype.** Will we have unrealistic expectations? Are we going to forget about preparing for risks? We should keep in mind that while the potential of quantum technologies is huge, so is the associated spectrum of risks.
- **Investors are too quick to turn off the money taps.** If the economy is heading towards recession, will there be enough money to cover the risks? Will the technology be so overhyped that investors grow tired of it before we get to see any results? Will some other innovation grab the investors' attention?
- **New blocs are emerging in international politics and division into spheres of influence is continuing.** Finland cannot manage on its own. European countries should join their forces and engage in closer collaboration with the United States.
- **Excessive specialisation.** If Finland focused on a single, narrow area, there is a risk that it might put all its efforts into a technology that becomes obsolete. There is also a risk associated with excessive specialisation and differentiation of experts, as this may result in competency gaps. Interdisciplinary understanding and communication are needed.
- **Rapidly implemented experimentations may result in moral panic.** We must make sure that the general public understands what is going on and disseminate information to avoid stirring fears related to development steps. It is important to raise awareness of quantum at all levels.
- **Focus on technology alone.** The impacts of quantum technology may be fundamental and wide-ranging. As a result, we must start ethical considerations in good time.
- **The development of quantum technology feeds global inequality.** Will the benefits and opportunities of quantum technology only reach wealthy Western nations? Is quantum technology only developed on their terms and for their benefit?

We must make sure that the general public understands what is going on and disseminate information to avoid stirring fears related to development steps.

3 POINTS TO DECISION-MAKERS

1. WE NEED TRUST AND PATIENCE.

> While the impacts of quantum technology will be significant, how exactly and when these will emerge remains unclear.

> Finland should develop competence in the field on a sufficiently broad scale.

> At the same time, quantum technology is such an extensive field that it is necessary to focus resources on areas where we have the best potential for success.

> Restrictive solutions, such as setting standards, should not be introduced too early.

2. INTERNATIONAL COOPERATION IS VITAL TO FINLAND.

> Finland must pay close attention to any solutions that may be unfavourable to us in the global arena. For instance, there are ongoing discussions in Europe on whether to centralise quantum development. For Finland, this poses a risk of being excluded. Measures related to intellectual property rights (patents) and protectionism (such as export restrictions concerning software and components), which countries such as the United States have already introduced, may also pose a threat to Finland.

> Finland's NATO membership will also bring new opportunities related to quantum technology: Finland could get to participate in the organisation's research activities, which may contribute to strengthening Finland's cooperation with the United States.

3. WE NEED EXPERTS TO SUCCEED AND MAKE USE OF THE OPPORTUNITIES.

> Skills shortage currently forms a bottleneck to the development in the field in Finland. Research organisations have to train their workforce. Experts are also migrating from science to business, where development occurs behind closed doors.

> Indeed, Finland must appear as an attractive country to both foreign and Finnish top talent.

> Similarly as in other fields, success requires high-quality education and basic research – in quantum technology, relevant disciplines include particularly physics, mathematics, computer science, chemistry and technology. To rank at the top of the world, we also need highly specialised education in quantum technology (such as master's and doctoral degree programmes).

Skills shortage currently forms a bottleneck to the development in the field in Finland.

> Education must be planned as a whole, making use of the strengths of various organisations and educational institutions.

+ We should raise awareness of quantum phenomena.

> From the perspective of everyday experiences, many quantum phenomena are unintuitive and challenge our current thinking patterns. How can something exist in many places at the same time?

> However, it is worth raising awareness of quantum phenomena in science, the world of business and among the general public to ensure that if there is greater interest in quantum technology, we will be able to utilise its potential and it will not cause unnecessary fear. We should also see this as an opportunity: quantum phenomena can teach us to think in new and more creative ways.

> Quantum phenomena should be brought closer to everyday contexts already at an early stage of education. The means provided by games and art could be utilised in this process.

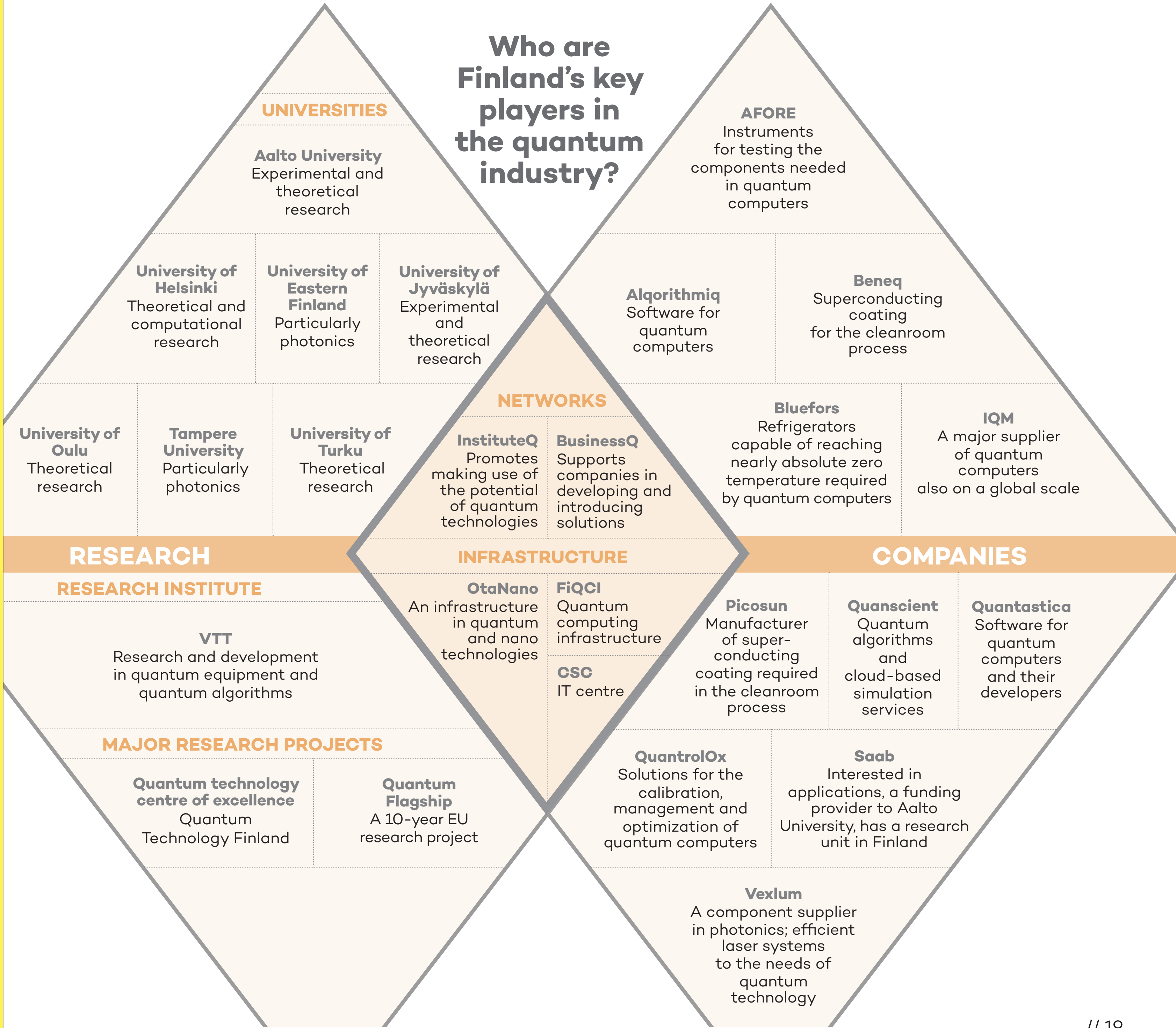
COMPETITIVE POSITION AT THE INTERNATIONAL LEVEL

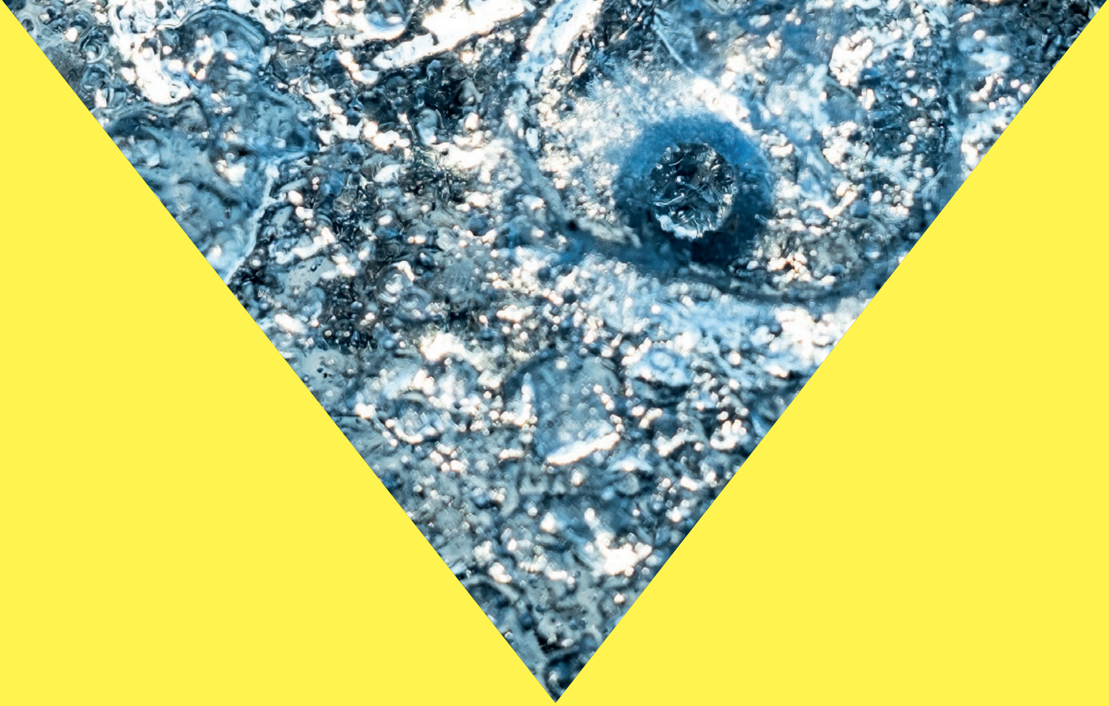
The United States is perceived as the leading player in quantum technology even though Europe has made clearly the most public investments in the industry. In the United States, big technology enterprises such as Microsoft, Google, Intel and IBM have driven commercial development efforts.

In Europe, development has been slowed down by fragmentation: the cooperation between research, start-ups, investors and industry players should be coordinated better. In Europe, rather little private equity is directed to the industry.

Quantum technology will probably have a major impact on key European industrial sectors. It is also important that Europe will be able to keep competing with China and the United States and aims at self-sufficiency, to which it has better prospects in quantum technology than in many other fields. The EU has identified this situation and is funding, for instance, the ten-year Quantum Flagship research project which includes the work of Finnish research groups.

At the international level, there are also significant knowledge hubs in the Netherlands, Japan and Israel. Considering their sizes, Finland and Sweden are doing well in the competition.





SUOMALAINEN TIEDEAKATEMIA

FINNISH ACADEMY OF SCIENCE AND LETTERS