Quantum Technologies

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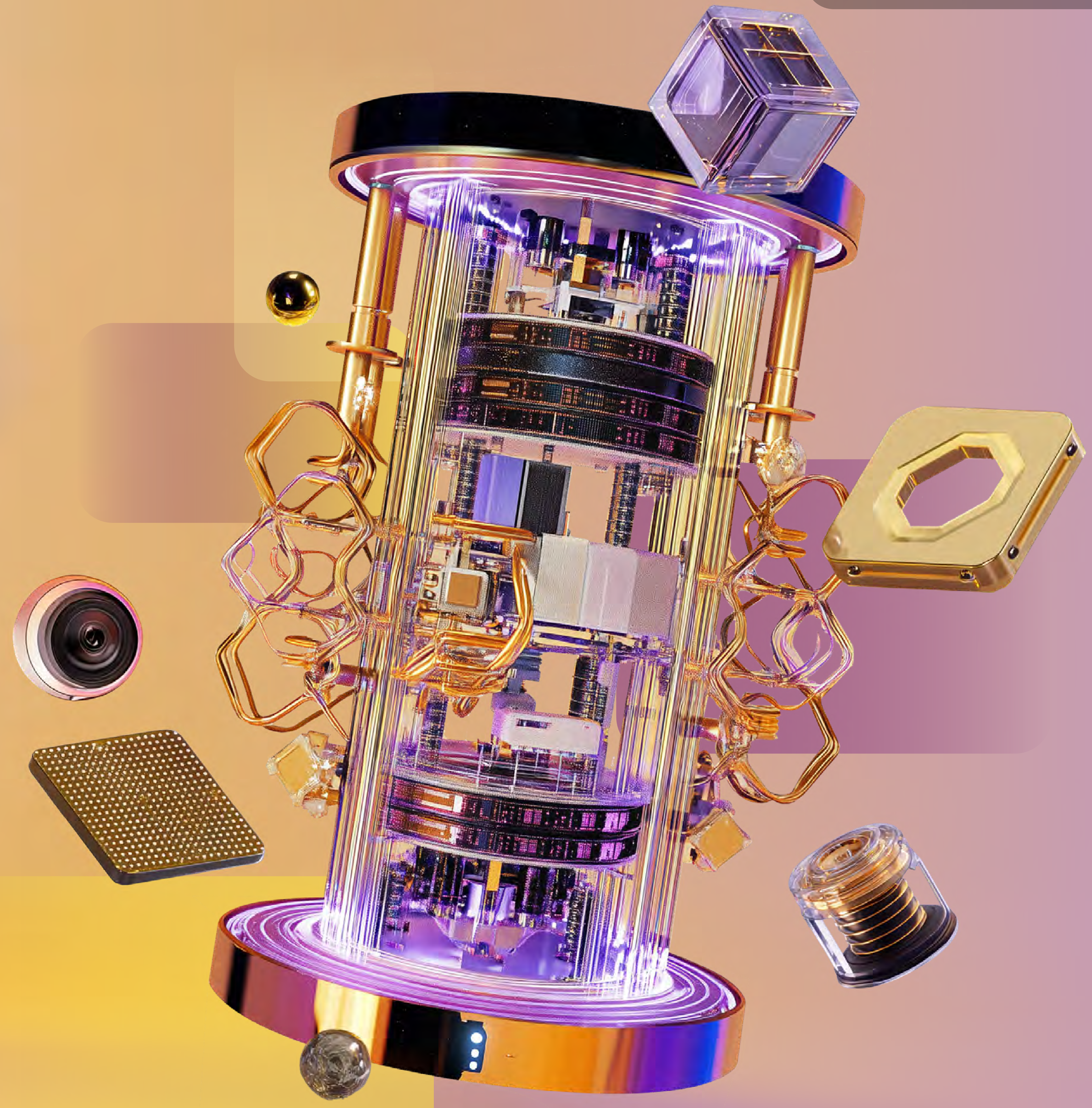

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Introduction

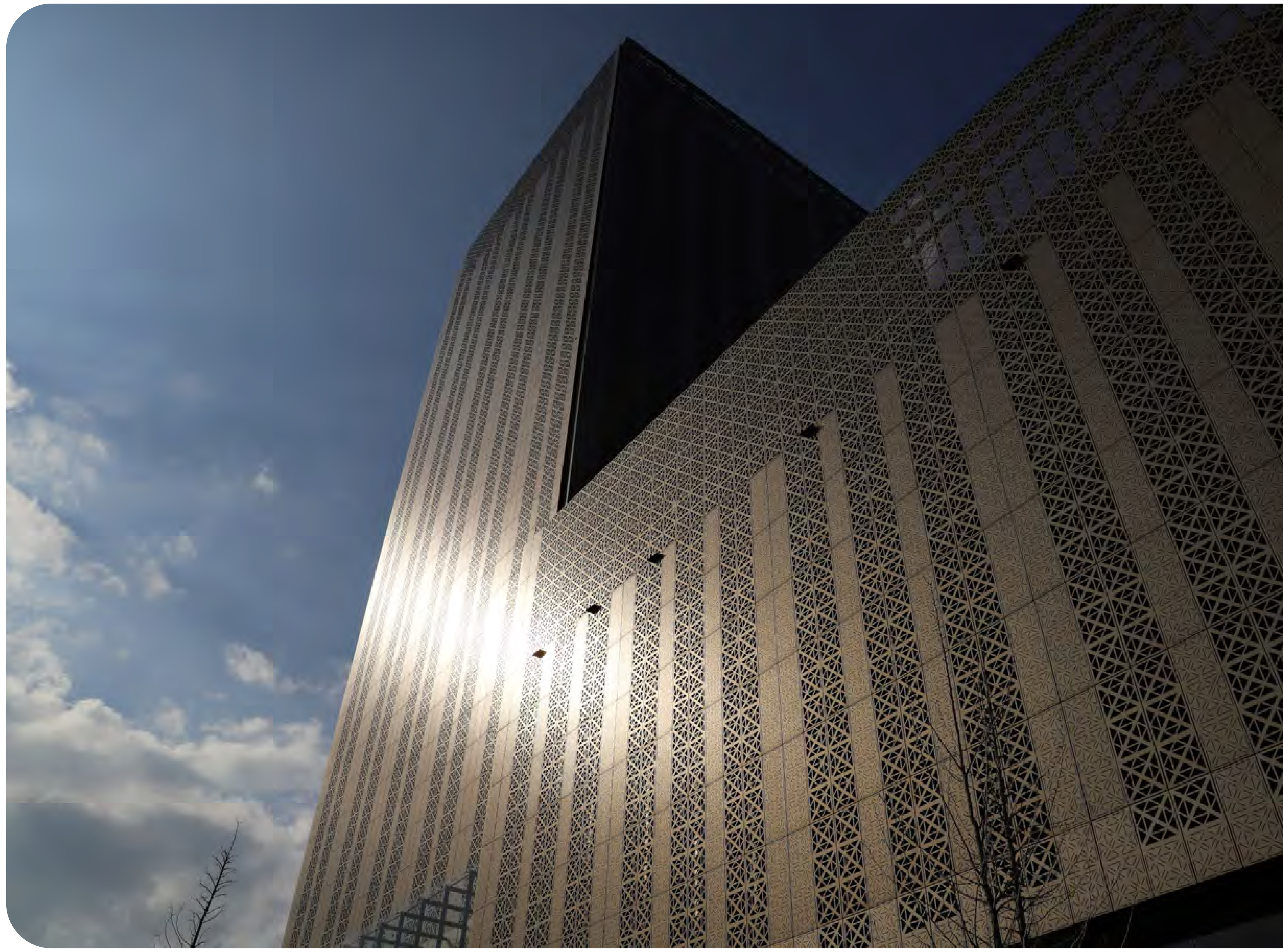
Quantum technology harnesses the principles of quantum mechanics. Quantum technology promises to revolutionise fields like materials science, medicine, and AI by enabling new simulations, order of magnitudes faster data processing, and enhanced security through quantum networking and quantum sensing.

Unlike the first *quantum revolution*, which produced technologies based on our understanding of quantum mechanics, such as the laser, we are now experiencing the second *quantum revolution*. This new phase leverages our increasing ability to manipulate particles at the quantum level, enabling computational, communication, and sensing capabilities that are impossible with purely classical (non-quantum) methods.

Over the past few years, the field has grown rapidly attracting interest well beyond research laboratories and sparking widespread efforts to explore its potential. This momentum, coupled with an urgent need for a skilled workforce, has driven the creation of new educational programs, training initiatives, and development tools across sectors.

Despite this progress, most quantum technologies are still in an early stage. They require specialised components, complex infrastructures, and an expert workforce. Sustained support for research, education and application developments is essential to unlock their full potential.

Quantum technologies can be grouped in three main areas: quantum computing, quantum communication and quantum sensing.



Quantum computing encompasses both hardware and software development. Current systems, known as Noise Intermediate Scale Quantum devices (NISQ), are limited by errors and noise. These systems need to evolve into Fault-Tolerant Quantum Computing (FTQC) to achieve full advantage, with applications in quantum simulation, optimisation, and machine learning.

Quantum communication refers to the capability of transmitting quantum information, offering unprecedented security and efficiency to our internet infrastructure. It will enhance classical internet with capabilities that are either provably unattainable or vastly less efficient when relying solely on classical technology. Furthermore, the development of a quantum internet will be key to connecting quantum computers into powerful distributed systems.

Quantum sensing uses quantum effects for exceptionally precise measurements, with applications in e.g. navigation, healthcare, and environmental monitoring.

Finally, a critical consideration in developing quantum technologies is their dual-use nature: they can serve both civilian and military purposes. As such, their progress is influenced by export controls and geopolitical dynamics, which in recent years have significantly shaped the pace of innovation.

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TREND #1

From ad hoc experiments to applications

Public Values

Autonomy		
Justice	Sustainability | Integrity | Inclusion	
Humanity		

Maturity WATCH **PLAN** ACT

Drivers

Digital transformation; Concentration of wealth & economic inequality; engineering advances & computation; automation & AI; critical infrastructure

Quantum technologies have advanced to the point where researchers can begin testing proof-of-concepts and realistic applications. In recent years, software tools, programming languages, and development frameworks for quantum computing have grown rapidly. A similar wave is emerging for quantum networks and quantum sensing, with new platforms for modeling communication links, designing quantum internet protocols, and handling the massive data sets produced by sensitive sensors. As these tools mature, they're expected to spark innovation much like the boom already seen in quantum computing.

User-friendly software and higher-level "abstraction layers" are lowering barriers for scientists, engineers, and businesses: instead of needing deep expertise in quantum physics, developers can focus on solving problems in, for example, cybersecurity, healthcare, climate science, logistics, finance, and advanced manufacturing.

Continued investment in compilers, cloud platforms, open-source libraries, and domain-specific toolkits will be key to unlocking quantum technology's full potential, drawing new talent, fostering collaboration, and enabling solutions to challenges once thought impossible.

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Increased interest of different sectors, industry and domains to explore the applications of quantum technology

The first successful demonstration of a novel quantum computing protocol to generate Certified Randomness (jpmorgan.com)

70% of business leaders are using and developing real-life use cases for quantum computing and 91% are investing or planning to invest in quantum computing (digitalisationworld.com)

Toyota and QuSoft (amsterdamsciencepark.nl)

Grants for use cases (grantfinder.co.uk)

Quantum internet use cases (quantuminternetalliance.org)

Software developments

First operating system for quantum networks (qutech.nl)

"Quantum advantage is unlikely to emerge from algorithms in the worst case, but rather from quantum heuristics and queasy instances: individual instances of practically relevant problems that are quantum-easy—solvable efficiently by quantum algorithms—yet classically queasy, resisting efficient solution by classical methods."

- **Prof. Dr. Harry Buhrman**, Chief Scientist for Algorithms and Innovation at Quantinuum

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Education

Learning and engagement becomes easier with quantum technologies.

Research

- In the near future there will be more potential use cases, more engagement and co-design with other fields.
- The opportunities for collaboration with industry will increase.

Operations

The situation may arise that there will be too much software to keep up with.

TREND #2

Towards Fault-Tolerant Quantum Computing (FTQC)

Public Values

Autonomy	Independence
Justice	Sustainability | Integrity
Humanity	

Maturity WATCH **PLAN** ACT

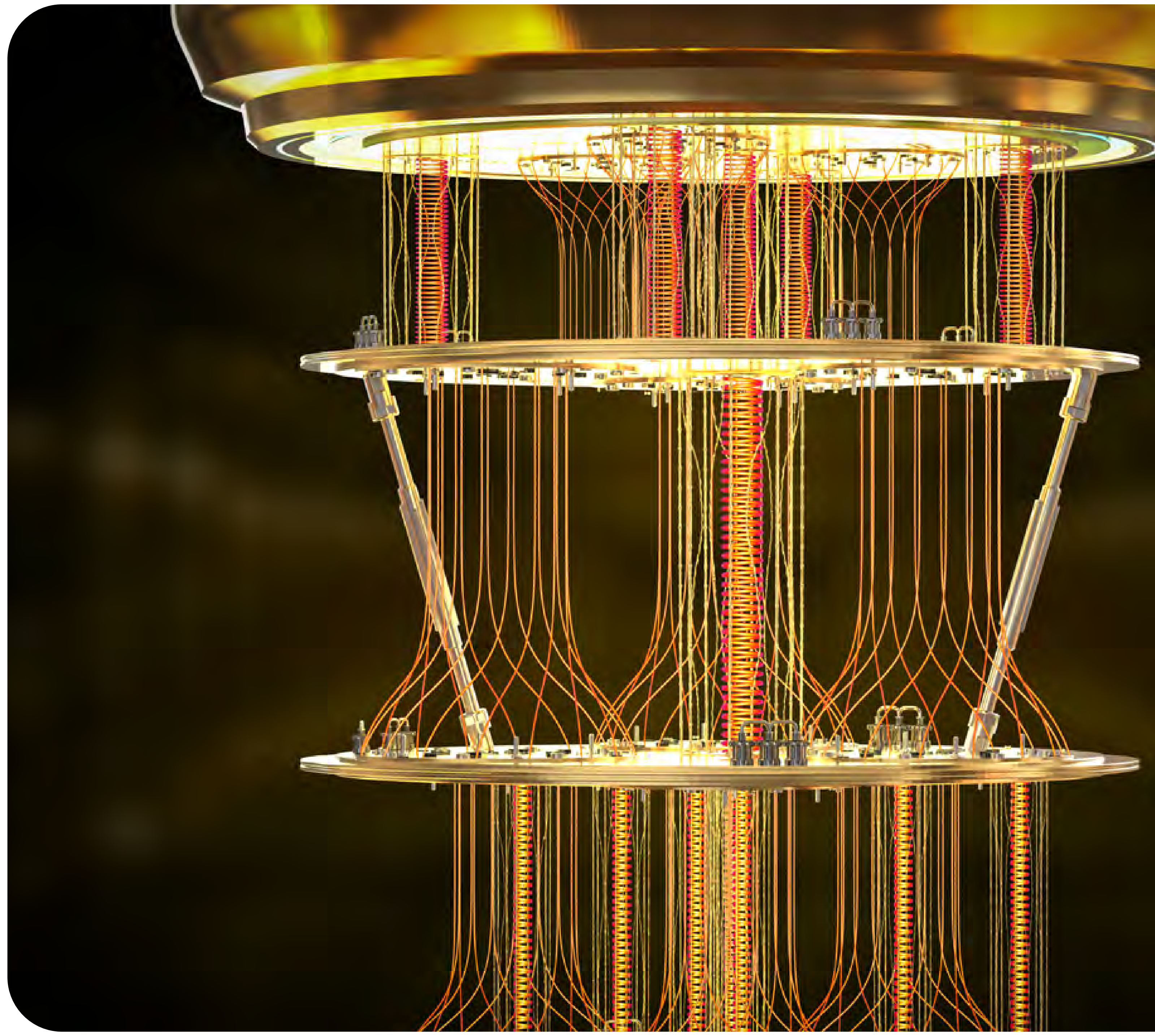
Drivers
engineering advances & computation; critical infrastructure

One of the main challenges in quantum computing is the vulnerability of quantum systems to errors, which leads to unreliable 'noisy' computations. These errors arise from decoherence, environmental noise, and imperfect quantum gates, and can quickly make computations unreliable.

Fault-tolerant quantum computing (FTQC) addresses this susceptibility with quantum error correction (QEC). By correcting errors without disturbing the encoded quantum information, 'noisy devices' can become reliable computers capable of executing complex algorithms.

Achieving FTQC requires not only advance in hardware, such as increasing the number and quality of physical qubits and keeping error rates below the required thresholds, but also the creation of more efficient error-correcting codes and fault-tolerant algorithms.

In the coming years, efforts to evolve today's Noisy Intermediate-Scale Quantum (NISQ) devices into fully fault-tolerant systems are expected to increase, with growing investment in research and development on error mitigation, quantum error-correction techniques, and algorithms designed for fault-tolerant execution.



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Roadmaps to reach FTQC

IBM roadmap (ibm.com)

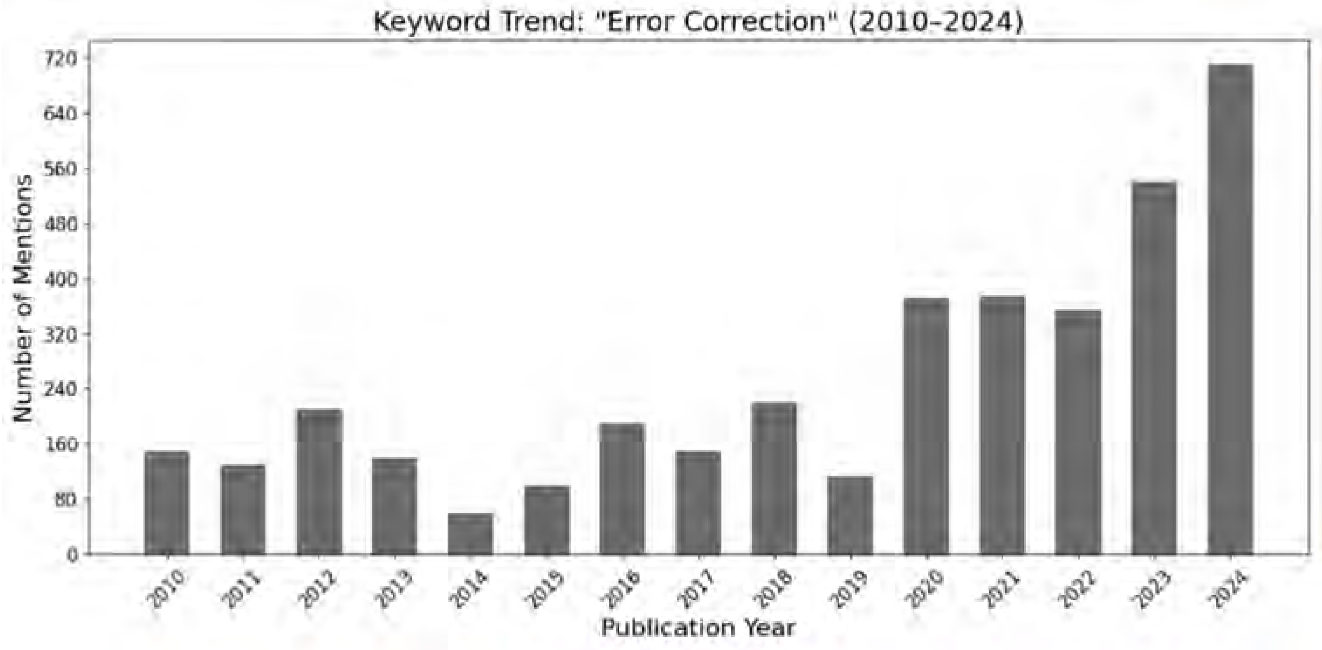
Google roadmap (quantumai.google)

Alice & Bob roadmap (quantumcomputingreport.com)

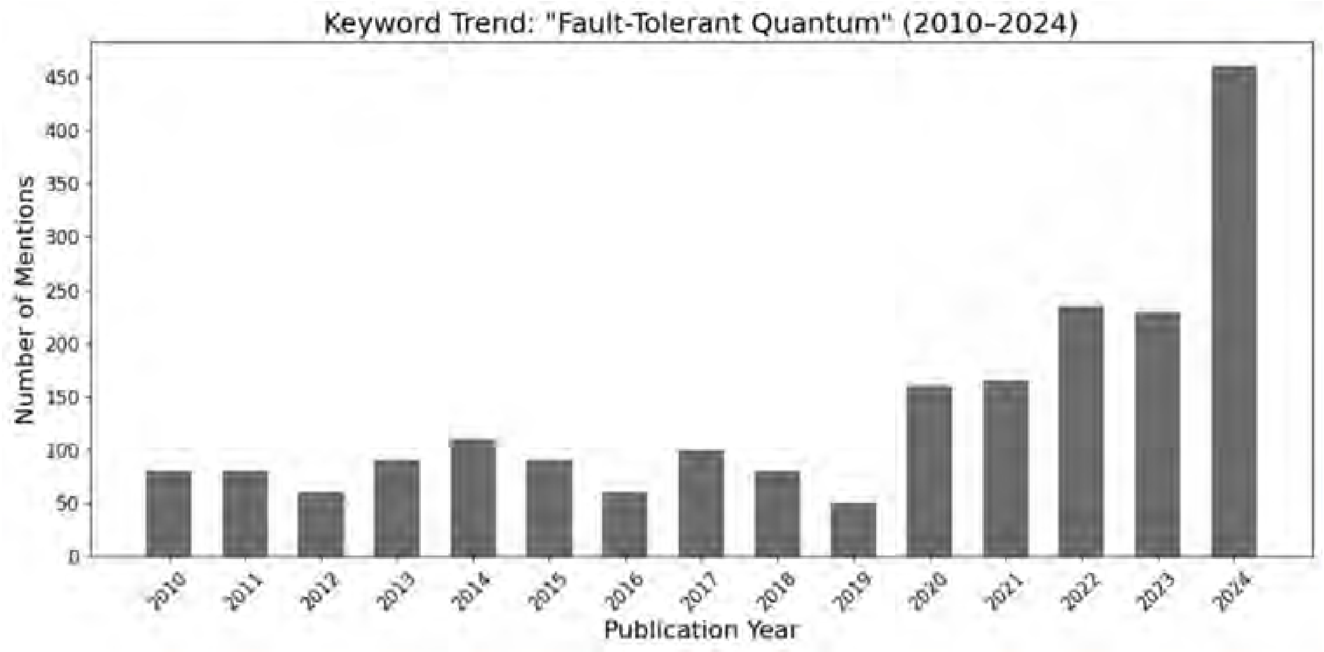
Quera roadmap (quera.com)

Quantinuum roadmap (quantinuum.com)

Increase in error correction research



Increased attention towards FTQC



Some impactful papers

Demonstrating dynamic surface codes, by Google AI and collaborators (arxiv.org)

Suppressing quantum errors by scaling a surface code logical qubit, by Google Quantum AI (nature.com)

Performance of quantum approximate optimization with quantum error detection (nature.com)

Quantum error-corrected computation of molecular energies (arxiv.org)

On the importance of error mitigation for quantum computation (arxiv.org)

"FTQC is no longer a distant goal, it's on a defined trajectory. To fully realise its impact, we must pair this momentum with optimised algorithms, meaningful use cases, and realistic resource estimates."

– **Cecile M. Perrault**, Head of Innovation & Partnerships, Alice & Bob

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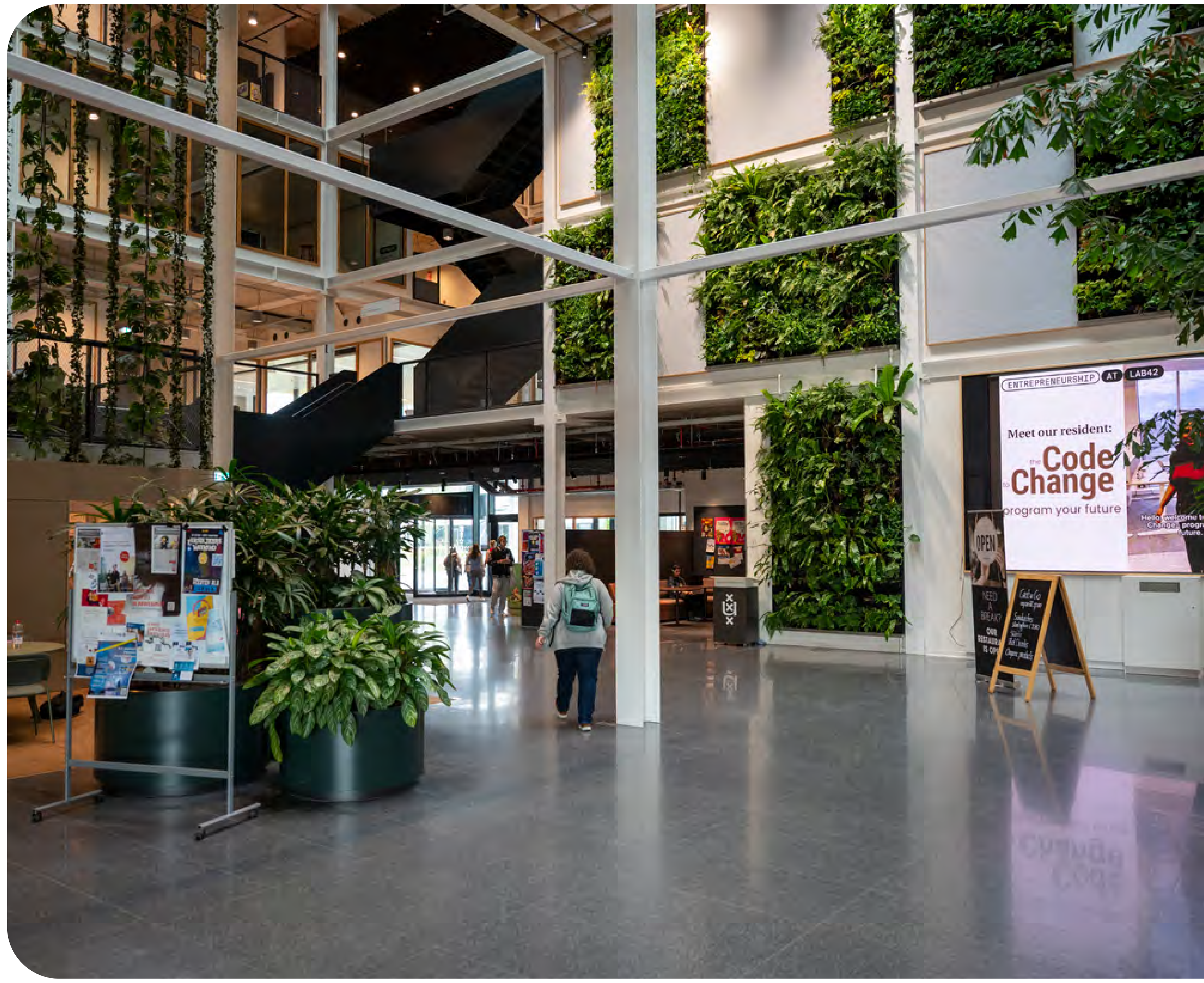
Education

A workforce with more specific skills sets and interdisciplinary knowledge is required. Specifically, a background in applied mathematical/theoretical physics is needed to further develop the field.

Research

- More funding will be available for research around FTQC.
- The first examples of FTQC are to be expected.
- New error correction and mitigation techniques are being developed.



TREND #3

Hardware development acceleration

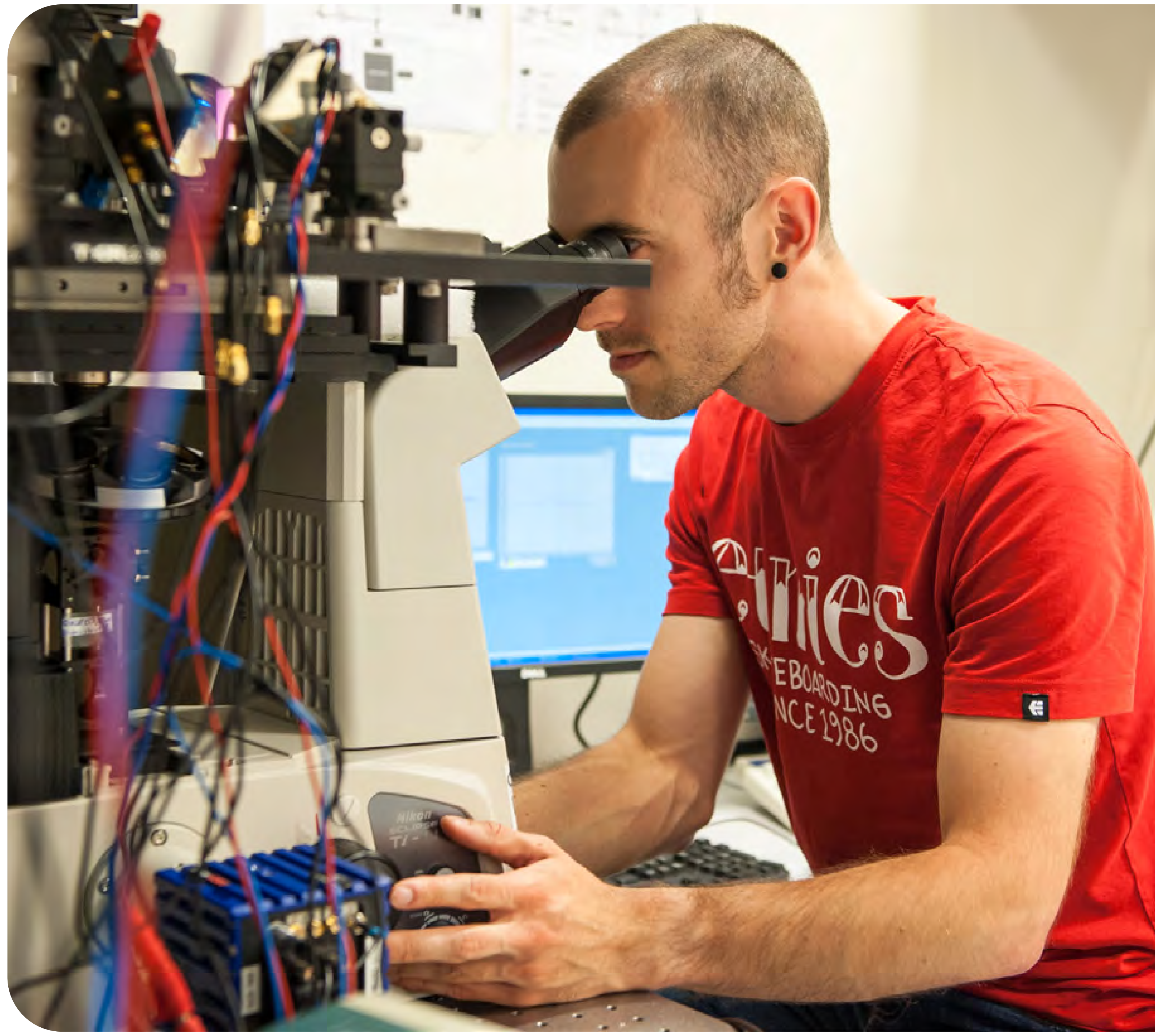
Public Values

Autonomy	Pluralism
Justice	Equity | Integrity | Accessibility
Humanity	

Maturity WATCH PLAN ACT

Drivers
Engineering advances & computation; raw material scarcity; Geopolitics & (digital) sovereignty

The different technologies being pursued for quantum processors (chips), such as superconducting circuits, trapped ions, photonic qubits, and newer contenders like neutral atoms or semiconductor spin qubits, each have their own advantages and challenges. Any small improvement in the qubits coherence, connectivity or accuracy can make a big difference. Breakthroughs in error correction, manufacturing, or hybrid designs can quickly shift the landscape. As research and investment accelerate, the race to build the most capable quantum hardware is intensifying.



Current research and developments in quantum chips focus on four main directions: 1) expanding the number and quality of the qubits, 2) creating processor architectures with built-in error correction, 3) harnessing the existing semiconductor manufacturing infrastructure and 4) improving scalability though modular designs that extend beyond a single chip.

The fast progress in chip development is also driving improvements in supporting tools such as cryogenics, control electronics, cabling, lasers, and photonic components.

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News and announcements of hardware-related improvements

Fujitsu and RIKEN develop world-leading 256-qubit superconducting quantum computer (fujitsu.com)

Quantinuum proves their quantum computers will scale with major hardware innovation (quantinuum.com)

Scalable multispecies ion transport in a grid-based surface-electrode trap (arxiv.org)

Quantinuum's H-Series hits 56 physical qubits that are all-to-all connected, and departs the era of classical simulation (quantinuum.com)

IBM launches its most advanced quantum computers, fueling new scientific value and progress towards quantum advantage (newsroom.ibm.com)

Increase of investments in companies and start-ups developing quantum platforms and enabling technologies

Funding for quantum computing startups reached a record $2B in 2024, up 4x in the last 5 years (app.dealroom.co)

This billion-dollar firm plans to build giant quantum computers from light (nature-com.saxion.idm.oclc.org)

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10 startups betting on quantum tech in 2025 in the UK and Europe (techfundingnews.com)

Yole group's quantum technologies 2024 report (yolegroup.com)

Qubit Type	Pros/Cons	Select Players
Superconducting	***Pros***: High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start. ***Cons***: Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood.	rigetti, Google, IBM Q, QuTech, OQC, IQM, qci Quantum Circuits, Inc, 本源量子 Origin Quantum
Trapped Ions	***Pros***: Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent. ***Cons***: Slow gate times/ operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability.	IONQ, AQT, QUANTINUUM, Universal Quantum, oxford ionics
Photonics	***Pros***: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs. ***Cons***: Noise from photon loss; each program requires its own chip. Photons don't naturally interact so 2Q gate challenges.	PsiQuantum, XANADU, QuiX QUANTUM, ORCA Computing
Neutral Atoms	***Pros***: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required. ***Cons***: Requires ultra-high vacuums. Laser scaling challenging.	ColdQuanta, QuEra Computing Inc., atom computing, PASQAL
Silicon Spin/Quantum Dots	***Pros***: Leverages existing semiconductor technology. Strong gate fidelities and speeds. ***Cons***: Requires cryogenics. Only a few entangled gates to-date with low coherence times. Interference/cross-talk challenges.	intel, Silicon Quantum Computing, diraq, QUANTUM MOTION, QUANTUM BRILLIANCE

SIGNALS

Increased interest in more scalable and modular systems

IBM debuts next-generation quantum processor & IBM quantum system two (newsroom.ibm.com)

Xanadu announces Aurora, a universal photonic quantum computer (thequantuminsider.com)

Quantum transduction and networking for scalable computing applications (research.google)

Modular superconducting qubit architecture with a multi-chip tunable coupler (rigetti.com)

Quantinuum researchers make a huge leap forward demonstrating the scalability of the QCCD architecture (quantinuum.com)

Fault-tolerant platforms by design

Cat qubits open a faster track to fault-tolerant quantum computing (physicsworld.com)

Meet Willow, our state-of-the-art quantum chip (blog.google)

Amazon joins quantum race with 'cat qubit' powered chip (bbc.com)

Microsoft unveils Majorana 1, the world's first quantum processor powered by topological qubits (azure.microsoft.com)

Microsoft's Majorana 1 chip carves new path for quantum computing (news.microsoft.com)

"The quality of qubits and better integration are two sides of the same challenge: scaling up."

– **Dr. Kees Eijkel**, general director of QuTech

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Education

- A workforce with more specific skills sets and interdisciplinary knowledge is required, e.g. by educating more professionals in engineering/applied physics.
- Potentially more hardware for education will be made available.

Research

- Hardware enabling technology developments due to quantum computing can also help the advancements in other fields.
- Potentially more hardware for testing and experimenting will be made available.

Operations

Start thinking about how to enable access to quantum computing resources for education, research and use cases development.

TREND #4

Enhancing quantum computing robustness and potential

Public Values

Autonomy	Independence | Freedom of choice | Pluralism
Justice	Equity | Integrity | Accessibility
Humanity	

Maturity WATCH PLAN ACT

Drivers
Digital transformation; Engineering advances & computation; Automation & AI; critical infrastructure; Geopolitics & (digital) sovereignty

For quantum computers (QCs) to be truly effective, they must solve meaningful problems. Exploring how to scale their computational power is done in three notable ways.

First, hybrid High-Performance Computing-QC (HPC-QC) uses quantum computers as co-processors for computations where it offers an advantage. HPC-QC can both enhance the capabilities of current quantum devices and accelerate the performance of classical HPC systems in the future. It also increases accessibility to quantum technologies by leveraging existing HPC infrastructure and encouraging their adoption within HPC communities.

Second, combining QCs with AI: the advances in one can help overcome challenges in the other. For example, quantum algorithms may improve machine learning performance, while AI techniques can assist in optimising quantum circuits and error correction.

Third, connecting multiple QCs using a quantum communication network can enable to combine their computational resources. This modular or distributed architecture offers a path to scaling quantum systems beyond the limits of individual devices.

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HPC-QC

Quantinuum and Riken (quantinuum.com)

IBM and Euskadi quantum (newsroom.ibm.com)

SURF quantum computer (surf.nl)

What is quantum-centric supercomputing (ibm.com)

Quantum computing unveiled: insights for the HPC community (quera.com)

"The quantum computing ecosystem underestimated the value of connectivity for scalability; it is hard to scale a single system."

– **Jesse Robbers** (Managing Director imec NL, Co-Founder and former board member Quantum Delta NL)

QC&AI Synergy

Generative AI for quantum (quantinuum.com)

The next breakthrough in Artificial Intelligence: how quantum AI will reshape our world (forbes.com)

Discover how AI is transforming quantum computing (thequantuminsider.com)

Enabling quantum computing with AI (developer.nvidia.com)

Quantum computers will make AI better (quantinuum.com)

Leading scientists urge EU to invest in combining AI & quantum to strengthen competitiveness (qt.eu)

Distributed QC

IonQ buys IDQ (idquantique.com)

Photonic demonstrates distributed entanglement between modules, marking significant milestone toward scalable quantum computing and networking (photonic.com)

Quantum datacenter alliance (qda.global)

Distributed quantum computing (quera.com)

Demonstrated network connection between quantum processors over metropolitan distances (qutech.nl)

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Education

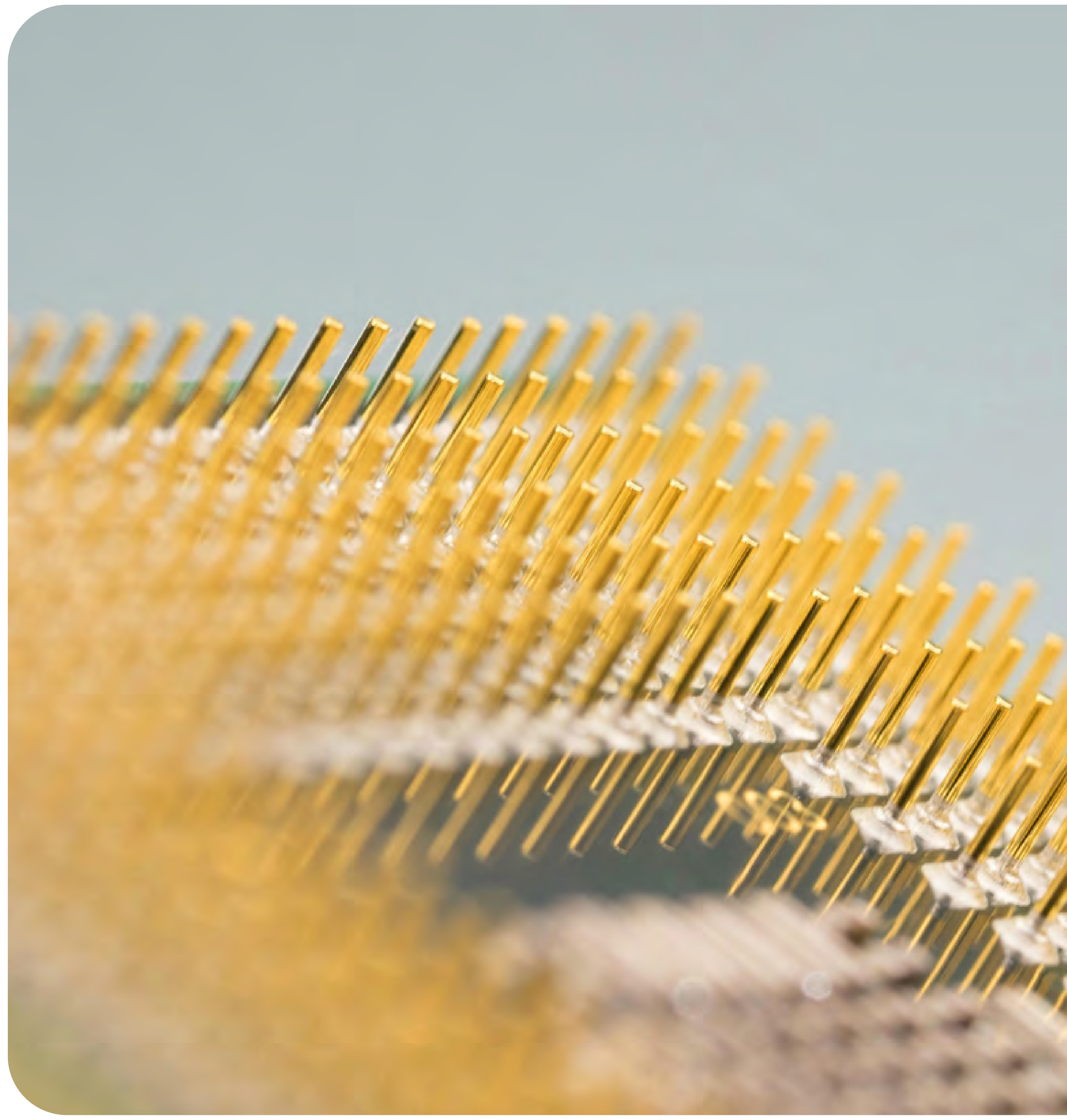
A workforce with more specific skills sets and interdisciplinary knowledge is required.

Research

- Improving the robustness of quantum computers will stimulate interest in quantum computing.
- Integrating QC with HPC will lower the barrier of usage for the HPC users.
- Research on QC&AI will increase.

Operations

- Start thinking and realising the integration of quantum computing to the existing infrastructure and ecosystem.
- Start thinking on how to give access for education, research and use case development.
- Develop quantum expertise for operation and user support.



TREND #5

Quantum sensing integration to other domains

Public Values

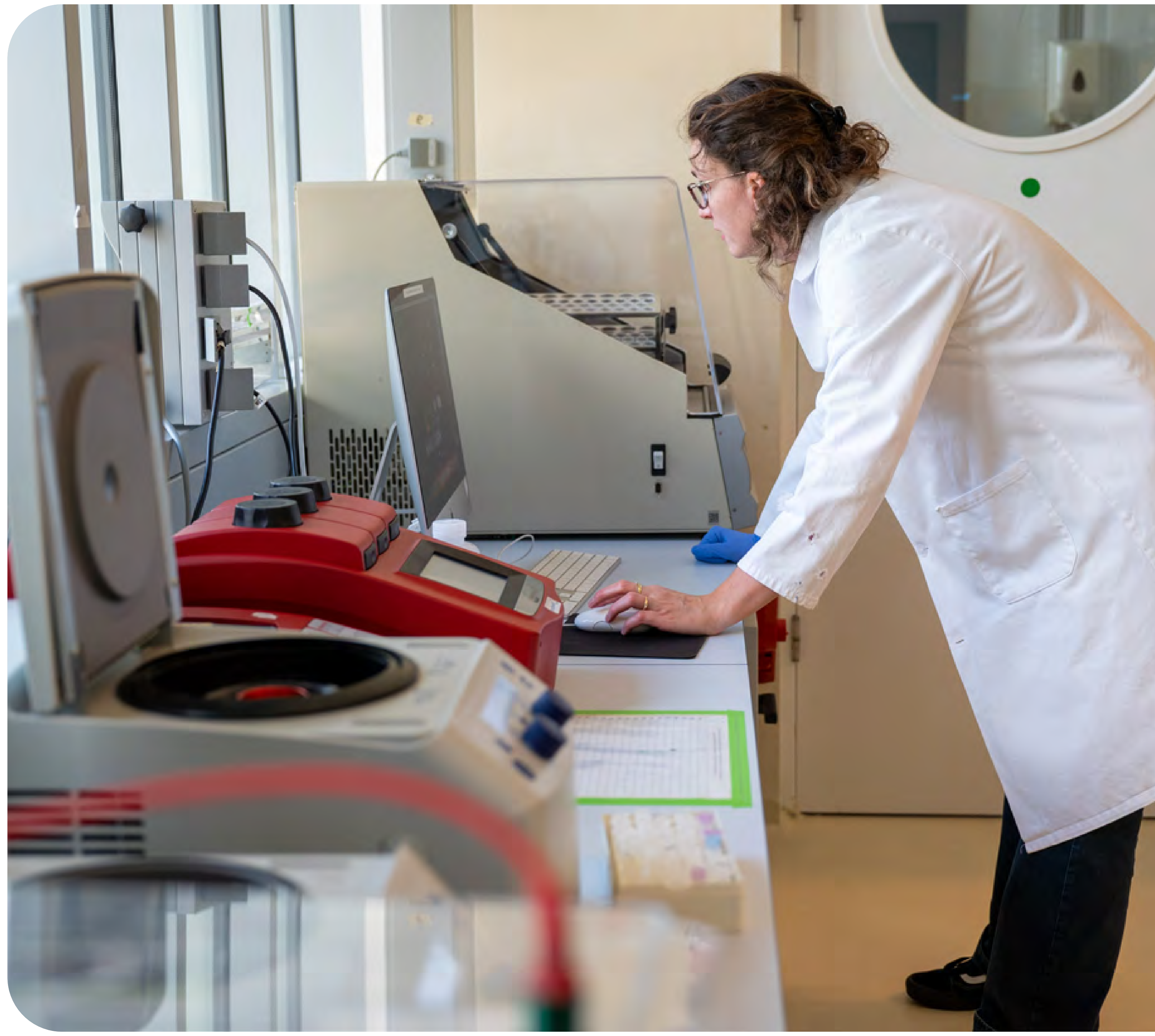
Autonomy	Independence | Freedom of choice | Pluralism
Justice	Equality | Integrity | Accessibility
Humanity	Integrity | Accountability | Sustainability

Maturity WATCH PLAN **ACT**

Drivers

Digital transformation; Geopolitics & (digital) sovereignty; weaponisation of knowledge; critical infrastructure; compliancy & regulation

Quantum sensing uses the incredible sensitivity of quantum particles to measure things that ordinary sensors can't detect, or that would take huge amounts of time and resources to observe. Among the three main areas of quantum technology, quantum sensing is the most mature, with several devices already on the market. Experts expect the global market for quantum sensors to grow to about €6 billion by 2035 and reach around €15 billion by 2040.



In the last years, quantum sensors have already demonstrated significant benefits in a wide range of applications: medical imaging (MRI), spectroscopy for material and chemical analysis, enhanced Position Navigation and Timing (PNT), gas-leak detection, remote target identification, as well as gravimeters and magnetometers to support industries such as mining, oil, and gas.

Because quantum sensors are already proving their value in so many fields, and because they're getting smaller, cheaper, and more reliable, we can expect their applications to grow rapidly in the coming years.

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More examples of use cases

Quantum sensing: poised to realize immense potential in many sectors (mckinsey.com)

Sensing the underground infrastructure (tcs.com)

Healthcare (qtsense.com)

Magnetic field sensing (bosch-quantumsensing.com)

Positioning and timing (q-ctrl.com)

Measuring magma streams under volcanos (exail.com)

AI might help in getting better high precision data by quantum sensors (postquantum.com)

"Four of the most promising quantum-sensing use cases include positioning, navigation, and timing (PNT); healthcare; semiconductor manufacturing; and subsurface exploration. Across these areas, Europe is seeing a growing wave of startups."

- dr. Clara Osorio Tamayo, QDNL CAT3 Program Leader, TNO Scientist

Report of QED-C (quantumconsortium.org)

Looking at real world use cases for quantum sensors (insidequantumtechnology.com)

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Education

- More awareness about quantum sensing is needed.
- Some quantum sensors are very easy to develop towards a prototype level, making them perfect for didactical use.
- Quantum sensing is about measuring real quantities. It's time to start the discussion what the political, ethical and public values implications are.

Research

- There will be advancements in fields that are already making use of quantum sensors (e.g. health care and medical sector, earth science, astronomy, etc.).
- New fields of research will emerge which will make use of quantum sensing.
- New applications of existing technology are being developed.

Operations

Start thinking on the acquisition of quantum sensing devices for research and education.

More info about Quantum Technologies? Visit surf.nl

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