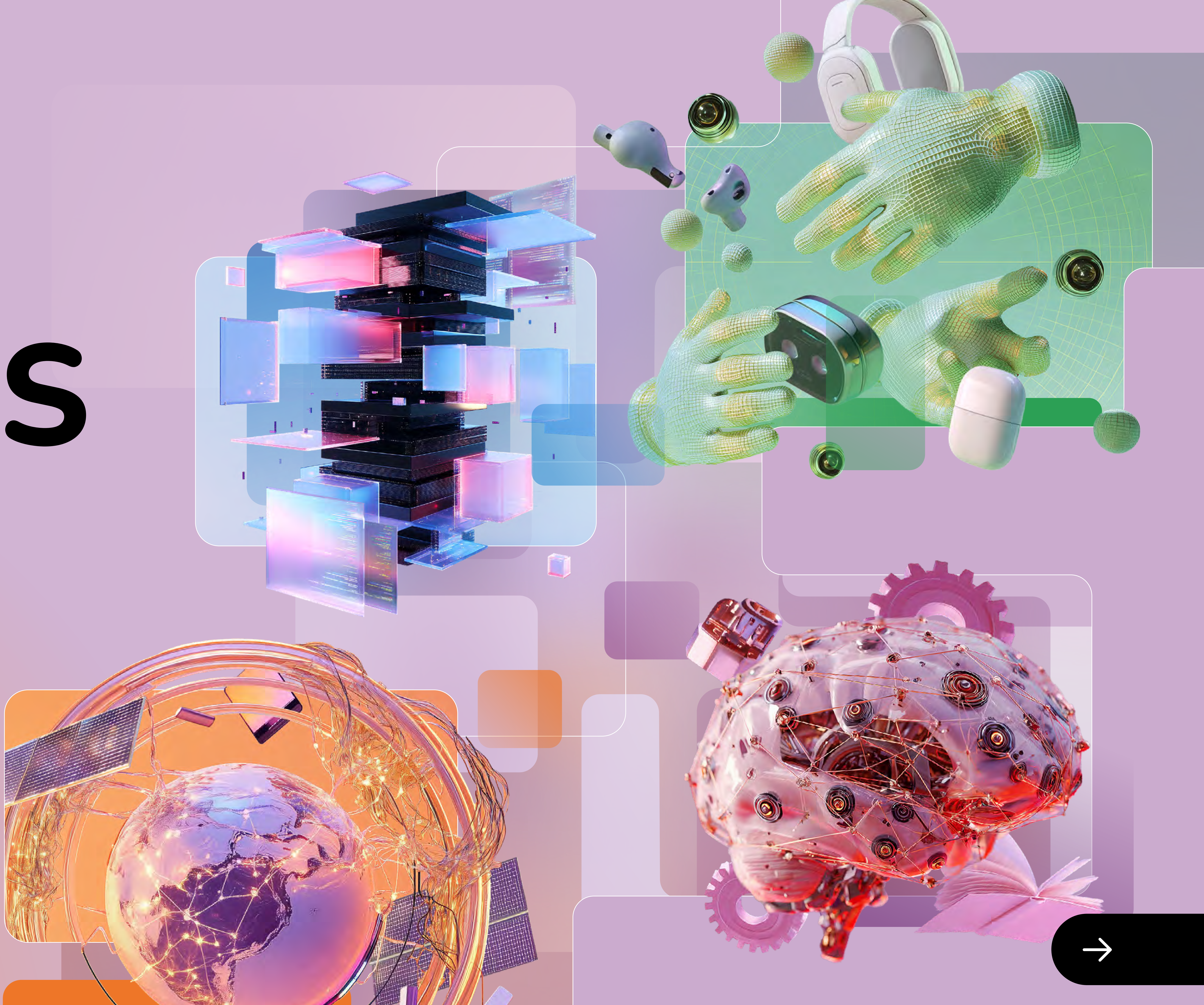
SURF TECH TRENDS 2026



SURF

Preface

The digital transformation is fundamentally affecting the way that participants in our society – from citizens to companies and public organisations – interact, collaborate, learn, and perform. Digital developments are accelerating, resulting in for example exceptionally steep adoption rates of artificial intelligence (AI) in recent years. This is also seen in AI integration in end-user applications (e.g. Copilot, WhatsApp), but also in other layers of the so-called digital technology stack, such as computing power, extended reality (XR), data networks, and data management.

This evolving digital transformation is of paramount importance for the cooperative SURF as a collaboration of national research organisations and education institutes. For most members of SURF, it is a challenge to anticipate the potential added value, risks, and impact of emerging digital technologies and to manage topics like digital trust, digital wellbeing, and digital autonomy, in a responsible manner.

Looking to the future horizons of digital developments is essential for SURF cooperative. It is important for the sector to harness emerging technologies for research and education, with public values as a foundation. Futuring, scenario planning, and technology exploration capabilities are needed. This to search these horizons, to identify what's likely to emerge and to identify the potential value and impact of digital technologies on research and education.

SURF's futuring activities are supporting the cooperative to collectively learn and enhance our capabilities regarding our future-readiness. SURF's continuous technology exploration and knowledge development supports a deep understanding of challenges, risks and impact of emerging technologies for our sector.

We are proud that this SURF Tech Trends Report is one of the activities and resources to collaborate and serve the members, and to give the various stakeholder groups in our cooperative insights to act.

Hans Louwhoff and **Ron Augustus**
(Board of Directors SURF)

Contents

Navigating through the stack

Introduction

In a fast-changing, dynamic environment, keeping up with the development can be a challenge. With the previous Tech Trends report (2023), we have made a start in supporting and facilitating the SURF cooperative by identifying and curating relevant trends for education and research. Compared to 2023, this edition is bigger, bolder and goes beyond.

Bigger
In the production of this Tech Trends report, about thirty professionals from over twenty member institutions participated in the working groups together with SURF colleagues. Together, we have covered ten technology-oriented chapters that we present in this report. Besides the working groups we engaged with other stakeholders with knowledge and experience to contribute to the tech trends.

Bolder
For each trend, we have looked at its potential impact on education, research and operations. Operations is a new impact area that has been added as we see IT becoming a more integral part of an institution or campus.

Along with the nine technology-driven chapters that are selected, we have added a chapter with wild cards that can either be black swans or grey rhinos due to their non-obvious and less predictable character.

Beyond
As we have our biases as people working in education and research, we have consulted “outsiders”: industry leaders and experts. The perspectives we have included represent not only big industry but also European and more global view points. Throughout this report, you might come across the insights they shared with us.

Some highlights to keep in mind
Overarching in this report, a few observations have stood out that demand attention moving forwards:

- There is a significant impact of AI on the trends. Therefore we can conclude AI as a system technology
- There is a strong aim for efficiency (doing more with less) in technologies
- More attention needs to be paid to digital skills to navigate the digital transformation, especially in the spirit of cybersecurity
- There is a strong tendency to look only towards the USA, and we shouldn’t overlook other countries like Singapore and China
- As a lot is happening, we see strategic options emerging to strengthen Netherlands’ position globally.

Gül Akcaova (lead Futurist SURF)

Approach

Our project principles

- In collaboration with SURF members as it is primarily for the members
- IT-oriented view
- Outside-in perspective
- Trend curation rather than trend watching
- Readable (introductions) for board members and C-suite
- (actionable) insights for CIOs, information managers, policy advisors, etc.
- Impact assessments (opportunities and threats) for Education, Research & Operations, rather than defined or prescribed recommendations by SURF
- Conversation starter rather than a “marketing” report or an “how-to”

Selection of the chapters

Over 23 technology reports are identified, scanned and clustered. Eventually, we have looked and identified the common denominators that led to the nine chapters. To ensure novelty and inspiration, an extra chapter (wildcards) is created.

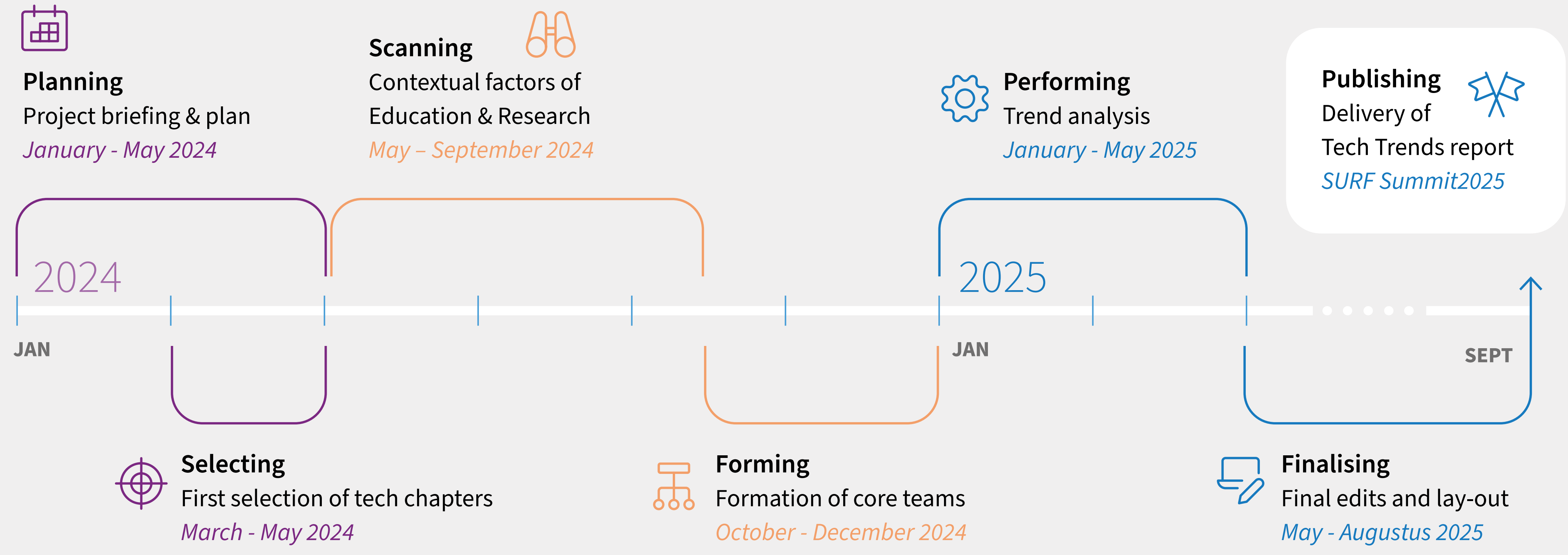
Selection of the trends

The working groups were formed based on a ‘call for expertise/contributions’, which was widely spread. Based on expressed interest, we aimed for well-balanced groups per chapter. We had a kick-off on Oct 10, 2024, to set the foundation to scan (literature review), validate (interviews and consultation), and analyse (group discussions) the trends as groups.

On May 7th, a wide expert consultation was organised where a mixed group from the cooperative was invited to assess the recognisability and relevance of the selected trends by the working groups (see acknowledgement).

Over the summer, the editors reviewed the content, assessed the quality and consulted reviewers to further improve and ensure accessibility of the content of this report.

Road to Tech Trends Report



AI disclosure

AI (LLMs) was used by various working groups to analyse documents, assess trends and improve the writing. AI was also used by the graphic designer for the chapters’ covers.

Reading guide

Introduction of the trend

Chapter

Signals for this trend

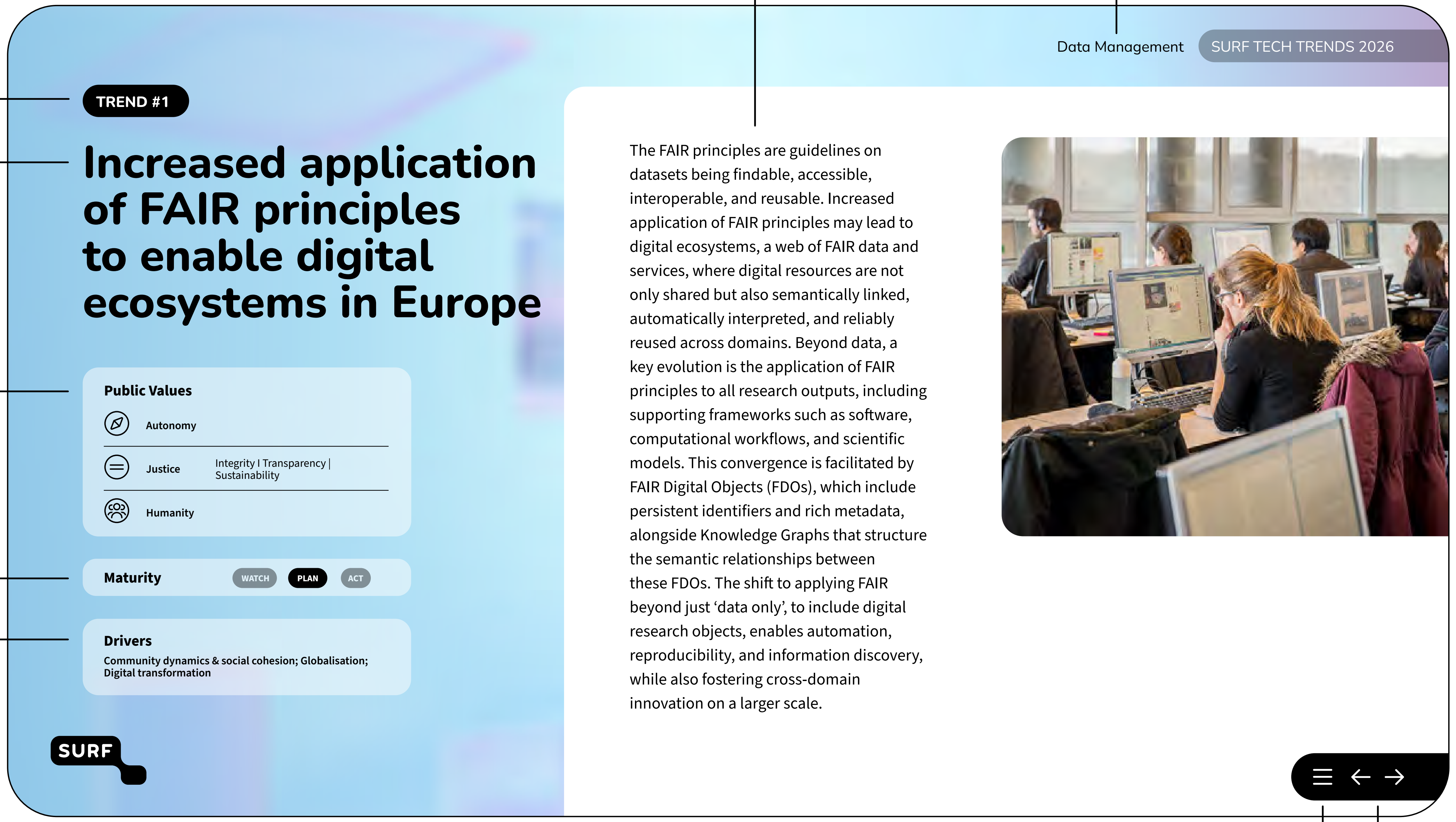
Trend number

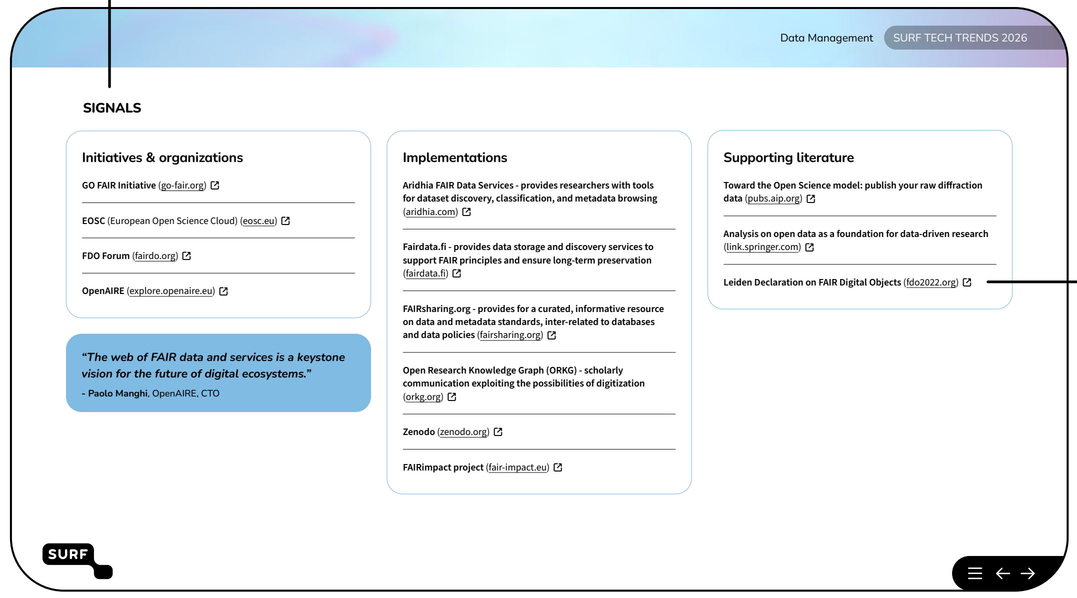
Trend

Public values

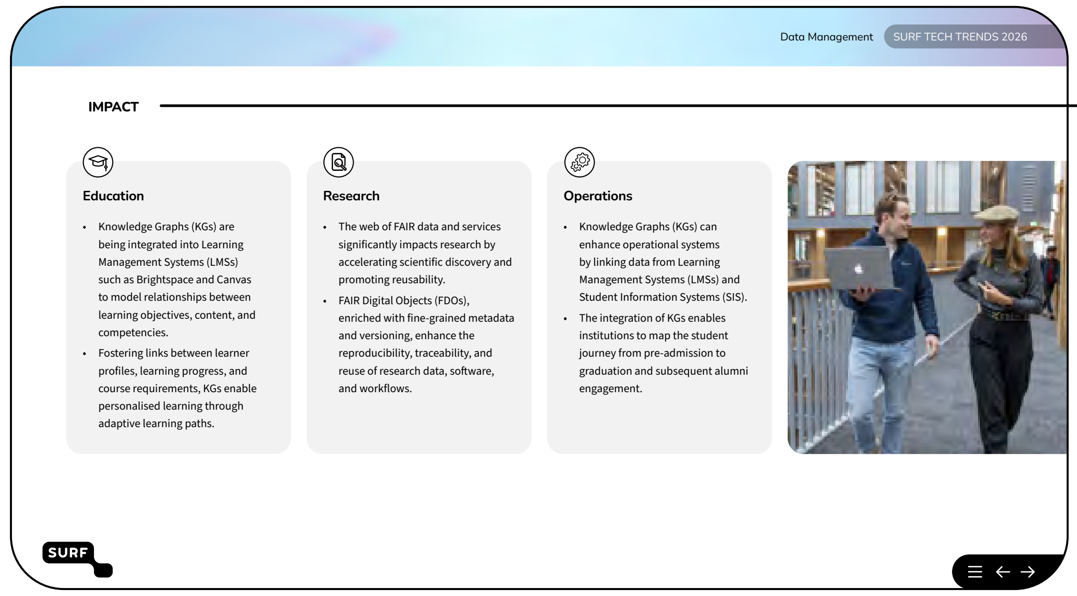
Readiness level

Drivers





Read more about the signal online



Impact of the trend on education, research and operations

Go to the table of contents

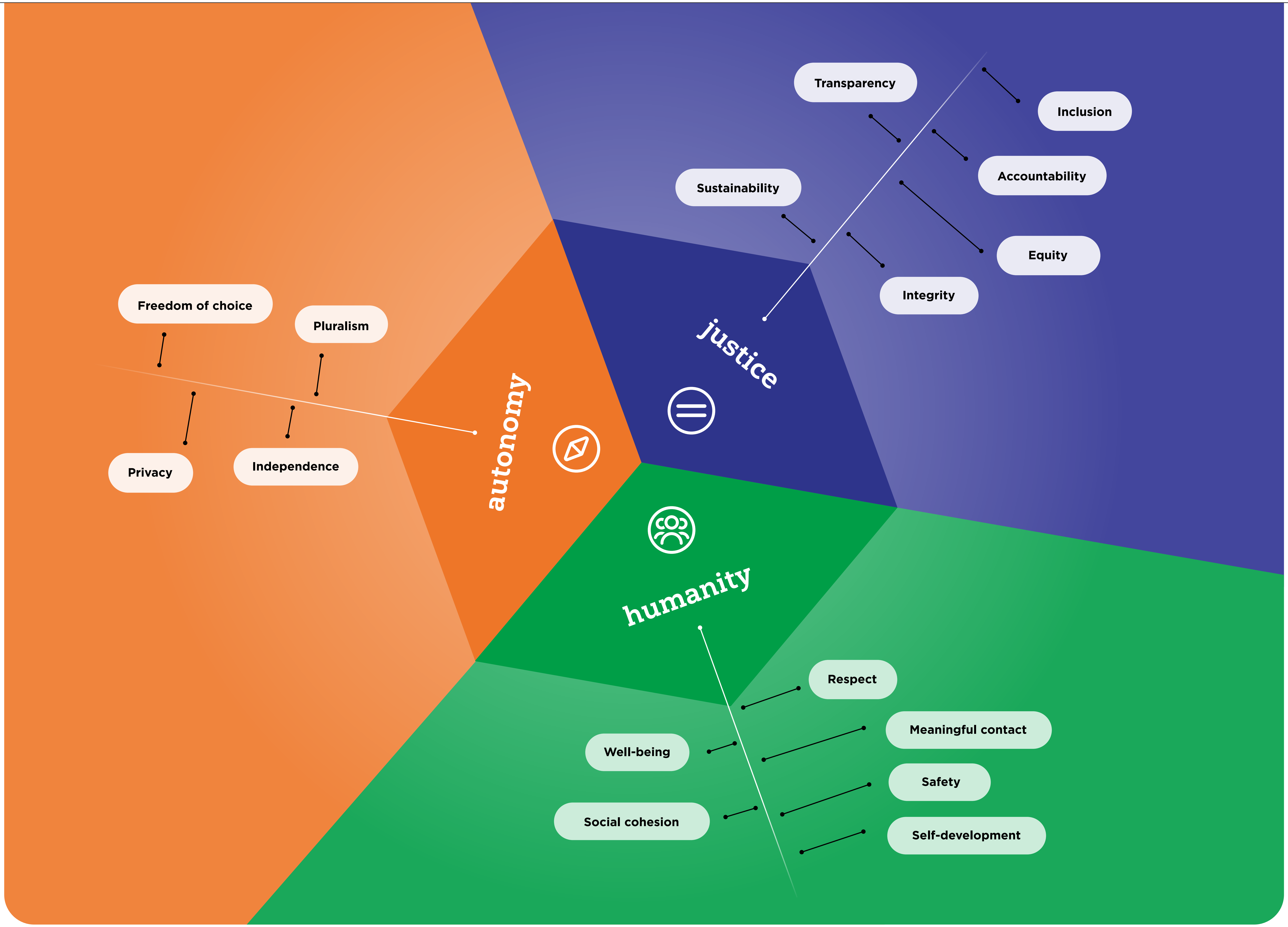
Navigate through the pages

Value compass

SURF and Kennisnet, the public IT organisations for education in the Netherlands, have developed the Value Compass to provide a common language to stimulate the dialogue about digital transformation in education and the importance of educational values.

The Value Compass provides a frame of reference for structuring digital transformation based on values.

For each trend we identified a relationship with public values. The value compass helps us to identify a value or multiple values driving the trend towards a certain direction.



Drivers

We are living in an increasingly complex and interconnected world where powerful forces (drivers) are influencing and reshaping the foundations of society and, therefore, education and research. These drivers span social expectations, cutting-edge technologies, economic shifts, environmental urgency, and evolving policy and regulatory landscape(s).

These drivers do not act in isolation; their convergence creates both disruption and opportunity, challenging traditional models of knowledge and institutional purpose, as the environment becomes uncertain and/or unpredictable. Understanding these drivers is essential not only to remain relevant but to make better decisions and prepare for a future that is already here.

Societal and demographic drivers

- Individualisation & empowerment
- Demographic shift (ageing, migration & identities)
- Value of knowledge & skills
- Mental health & well-being
- Community dynamics & social cohesion

Economical drivers

- Global trade & tariffs
- Globalisation
- Concentration of wealth & economic inequality
- Service-oriented & value-based economies
- Digital transformation

Political and regulatory drivers

- Geopolitics & (digital) sovereignty
- Compliance & regulation
- Critical infrastructure
- Weaponisation of knowledge
- Ideologic polarisation

Technological drivers

- Automation & AI
- Engineering advances & computation
- Biotechnology
- Connectivity & interaction
- Cybersecurity & trust

Ecological drivers

- Climate change & global warming
- Energy supply & demand
- Raw material scarcity
- Clean water demand
- Biodiversity

Artificial Intelligence

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Introduction

Over the past years, the full realisation of the transformer architecture (a digital neural network that can process vast amounts of data) has completely transformed the Artificial Intelligence (AI) landscape. Most AI research and development has pivoted towards Generative AI (GenAI), a subfield that employs computational models to generate text, images, video, and audio.

In many countries, government-funded organisations are developing large AI models for use in fields such as education, research, and healthcare. Unsurprisingly, many organisations are also integrating GenAI into their products and services in pursuit of profitability. Businesses are also seeking real-world applications in the name of efficiency, while also aligning with the responsible deployment of AI in those applications.

For example, there is an increase in the use of AI-Concierge, where AI can assist users (like hotel guests) with enquiries around the clock via popular messaging apps.

A key adoption bottleneck is the lack of knowledge that the general consumer, as well as many employees in organisations, have about prompt engineering for GenAI. Put simply, for any GenAI model to produce what a user wants, the user needs to know what type of instructions to provide the model with to get a desired result. This has pushed Agentic AI into the spotlight as an obvious solution for the novice AI user. In Agentic AI, the AI system serves the user by operating autonomously to perform pre-defined tasks with little or no human involvement or supervision.

Large-scale AI models (which are trained using enormous datasets) are becoming widely available and accessible, and applications built around them are increasingly being integrated into everyday life. The emergence of other new Human-Computer Interactions (HCI) powered by AI and concepts such as AI Love (where humans form intimate connections with AI) is also gaining traction.

A major consequence of the advancements in AI is that it is now a significant topic of geopolitical interest and controversy. In essence, AI is a key tool in the political world and as it now represents the greatest asset in the geopolitical game of AI supremacy. Governments are investing more in developing AI models and supporting infrastructure as they seek to establish themselves as AI superpowers to realise the full potential of AI for broader society and national security. The unfortunate result of the race for AI dominance appears to come at the cost of a responsible or ethical AI based on principles such as trustworthiness, explainability, and human-centric AI.

Contributors
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TREND #1

More diversified access to large AI models

Public Values

Autonomy	Privacy | Independency
Justice	Transparency | Trustworthiness | Sustainability
Humanity	Wellbeing

Maturity WATCH PLAN ACT

Drivers

Individualisation & empowerment; Mental health & well-being; Value of knowledge & skills; Automation & AI; Connectivity & interaction

Since ChatGPT became available and accessible for widescale use in 2022, large language models (LLMs) have gained massive worldwide traction. For example, ChatGPT reached 1 million users in just a few days after its launch, prompting more diversified access to LLMs and acted as the catalyst for AI to be increasingly part of many daily workflows. Access to AI is facilitated by browser-based tools (ChatGPT, Claude, and DeepSeek) as well as integrations in services and products from vendors like Google (e.g. Docs) and Microsoft (e.g. Copilot, Outlook).

Business models range from freemium tiers to pay-per-use APIs. Users now have the option to choose between cloud-based AI solutions or smaller, lightweight models running locally. Concurrently, open-source initiatives have contributed to the varied access to and democratisation of LLMs and tools. This development is reshaping how we write, code, research, and interact with AI, and even each other.

SIGNALS

Number of GPT users

Most students are using at least one of the available platforms to access a foundation model

- hepi.ac.uk
- campustechnology.com
- insidehighered.com
- library.educause.edu

OpenAI is now the most popular. Other options are Anthropic's Claude, Meta, Google options e.g. LM Notebook & Gemini (datastudios.org)

As of late 2024-early 2025, DeepSeek has been getting quite some traction despite security risks (dig.watch)

According to Semrush, OpenAI was the number five website in April 2025 (semrush.com)

ChatGPT isn't the only chatbot that's gaining users (techcrunch.com)

Gartner: why task-specific AI models will take over LLMs (aimagazine.com)

Rapid rise of Generative AI: the leading companies (iot-analytics.com)

Growing available models (& providers) on Huggingface (huggingface.co)

Vatican: new Vatican document examines potential and risks of AI (vaticannews.va)

European AI on the rise

- openeurollm.eu
- swiss-ai.org
- gpt-nl.nl
- galaxus.nl
- swiss-ai.org

Is the search engine losing ground to AI chatbots?

- economictimes.indiatimes.com
- mashable.com

IMPACT

Education

- The diversified access to AI presents both opportunities and challenges for educators by automating mundane tasks, allowing them to focus on teaching and personal guidance, while necessitating adaptation to an AI-driven educational landscape.
- As students increasingly utilise AI chatbots for learning, productivity and general cognitive offloading, there may be significant implications for traditional tutoring roles and human skills such as critical thinking. Amongst students, the digital divide might widen due to variations in knowledge, access and permission to use.

Research

- In scientific research, AI can accelerate data analysis, enhance text interpretation, and support hypothesis generation. This serves to improve the speed and depth of scientific inquiry.
- Challenges include concerns over copyright and intellectual property, the risk of disinformation in generated content, and the danger of researchers becoming over-reliant on AI tools. More proposals and papers are produced which increases the reviewing burden.
- LLM’s are increasingly being used as a research partner (research agents/co-scientists).

Operations

- Institutional processes are simplified by automating routine or repetitive tasks, enhancing information management, and enabling smarter workflows.
- Institutions have to navigate challenges such as potential copyright and data ownership issues, the risk of spreading disinformation, the reduction of human oversight, and concerns regarding the environmental sustainability of large-scale AI implementations.
- Services and products enabling AI lead to unauthorised data processing/contract breach and DPIAs.

TREND #2

Changing dynamics in Responsible AI

Public Values

Autonomy	Privacy
Justice	Integrity | Equity | Inclusion
Humanity	Safety

Maturity WATCH **PLAN** ACT

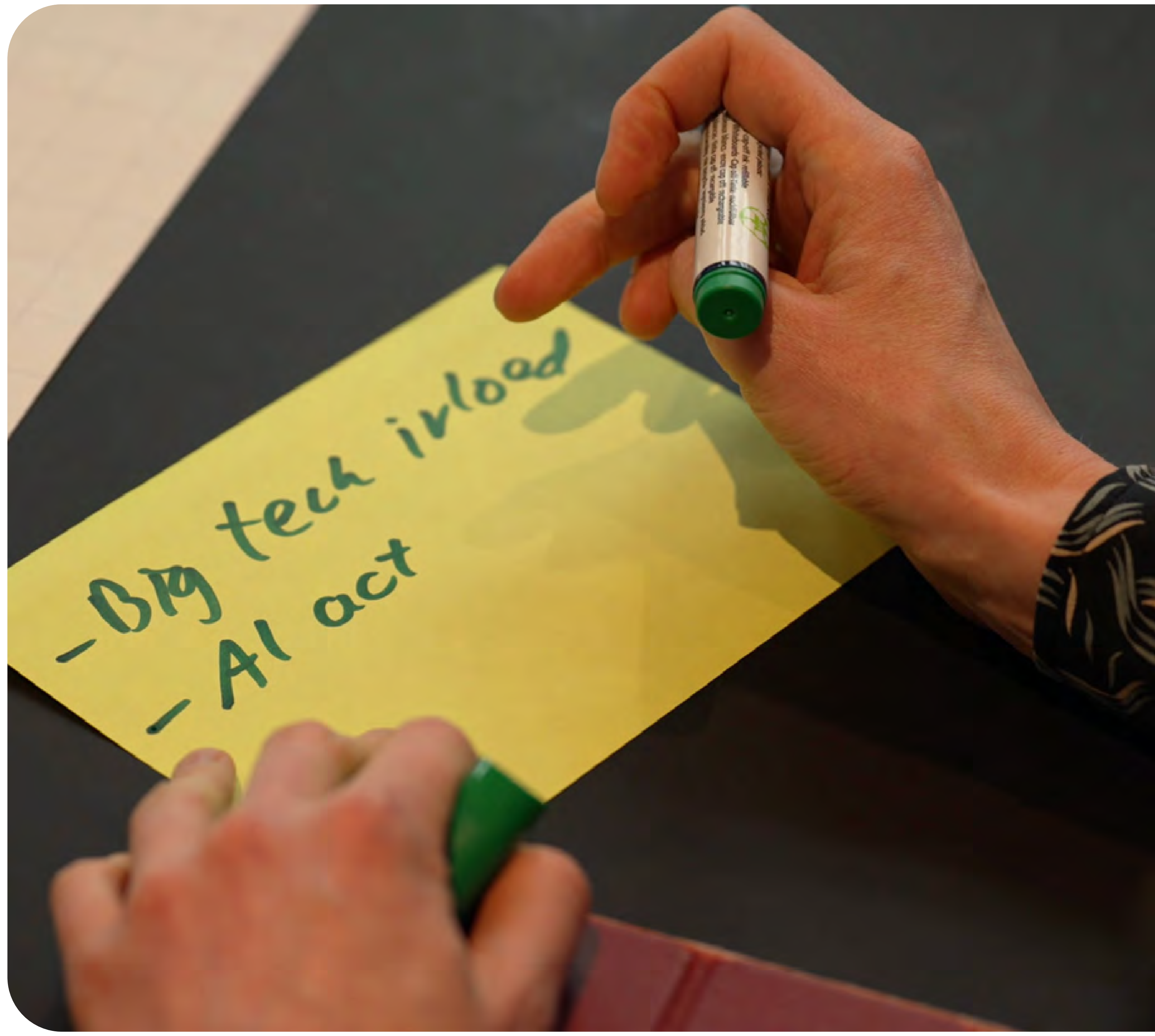
Drivers

Geopolitics & (digital) sovereignity; Concentration of wealth & economic inequality; Compliance & regulation

The EU is perceived as the global leader in regulation in comparison with the US. The AI Act, the world's first regulatory framework grounded on risk, transparency, and rights, demonstrates the EU as the defender of Responsible AI .

Despite this pioneering legislation, recent geopolitical events – mainly in the US - have shifted attention from ethics and human-centric AI towards national security and economic competition. Big tech companies are downsizing their Responsible AI commitments by laying off their ethics boards and prioritising competitiveness over transparency and responsible deployment.

However, there are signals that many businesses across the globe do want to implement Responsible AI, though they lack support or mechanisms to act upon it. Although generally small in scale, progress is being made to put Responsible AI programs in place. Nevertheless, the gap between intention, talk, and action on Responsible AI remains.



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SIGNALS

Companies like Google and others are disbanding their ethics boards and firing ethics-aligned employees

- wired.com
- startupdaily.net
- wired.com

Think twice before using DeepSeek: security and trust issues explained (carleton.edu)

The UK has delayed plans to regulate AI as ministers seek to align with the Trump administration (theguardian.com)

European Commission has withdrawn the proposed AI Liability Act (that would have made using copyrighted material for training models subject to copyright infringement)

- openai.com
- mayerbrown.com
- musicbusinessworldwide.com

Harvard business review (HBR) research: how responsible AI protects the bottom line (hbr.org)

Little more than half (52%) of companies actually have a responsible AI program in place, BCG data shows (bcg.com)

87% of managers acknowledge the importance of responsible AI (RAI) - MIT Technology Review (technologyreview.com)

"There is growing evidence that many big tech companies are backsliding on their commitments to responsible AI."

- **Virginia Dignum**, Professor AI and Director of AI Policy Lab, Umeå University

IMPACT

Education

- Copyright protection for teaching materials is been eroded, and there is a need to educate students in a more effective manner on how to use GenAI responsibly and safely.
- Students need to learn not to blindly trust GenAI models, and as Virginia Dignum says, educate them in navigating an industry culture that may be increasingly ambivalent towards responsible AI.

Research

- Copyright issues are impacting research involving GenAI models. Researchers require access to independently developed models, rather than just those derived from major tech companies, to avoid legal complications and foster responsible innovation.
- Industrial collaborations may be affected because of diverging policies on data management and processing.
- Independent research into AI's impact on society needs to be prioritised.

Operations

- Assessment methods should be reassessed due to a lack of measures from OpenAI to prevent coursework cheating.
- Clear guidelines for students and staff on using GenAI are needed.
- Offline models for educational use should be provided to end-users.
- Caution is required when using GenAI for administrative tasks, especially regarding data protection and ethical issues.

TREND #3

Increase in co-evolution between hardware and AI

Public Values

Autonomy	Independency
Justice	Equity
Humanity	

Maturity WATCH PLAN **ACT**

Drivers
Automation & AI; Engineering advances & computation; Energy supply & power demand; Raw material scarcity

While hardware initially facilitates the computing for AI, it is now becoming the limiting factor, forcing AI developments to fit with computing infrastructure. The growing popularity and accessibility of AI models are driving a significant shift in hardware innovations. AI models are increasing in size and complexity faster than the advancements in general-purpose computing technologies for processing.

In the previous SURF Tech Trends Report 2023, the surge in specialised AI hardware was highlighted. In addition to this trend, more devices (phones, laptops, etc.) are being produced to support daily AI workflows. Another development driven by this mismatch is the design of AI models to use available computational resources more efficiently. With innovations such as low-precision models and AI-aware hardware implementations, AI is being reshaped, driven by the need to achieve 'more with less' in system capabilities.

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SIGNALS

Nvidia's CES 2025 announcements promise a personal supercomputer (nvidianews.nvidia.com)

Projected growth of AI chip market (gcom.pdo.aws.gartner.com)

More AI hardware-focused companies coming into the market, e.g, Cerebras

- forbes.com
- axelera.ai

Many existing companies are pivoting towards making AI hardware

- digitaltrends.com
- gartner.com

There is an increase in hardware-aware model design (pytorch.org)

The pivot to focusing on AI solutions in most hardware marketing (gartner.com)

The AI revolution will require hardware resources with large energy requirements. This makes enterprise infrastructure a strategic differentiator once again (deloitte.com)

"The gains in AI training performance since MLPerf benchmarks have dramatically outpaced Moore's Law."

\- **David Kanter**, executive director of MLCommons (deloitte.com)

IMPACT

Education

- Personal AI workstations and increased attention for trusted compute architectures may help mitigate current privacy issues with big tech LLMs, as well as reducing data traffic across networks.
- High-performance compute for (HPC) for AI will offer students the possibility to handle more complex data tasks, however training may be required.

Research

- More accessible computer hardware with higher performance (personal supercomputers) means that there will be enhanced research capabilities for the research community.
- A dependency on a handful of vendors for AI-hardware exposes a risk of a potential scarcity of AI-devices as global supply chains come under pressure.

Operations

- Personal AI workstations and more efficient AI models, at lower cost, mean students and researchers are less likely to require large-scale high-performance computing (HPC) systems to experiment with cutting-edge AI. Unlike the computer science, data science, and AI communities who will still need to carry out internationally competitive research.
- Global demand for resources enabling AI specific chips, could limit hardware availability of edge devices supporting smart campus automation, research and education.

TREND #4

Collaboration between humans and AI

Public Values

Autonomy	Freedom of choice | Independency | Privacy | Diversity
Justice	Inclusion
Humanity	Safety | Social cohesion

Maturity WATCH PLAN **ACT**

Drivers

Individualisation & empowerment; Value of knowledge & skills; Automation & AI; Connectivity & interaction; Digital transformation; Concentration of wealth & economic inequality

Rather than taking over jobs, which is the way that AI is regularly framed, AI is becoming a partner at work and in our daily lives. In certain ways, AI is already taking over routine tasks to allow humans to focus on complex and creative work.

Next to routine tasks, AI is already considered a companion to turn to for therapy, identifying one's purpose, and resolving life issues. This AI partnership will be further strengthened by the growth of multi-agent systems.

Agentic AI, which has been in development since the late 1990s, promises to significantly enhance human-computer interaction through its natural language interfaces. Additionally, other interfaces are emerging in collaborative robots (cobots) and humanoid robots, enabling more human-like interactions.

Furthermore, AI is being integrated as ambient intelligence into various tools and devices. Consider wearables with optics and microphones that can analyse the wearer's surroundings and assist in the same manner as a personal assistant or AI companion. A noticeable sentiment about this development relates to the use of LLMs from big tech companies for running the applications.

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SIGNALS

Healthcare

AI assistants like PathAI are helping doctors analyse medical images (pathai.com)

Humanoid robots

Will be mass-produced in the US and China over the next three years

- tesla.com
- unitree.com

OpenAI's next big bet won't be a wearable: Report (techcrunch.com)

Software development

Tools such as Github copilot in Character.AI are set to increase productivity and quality in the software development life cycle

- github.com
- character.ai

Your next AI wearable will listen to everything all the time (wired.com)

Project Astra | Exploring the future of learning with an AI tutor research prototype (youtube.com)

More powerful AI is coming. Academia and industry must oversee it – together (doi.org)

"Once AI becomes part of the background, it's no longer optional. It's invisible but irreversible."

- **Pieter Loman**, Utrecht University

IMPACT

Education

- Changes are necessary in the curriculum to meet the new ways of collaborating with AI in professions, and all without compromising public values.
- Agentic AI may reduce teacher workload by automating assessments, feedback, and lesson planning – but raises questions about student agency, bias in feedback, and surveillance concerns.
- As workplace collaboration between humans and AI has a profound impact on jobs, students will need adaptability and a change in mindset as crucial skills for the future.
- Students, and teaching staff are becoming a data source for big tech, as the availability of AI tools become more widespread and accessible.

Research

- Researchers could benefit from AI agents to handle repetitive tasks (e.g., formatting, summarising, and literature scanning).
- Assuring reproducibility, data privacy, and authorship attribution are more complex for AI agents to handle.
- By streamlining data analysis, supporting experimental design, and managing laboratory tasks through robotic and predictive systems, AI promises increased automation and efficiency.
- Ownership of research data and associated questions are exposed with the use of publically available LLMs.

Operations

- AI can increase efficiency and productivity, but care needs to taken with ethical judgements. Importantly, the main goal of education is not to lower costs, but to create a meaningful learning environment for students, as well as a safe and inspiring place to work for educational professionals.
- Institutions risk vendor lock-in and rising IT costs due to their reliance on embedded AI tools.
- AI-powered services could optimise scheduling, student support, and administration, lowering operational costs.
- Human-AI collaborative systems will be fed with huge amounts of physical and personal data, necessitating strict privacy regulations and ethical considerations to safeguard users and promote responsible AI practice.

TREND #5

From large to small language models

Public Values

Autonomy	Privacy | Diversity
Justice	Transparency | Inclusion | Accountability
Humanity	Safety | Social cohesion

Maturity

WATCH **PLAN** ACT

Drivers

Individualisation & empowerment; Value of knowledge & skills; Connectivity & interaction; Cybersecurity & trust; Concentration of wealth & economic inequality; Energy supply & power demand; Climate change and global warming

After the revolutionary introduction of LLMs, there is growing interest in Small Language Models (SLMs). These are models with up to 10 billion parameters, in contrast with LLMs, which can have hundreds of billions or even trillions of parameters.

Training and using LLMs requires enormous amounts of computational resources. In contrast, SLMs are significantly smaller. Therefore, they are less intensive in terms of data processing, hardware, and training time requirements. SLMs also consume less energy, making them more suitable for applications on smaller devices.

SLMs are more accessible to users who want to train and run these models on consumer hardware at the edge of a network, especially for single-purpose devices (e.g. sensors). In addition, SLMs are particularly useful for specific tasks rather than for use as general-purpose tools.

SIGNALS

On-device deployment

Gemini Nano on Android: Building with on-device gen AI (io.google)

Qualcomm also enables the running of models like Meta's Llama 2 on smartphones using optimised, quantised versions (qualcomm.com)

Specialised hardware

European tech ecosystems focus on developing edge AI chips designed to deliver server-grade AI power on compact hardware

- axelera.ai
- edge-ai-tech.eu

Industry integration

EU-funded research programs (like AI-PRISM) explore embedding AI directly into manufacturing and industrial sectors to facilitate real-time analytics (aiprism.eu)

- AI-Powered human-centred Robot Interactions for Smart Manufacturing (cordis.europa.eu)
- Social industrial collaborative environments integrating AI, Big Data and Robotics for smart manufacturing (cordis.europa.eu)

Call for more environmentally friendly alternatives (nos.nl)

SLMs are well recognised for their lower energy consumption, providing a low-emission option for institutions looking to minimise their carbon footprint (unesco.org)

Why do researchers care about small language models? (quantamagazine.org)

The transformative potential of AI depends on energy (iea.org)

Privacy-preserving applications

AIFI pilot started in five Dutch hospitals (radiobotics.com)

IMPACT

Education

- SLMs and edge AI can enhance personalised learning experiences directly on students' devices, ensuring privacy and accessibility. However, institutions must manage infrastructure upgrades and maintain equitable access to avoid technology gaps. New skills in model compression and hardware optimisation will be needed.
- The affordability of SLM devices and enabling technology may increase the digital divide.

Research

- Researchers can benefit from local, real-time analytics, without extensive computational resources. This facilitates studies in resource-constrained environments.
- Local devices acting as sensors will be able to process data on the fly, offering greater possibilities for location independent research.

Operations

- Institutions can deploy SLMs and edge AI to enhance operational efficiency, such as automating administrative tasks, while reducing dependency on external cloud services and potentially lowering costs. However, device-level infrastructure and skill development investment are necessary to avoid vendor lock-in and maintain long-term flexibility.
- Institutions should proactively plan for necessary infrastructure upgrades and training programs to effectively leverage the benefits of edge AI and SLMs.

Immersive Technologies

Authors
Mark Cole (SURF), **Rufus Baas** (Media College Amsterdam), **Funda Yildirim** (University of Twente), **Nick van Breda** (Avans Hogeschool), **Silvia Rossi** (CWI), **Hizirwan Salim** (SURF), **Paul Melis** (SURF)

1. AR and smart glasses become more prominent

2. Democratisation of XR content creation using generative AI

3. Increasing AI-enhanced user experience

4. Growing big tech competition for the XR stack

5. Public investments in XR continue to increase

Introduction

Immersive technologies create simulated experiences for users where the boundary between the virtual and physical worlds blurs. Examples of these technologies include virtual reality (VR), augmented reality (AR), and mixed reality (MR). It also encompasses concepts like 360-degree video, spatial audio, and interfaces that provide haptic (touch-based) feedback. Extended reality (XR) is mainly an umbrella term for VR, AR, and MR, and in this chapter, the term immersive technologies is used interchangeably.

Immersive technologies have progressed over the last decade due to advancements in computation and AI. This development has led to more mature functionalities from the user perspective (like better user-friendliness and higher levels of experience), and best practices have transitioned to real-world uses (see also SURF Tech Trends 2023 and XR trend update 2024). Organisations across societal domains and industries are recognising where immersive experiences (IX) can add value. Currently, the focus is on technologies tailored to address real-world practical challenges and training individuals for real-life scenarios.

The technological focus regarding the development of immersive technologies and their XR applications is shifting. Until recently, the focus was on hardware innovations that led to incremental gains in ergonomics, styling/elegance, miniaturisation, and display quality of VR/AR headsets and smart glasses. Gains in comfort and appearance have emerged as a decisive factor for users to (potentially) adopt these headsets and glasses, followed by affordability, functionality, and content.

Currently, the technological developments are moving to middleware infrastructures and platforms supporting the deployment of XR applications. These act as service layers for instructors and operational staff to create or adapt content without specialist support, and it could also include easy-to-use platforms ('low coding') to create immersive applications. It is expected that Generative AI (GenAI), virtual assistants, and other AI-based tools will further enhance the functionalities and content capabilities of immersive applications over the coming period.

The primary obstacle to general adoption of immersive technologies is not the technological capabilities of XR systems but rather change management within organisations: helping professionals like teachers, researchers, engineers, service technicians, police officers, or military personnel to embrace XR as an everyday tool rather than a lab curiosity or gaming device.

Contributors
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TREND #1

AR and smart glasses become more prominent

Public Values

Autonomy	Privacy
Justice	Inclusion | Equity | Transparency |
Humanity	Safety | Meaningful contact | Well-being

Maturity WATCH **PLAN** ACT

Drivers

Individualisation & empowerment; Automation & AI; Engineering advances & computation; Connectivity & interaction; Concentration of wealth & economic inequality

AR and smart glasses have faced adoption barriers in recent years due to bulky designs. Now, they are lighter, more comfortable, and resemble conventional eyewear. A broader range of products has targeted niche and general markets. Major companies like Apple, Meta, and Google are signalling imminent launches, thus indicating that smart glasses will become mainstream and more widely used. However, it is not expected that smart glasses will fully live up to their potential and become mainstream in the next 15 years. Till then, it is anticipated that AR and smart glasses will be developed mostly for specific use cases.

To date, several AR devices and smart glasses have been introduced into the market. While some glasses are still in the beta-testing phase, others are launched softly and in a controlled manner, for example on a country-by-country basis. However, key questions concerning functional added value, appearances, usability, and ethics will remain.

SIGNALS

Sales

Meta Ray-Ban glasses are selling well (2 million already, and production will vastly increase to 10 million per year) (uploadvr.com)

Promise by big tech companies

Google showing off their AR glasses at TED and call them "The next computer" (youtube.com)

Apple Working on smart glasses to beat Ray-Ban Meta, new report claims (forbes.com)

Acceptance perspectives

Perspectives on the acceptance and social implications of smart glasses (ris.utwente.nl)

New launches of products

HTC Vive Eagle (vive.com)

Meta's next-gen smart glass (hiverlab.com)

Product reviews & sneak peek demos (wired.com)

Amazon developing consumer AR glasses to rival Meta (reuters.com)

"AR glasses enable seamless assisted reality, allowing for researchers outside a lab to easily view and collaborate on physical lab tasks in real-time."

- **Remco de Jong**, CEO UnboundXR

IMPACT

Education

- Faster skills transfer is foreseeable in practical lab settings based on for example augmented instructions.
- Augmented reality functionality of glasses assists in an easier wayfinding and provision of student information through the campus.
- Easier live caption of education & training activities for students and teachers with impaired vision or language barriers.
- Attention to the use of AR glasses within the classrooms, exam settings and communal areas, including the processing of biometric data may need a policy review.

Research

- Devices support through augmented reality and forms of user interaction, enhanced remote collaboration with research peers, such as lab team members.
- Easier accessibility of captured (live) data through smart glasses.
- Interaction with research information and communication related to open science.

Operations

- Smart glasses in combination with augmented reality and digital overlays support equipment installation, operations, and maintenance.
- Augmented reality functionality of glasses assists in an easier wayfinding for visitors through the campus.

TREND #2

Democratisation of XR content creation using generative AI

Public Values

Autonomy	Independence | Freedom of choice
Justice	Inclusion | Transparency
Humanity	Personal development

Maturity WATCH PLAN ACT

Drivers

Individualisation & empowerment; Value of knowledge & skills; Automation & AI; Energy supply & demand

Recently, GenAI and other AI-based tools have emerged to support XR, mainly VR, content creation. This development reshapes and democratises content creation by lowering technical barriers and costs and enabling faster development and deployment.

The tools empower actors, such as independent creators, enterprises, educators, and researchers, to prototype ideas and produce 3D-constructed assets and virtual worlds faster, more efficiently, and at scale, without extensive technical skills.

In other words, AI is facilitating low-code to no-code XR creations for everyone in the community. The adoption is gradual and use-case dependent. Challenges emerge surrounding copyright, content ownership, skill development in creative design and content creation, and excessive energy consumption.

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Platform integration

Major XR platforms are embedding generative AI directly into their toolchains lowering entry barriers:

Adobe Project Scenic builds and manipulates full 3D scenes from simple prompts, integrating seamlessly into creative workflows (theverge.com)

Unity 6 includes Generative AI Features for smart NPCs, real-time speech synthesis, and asset generation (unity.com)

Meta Horizon Worlds allows now to generate entire VR environments via AI prompts, lowering the barrier for social XR world-building (developers.meta.com)

Faster 3D asset creation with AI

Generative AI tools are significantly reducing time and effort required for 3D asset creation:

AI modelling tools can reduce 3D asset creation time by up to 70% for complex scenes (alpha3d.io)

Meta 3D AssetGen generates high-quality meshes with realistic texture and materials in under 30 seconds (assetgen.github.io)

“In the past, users without technical skills weren’t able to do 3D creation on their own. Now, out of the blue, they have easy to use AI-based tools that help them do something without any 3D modelling experience.”

- **Keith Mellingen**, VRINN

IMPACT

Education

- The AI-XR convergence trend supports faster creation of bespoke XR learning environments once the visual fidelity performance is met by XR platforms and applications for education.
- Despite the low-code and no-code, teachers might still require assistance and support from experts and skilled professionals to guide students.

Research

The democratisation of AI-enabled XR content can support rapid prototyping of experimental XR-based setups and access to graphical and 3D-modelled assets for research.

Operations

- Lower production costs for simulations require high levels of functional validation (for example, safety-critical simulations).
- Facilitating platforms for creation and deployment of XR emerge.

TREND #3

Increasing AI-enhanced user experience

Public Values

Autonomy	Freedom of choice | Diversity
Justice	Inclusion
Humanity	Safety | Well-being | Personal development

Maturity WATCH **PLAN** ACT

Drivers

Individualisation & empowerment; Community dynamics & social cohesion; Automation & AI; Connectivity & interaction

AI is enhancing the user experience in real-time by augmenting realism, context-aware interactivity, and personalisation. Predictive models, sensory input (eye tracking, voice recognition), and continuous data analysis enable XR systems to interpret human gaze, gestures, emotions, and spatial mapping in real time. Simultaneously, this adapts the immersive experience to the user without prompting.

Virtual assistants enhance engagement, while other AI-based engines optimise graphics performance and provide dynamic content and visual fidelity. Emerging technologies like brain-computer interfaces (BCIs) and neurotechnology could minimise physical efforts when using XR. This AI/XR convergence will lead to AI-enhanced XR that anticipates user needs and behaviours.

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SIGNALS

Always-available, adaptive AI-agents

(Ai)Daptive XR platform empowers students and instructors to run fully immersive (qualcomm.com)

Digital identity convergence

Immersive Technology, blockchain and AI are converging (weforum.org)

AI as storyteller and choice architect

Enhancing User Experience in VR Environments through AI-Driven Adaptive UI Design (researchgate.net)

Seamless multimodal engagement

User Tracking and Haptic Feedback driving more realistic XR interaction (xrtoday.com)

Emerging brain–computer interfaces enable hands-free control by translating neural signals directly into commands (medium.com)

Meta-review on Brain-Computer Interface (BCI) in the metaverse (doi.org)

Even lower latency gameplay with frame warp (nvidia.com)

Meta Quest 4 and Quest 4S (androidcentral.com)

Genie 3: Creating dynamic worlds that you can navigate in real-time (youtube.com)

"Voice recognition, eye tracking – these are all about lowering interaction effort for enhanced user experiences. Eventually, with brain-computer interfaces, we could all become XR developers!"

- **Omar Niamut**, TNO

IMPACT

Education

- Conversational AI-based tutors could reduce instructor workload and reach larger student cohorts.
- AI-driven interactivity (including, for example, gamification) may enhance long-term student engagement, especially amongst younger learners.
- Conversational agents and personalised feedback systems support student study when human instructors are not available 24/7.

Research

- Context-aware virtual assistants accelerate scientific literature reviews and experiment configuration.
- Researchers can benefit from intelligent systems with AI-XR functionalities that adapt experimental pathways, offer real-time suggestions, and track engagement metrics for cognitive and emotional responses.

Operations

AI chatbots are already being used to answer routine queries from employees / professionals (for example IT or human resources queries), freeing staff time for more complex cases. This could evolve into 3D assistants in virtual or augmented workspaces.

TREND #4

Growing big tech competition for the XR stack

Public Values

Autonomy	Freedom of choice | Independence | Diversity
Justice	Equity | Inclusion
Humanity	Well Being | Social cohesion

Maturity WATCH **PLAN** ACT

Drivers

Globalisation; Concentration of wealth & economic inequality; Ideologic polarisation

The XR stack is the set of technologies, components, platforms, and applications that is needed to offer XR/immersive experiences. A key development is the competition between big tech companies (Apple, Meta, Microsoft, and Google) – which is a repeating pattern – to create complete and leading XR stacks with associated ecosystems.

Control over head-mounted display hardware, operating systems, (AI-based) XR engines, middleware, and the adoption of virtual assistants is central to gaining a competitive edge in the XR market.

Big tech companies are progressing substantially on their XR stack control as they look at their portfolios of technologies, products, services, and partnerships. On the contrary, these same big tech companies are also participating in standardisation bodies and open XR initiatives.

SURF

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Meta opening up their Horizon OS to other manufacturers together with partners, AndroidXR announced with major partners

Introducing our open mixed reality ecosystem (about.fb.com)

Learn more about Android XR (android.com)

Strategic acquisitions

First smartphones, now Google acquires another HTC Division and also obtains a non-exclusive license to use HTC's XR intellectual property (androidauthority.com)

Most manufacturers have announced to use Meta's or Google's OS and platform

AndroidXR- Samsung, Lynx, Qualcomm, Xreal, Sony: Android XR: A new platform built for headsets and glasses (blog.google)

Meta Horizon OS- Microsoft, Lenovo, Asus Android XR: A new platform built for headsets and glasses (blog.google)

Google demos Android XR glasses at Google I/O 2025 with Gemini integration (youtube.com)

"The most forward-thinking creators are adopting AI tools quickly. They're not afraid—they're using them to push the limits of what's possible in immersive creation."

- Julie Smithson, METAVRSE & XR Women

IMPACT

Education

XR stack competition will affect the degree of privacy and data control within XR platforms and applications for educational purposes. Platform lock-in dictates long-term portability and interoperability of (costly) content, and therefore, careful procurement is needed.

Research

Access to lower levels of software within XR-related platforms and applications for certain research activities will likely be restricted within closed stack systems. This is particularly relevant to consumer-grade price point products available in the market.

Operations

The strategic choice of an XR ecosystem will significantly influence vendor dependence in areas such as interoperability, privacy and control, and ongoing maintenance costs.

TREND #5

Public investments in XR continue to increase

Public Values

Autonomy	Freedom of choice | Diversity | Independence | Privacy
Justice	Inclusion | Transparency | Equity
Humanity	Safety | Well-being

Maturity WATCH PLAN ACT

Drivers

Value of knowledge & skills; Global trade & tariffs; Digital transformation; Geopolitics & (digital) sovereignty; Compliance & regulation; Critical infrastructure

Besides the large investments of big tech and other companies in (segments of) the XR stack also governments are starting to recognise XR's potential in innovation, productivity, and economic growth.

Therefore, in various domains and sectors, public investments in XR are growing both nationally and internationally, with a shift towards funding more practical applications and use cases. For example, in healthcare (surgical training and mental health therapy), in defence (combat training, drone management and operations), in urban planning, and in education programmes (simulator-trained professionals).

In the Netherlands, the establishment of large public-private research and innovation programs indicates substantial national public investment, alongside several Horizon Europe calls focusing on Virtual Worlds.

SIGNALS

Horizon Europe projects

XR Projects Financed under H2020 and Horizon Europe (ec.europa.eu)

Varjo suggests a shift to practical applications (varjo.com)

"Healthcare is a big area where investment is set to increase. There's a lot of funding going towards VR training and applications in the healthcare sector."

- Michael Barngrover, XR4Europe

National investments in education and training in Netherlands

- npuls.nl
- ciiic.nl
- dutch.technology
- rif-smart.nl
- oasis.nl

Defence

Five US navy warships get AR tech for remote-assisted repairs (thedefensepost.com)

European Defence Fund (eufundingoverview.be)

IMPACT

Education

Increasing public investments in XR accelerate adoption in education, leading to more institutions gaining access to high-fidelity virtual environments like simulators and training applications.

Research

XR focused public funding could shift priorities to applied studies validating measurable quality gains of the real-life usage of virtual environments for training and simulations (such as fewer accidents and higher pass rates).

Operations

Better-organised research and innovation consortia accessing specific public funding pipelines on XR enable faster adoption and shared usage of XR infrastructures.

Data Management

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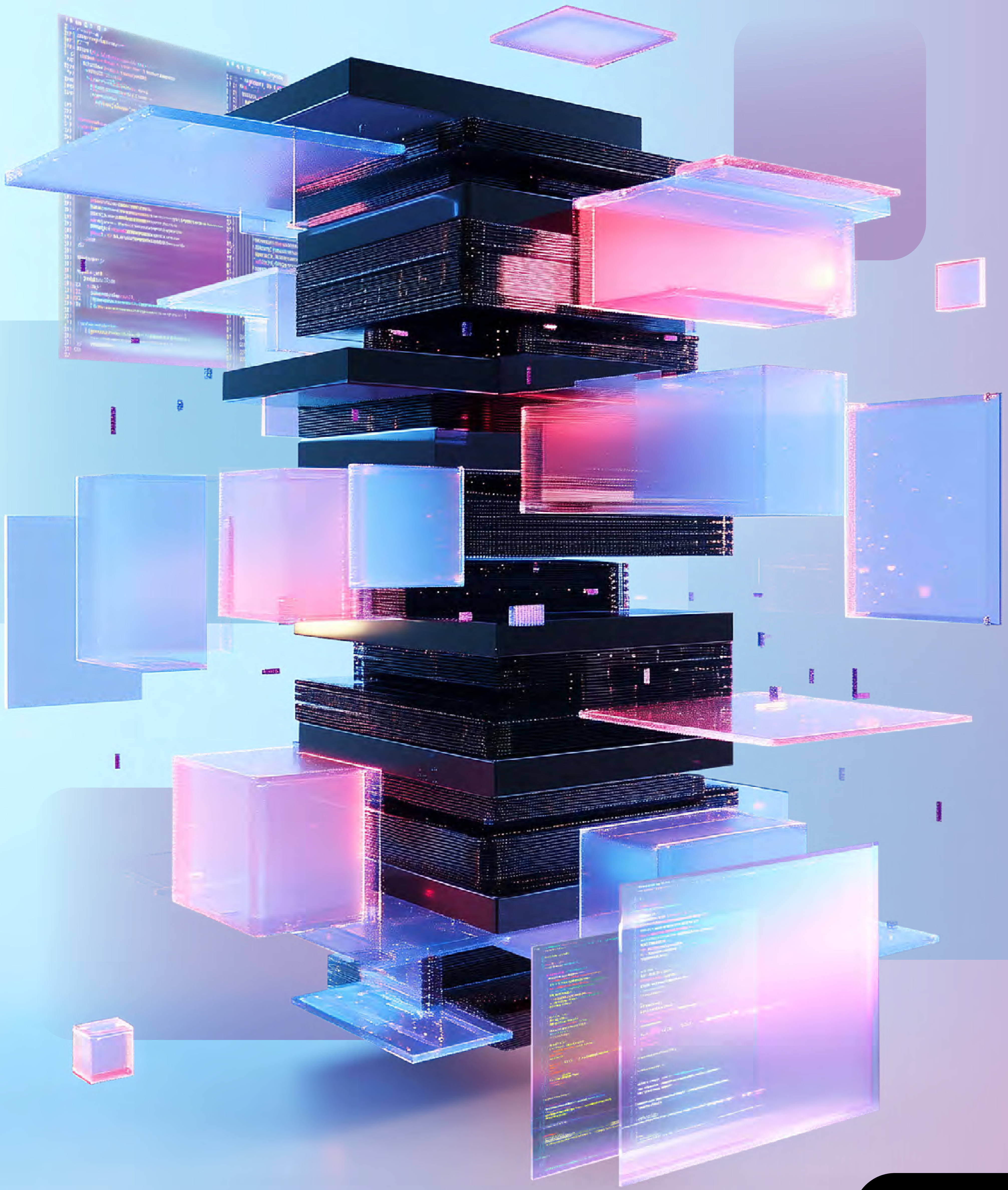


1. Increased application of FAIR principles to enable digital ecosystems in Europe
2. Standardisation of data space architectures for secure and trusted data sharing
3. Growing relevance of TRUST principles for data repositories to secure data
4. Growing significance of augmented data management
5. Emergence of DNA-based data storage to preserve data for a very long time

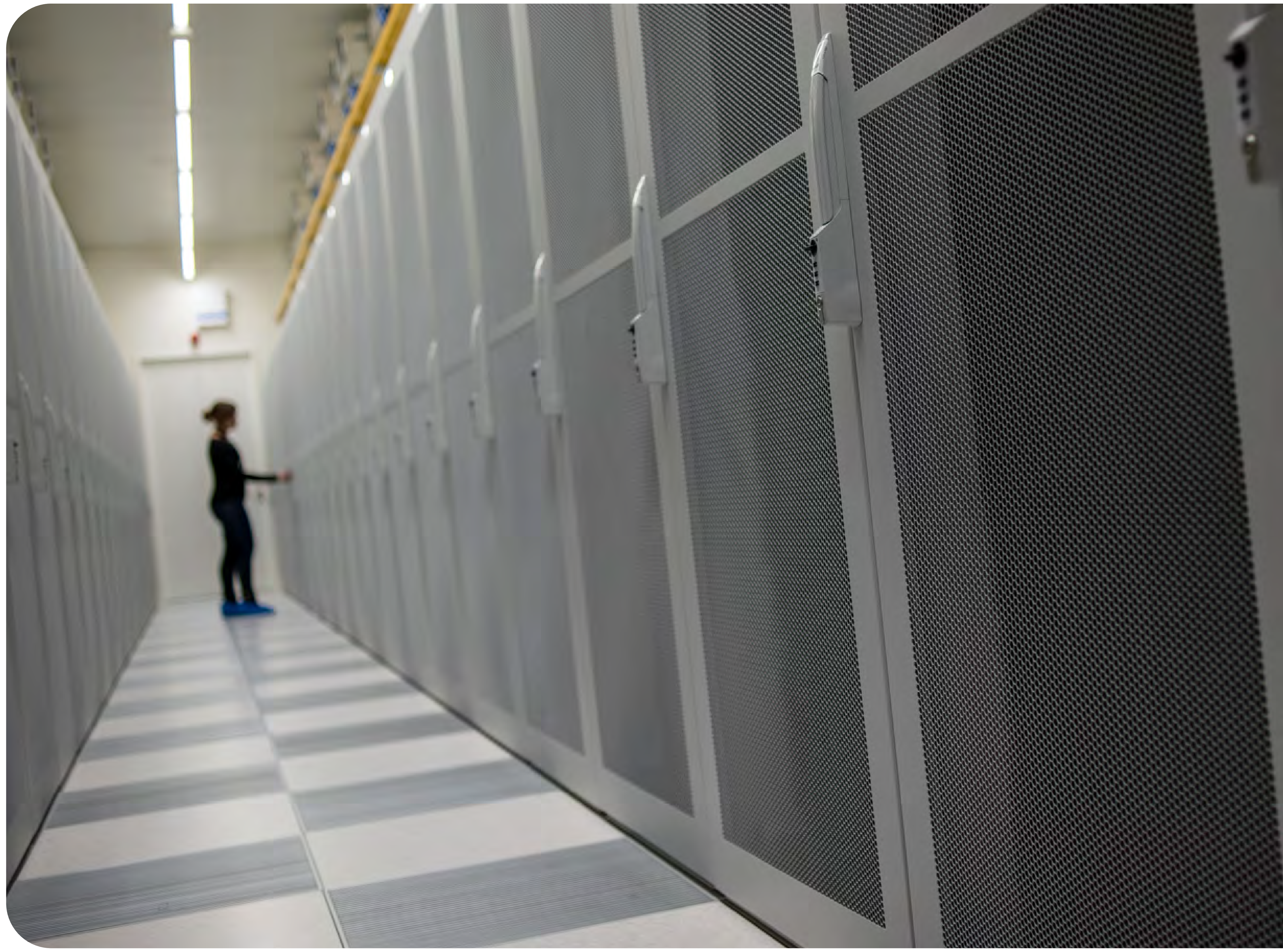
Introduction

Today's growth in data is enormous, and this growth is coming from a vast amount of sources such as industrial IoT devices (internet of things), medical imaging systems, synthetic data generators for AI model training, and big science instruments like CERN's Large Hadron Collider (particle physics) and the Vera C. Rubin Observatory (in astronomy). Current scientific experiments can already generate tens of terabytes of data on a daily basis, while future ones will push the scale to hundreds of terabytes per day.

While the current data explosion is nothing new, managing these increasing data volumes with current technologies poses challenges which require new approaches and technologies. As an example, storage media like tape and hard disk drives are reaching their physical limits regarding data densities.

Simultaneously, the variety of data sets is expanding due to various types of data. Innovative approaches and technologies are necessary, not only for the proper management of vast amounts of data, but also to combine data originating from different domains such as scientific disciplines, industries, and societal domains. This serves to enhance the capability for those managing data to uncover the key insights contained within data sets.

Next to the amount of data, the data complexity presents certain challenges. For example, on the multiple roles of organisations – like research organisations – regarding the processing of large data sets. Not only as a producer of data, not only as an user of data, but also as an actor that combines, enriches, co-creates, and aggregates large



data sets for and with a variety of other actors. Data management principles and tools help to unlock the value in data. Data management covers the systematic process of handling data throughout its lifecycle: collecting, organising, analysing, sharing, and preserving data while ensuring its integrity, accessibility, and security. AI has shown great promise already in this area, where AI-driven automation can minimise manual effort. Beyond current standard data storage solutions, there is a growing demand for data and content-aware solutions for data management as well as for offering new data insights.

Recently, it became clearer how important data management and data preservation are. Looking at developments on data sovereignty, data ownership and security, and open science. These developments are decisive for the way researchers and research organisations cooperate internationally. An example is the recent activity of the research community to preserve large climate data sets stored in the US by saving them on EU-based servers to keep the data freely available for the international climate research community. Besides this data repatriation in the scientific community, national governments and organisations in the EU are also aware of taking stronger measures to secure data ownership. For example, regarding the usage of cloud services by relocating data from the (big tech) servers in the US to servers in Europe.

New data management practices and technologies are very much on the horizon and are being formulated to tackle the current and future data challenges.

Contributors
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TREND #1

Increased application of FAIR principles to enable digital ecosystems in Europe

Public Values

Autonomy

Justice — Integrity I Transparency | Sustainability

Humanity

Maturity WATCH **PLAN** ACT

Drivers

Community dynamics & social cohesion; Globalisation; Digital transformation

The FAIR principles are guidelines on datasets being findable, accessible, interoperable, and reusable. Increased application of FAIR principles may lead to digital ecosystems, a web of FAIR data and services, where digital resources are not only shared but also semantically linked, automatically interpreted, and reliably reused across domains. Beyond data, a key evolution is the application of FAIR principles to all research outputs, including supporting frameworks such as software, computational workflows, and scientific models. This convergence is facilitated by FAIR Digital Objects (FDOs), which include persistent identifiers and rich metadata, alongside Knowledge Graphs that structure the semantic relationships between these FDOs. The shift to applying FAIR beyond just 'data only', to include digital research objects, enables automation, reproducibility, and information discovery, while also fostering cross-domain innovation on a larger scale.

SIGNALS

Initiatives & organisations

GO FAIR Initiative (go-fair.org)

EOSC (European Open Science Cloud) (eosc.eu)

FDO Forum (fairdo.org)

OpenAIRE (explore.openaire.eu)

"The web of FAIR data and services is a keystone vision for the future of digital ecosystems."

- **Paolo Manghi**, OpenAIRE, CTO

Implementations

Aridhia FAIR Data Services - provides researchers with tools for dataset discovery, classification, and metadata browsing (aridhia.com)

Fairdata.fi - provides data storage and discovery services to support FAIR principles and ensure long-term preservation (fairdata.fi)

FAIRsharing.org - provides for a curated, informative resource on data and metadata standards, inter-related to databases and data policies (fairsharing.org)

Open Research Knowledge Graph (ORKG) - scholarly communication exploiting the possibilities of digitisation (orkg.org)

Zenodo (zenodo.org)

FAIRimpact project (fair-impact.eu)

Supporting literature

Toward the Open Science model: publish your raw diffraction data (pubs.aip.org)

Analysis on open data as a foundation for data-driven research (link.springer.com)

Leiden Declaration on FAIR Digital Objects (fdo2022.org)

IMPACT

Education

- Knowledge Graphs (KGs) are being integrated into Learning Management Systems (LMSs) such as Brightspace and Canvas to model relationships between learning objectives, content, and competencies.
- Fostering links between learner profiles, learning progress, and course requirements, KGs enable personalised learning through adaptive learning paths.

Research

- The web of FAIR data and services significantly impacts research by accelerating scientific discovery and promoting reusability.
- FAIR Digital Objects (FDOs), enriched with fine-grained metadata and versioning, enhance the reproducibility, traceability, and reuse of research data, software, and workflows.

Operations

- Knowledge Graphs (KGs) can enhance operational systems by linking data from Learning Management Systems (LMSs) and Student Information Systems (SIS).
- The integration of KGs enables institutions to map the student journey from pre-admission to graduation and subsequent alumni engagement.

TREND #2

Standardisation of data space architectures for secure and trusted data sharing

Public Values

Autonomy	Privacy | Independence
Justice	Transparency | Integrity | Accountability | Equity
Humanity	Safety

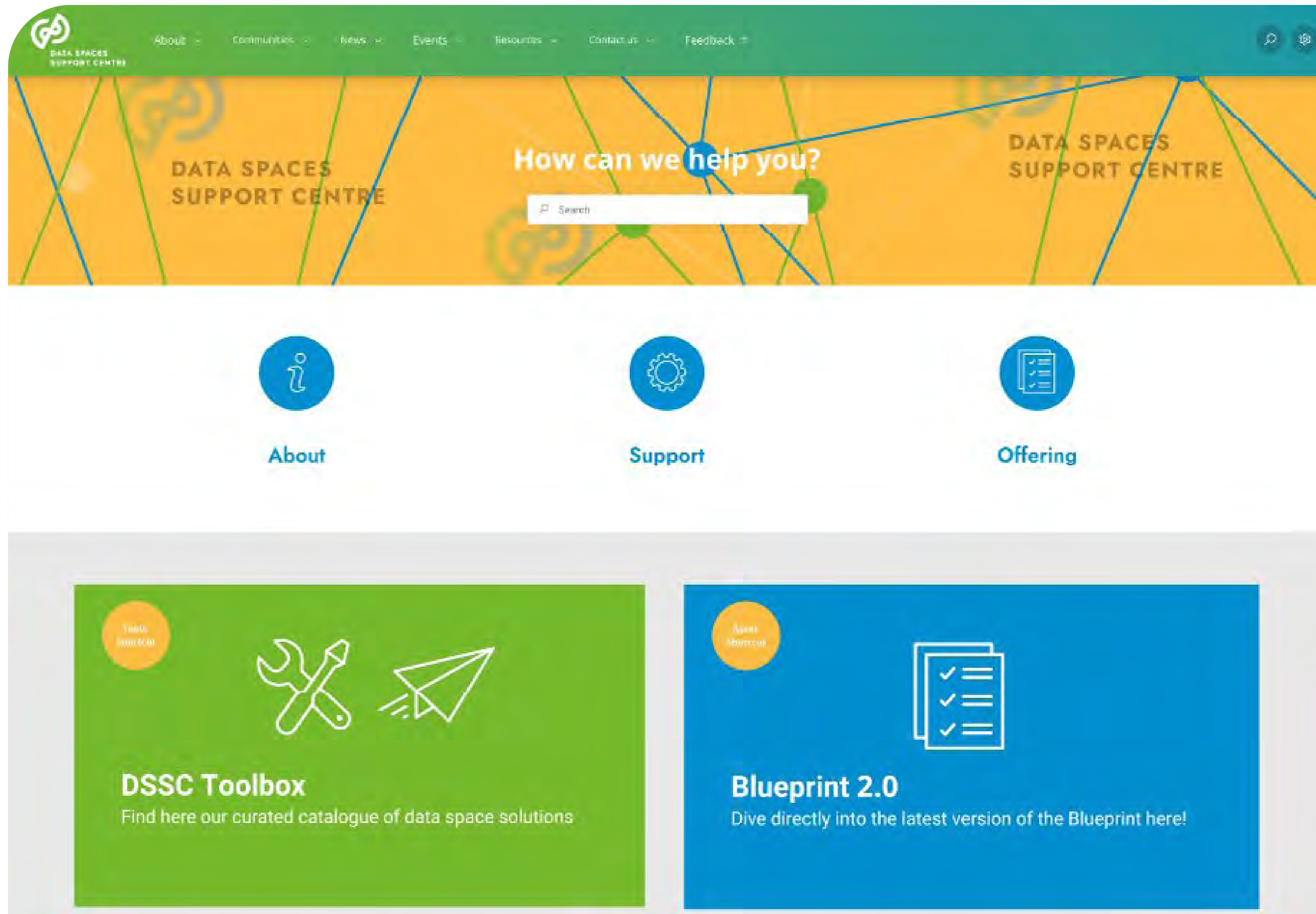
Maturity WATCH PLAN **ACT**

Drivers

Compliance & regulation; Cybersecurity & trust; Value of knowledge & skills

Data spaces allow participants to share, trade, and collaborate on data assets in a manner that is compliant with the participants' needs and regulations. These spaces could unleash the enormous potential of data-driven innovation. However, large-scale data sharing is hampered by concerns about trust and the lack of control mechanisms for sharing secure and trusted data. Therefore, standardisation of data space architectures that better support secure and trusted exchanges has received notable attention. The need for structured data spaces has grown, and considering the geopolitical situation, there are significant efforts by the European Commission to stimulate the development of common European Data Spaces.

In addition, the maturity heavily varies per domain. The maturity of a metadata standard within the domain enhances the data space's maturity. Also, the legal basis used within the domain can be very different from domain to domain.



dssc.eu

SIGNALS

European and national level Data Spaces being established

European Commission strongly supports the development of the common European Data Spaces (digital-strategy.ec.europa.eu)

Future Mobility (marketplace.future-mobility-alliance.org)

European Health Data Space (EHDS) common framework for the use and exchange of electronic health data across the EU (european-health-data-space.com)

“In the early days of electricity everything was invented. You didn’t come to determine what you could do with it. Now it is standardised, and you can look at where a plug can be connected. This now applies to the standardization of Data Spaces.”

- **Matthijs Punter**, TNO, Data Spaces Support Centre

Reports

European Commission update on the status of the common European Data Spaces (digital-strategy.ec.europa.eu)

Critical success factors for Data Space deployment (tno.nl)

Challenges of the clean energy transition and meeting the ambitious targets of the European Green Deal (energy.ec.europa.eu)

Reference architectures being developed to support Data Spaces

Data Space Support Centre publishes version 2 of the Data Spaces Blueprint (dssc.eu)

Draft functional and technical specifications Simpl architecture published (simpl-programme.ec.europa.eu)

Npuls uses the HOSA domain architecture for education and flexibility as a cornerstone (surf.nl)

tehdas.eu

IMPACT

Education

Data spaces based on advanced blueprints enable secure, EU-compliant data sharing among educational institutions. They support AI-driven learning, ensure data sovereignty, and reduce dependence on non-European platforms.

Research

Data spaces organised by the latest blueprints in research enable secure, faster data access and facilitate cross-border sharing. They enhance scientific collaboration, accelerate research reproducibility, and drive innovation while ensuring ethical and legal data use.

Operations

By enabling secure data exchange amongst members of a data space, operations can be streamlined. The standardised architectures enhance agility, transparency, and alignment with national and European regulations and digital transformation goals.

TREND #3

Growing relevance of TRUST principles for data repositories to secure data

Public Values

Autonomy	Privacy
Justice	Transparency | Sustainability | Accountability | Integrity
Humanity	Safety

Maturity WATCH **PLAN** ACT

Drivers

Value of knowlegde & skills; Community dynamics & social cohesion; Cybersecurity & trust; Service-oriented & value-based economies; Compliance & regulation

Data repositories are integral in digital ecosystems, facilitating long-term access to data. Therefore, TRUST principles (Transparency, Responsibility, User focus, Sustainability and Technology) are gaining more relevance recently. These principles ensure repositories are transparent in their operations, handle data responsibly and reliably, use user-focused approaches, use resources sustainably, and deploy technology to secure data management.

The TRUST principles complement the FAIR principles and enhance them by making the data infrastructure more reliable and long-term sustainable. In essence, FAIR is about the data, while TRUST is about the repository that manages and preserves the data. So this combination ensures that research data remains a reliable, accessible, and valuable resource for science and society, both now and in the future.

SIGNALS

Transparency

Open source infrastructure and open governance models

Open Science NL drives the transition to open science in the Netherlands, focusing on research data management (nwo.nl)

Open science is central to European research policy, emphasising immediate, unrestricted access to research outputs in shared repositories (research-and-innovation.ec.europa.eu)

Responsibility

Accountability compliance checks

Compliance assessment of the TRUST principles is developed by initiatives related to EOSC (faircore4eosc.eu)

Robust digital preservation strategies and a network of trustworthy repositories ensure data authenticity, integrity, and reliability (EDEN and FIDELIS projects) (eden-fidelis.eu)

Sustainability

Managing human and natural resources responsibly, e.g. by reducing energy consumption (using "green" data centres)

The "Green IT maturity model" helps organisations assess their responsibility for the environmental impact of IT and convert intentions into actionable practices (surf.nl)

Digital technology accounts for 5-9% of global electricity use, making energy efficiency vital. The EU's green cloud initiative aims to promote energy-efficient cloud computing (digital-strategy.ec.europa.eu)

User Focus

Fine-grained data control and consent management (as this is increasingly asked for by the user-community)

ODISSEI is a secure environment in the Dutch social science research infrastructure that facilitates easy access, sharing, and processing of sensitive data (odissei-data.nl)

The SIESTA project develops EU-level tools and methodologies for sharing sensitive data, aiming to provide researchers access to confidential information while ensuring privacy and usability (eosc.eu)

Technology

Semantic web standards and APIs enhance interoperability by providing a common language and framework for data exchange, enabling systems to understand and interact with each other more effectively.

Researchers, publications, data, funders, etc. are connected by semantic web technologies to form a "Global Open Science Graph" (graph.openaire.eu)

IMPACT

Education

The TRUST principles enable data repositories to better facilitate the education sector with the management of data in a more effective manner. They foster collaboration and shared learning through better data sharing and reuse.

Research

Researchers can (re)use and share research data more effectively when data repositories are based on the TRUST framework.

Operations

The TRUST principles can form the basis of the operational activities of next-level data repositories that consider data management dimensions like ethics, user needs, and sustainability. Such an approach will serve to enhance institutional reputation with robust and inclusive data management.

TREND #4

Growing significance of augmented data management

Public Values

Autonomy	Privacy
Justice	Transparency | Equity | Accountability | Integrity
Humanity	

Maturity WATCH PLAN **ACT**

Drivers

Automation & AI; Connectivity & interaction; Digital transformation

Data volumes are growing rapidly, increasingly generated through automated means, and AI is now accelerating this ongoing trend. Additionally, data sources such as scientific instruments, large sensor networks, and the IoT (Internet of Things) devices in general are becoming more prevalent. Managing these data volumes, extracting information, generating insights, and preserving data value is a challenging task.

Augmented data management, a form of AI-based automation, is evolving and radically reducing the manual tasks of data management teams, such as building data orchestration pipelines, assessing data quality, and running repetitive data integration workflows.

To properly harness the growing use of AI for data management, data quality is essential. Therefore, AI is recognised as an important pillar for more content-aware and data quality-aware data management solutions.

SURF

SIGNALS

Augmented data management initially recognised as trend by Gartner and Deloitte 5 years ago

Top 10 Trends in Data and Analytics for 2020 (gartner.com)

Tech Trend 2021: Machine data revolution - feeding the machine (deloitte.com)

IBM launches new content-aware storage solutions (ibm.com)

Data Direct Networks introduces the Data Intelligence Platform (ddn.com)

Augmented data management becomes mature

Development of a maturity model for AI – augmented data management (essay.utwente.nl)

Trusted European media data space (TEMS) (beeldengeluid.nl)

AI is transforming research and education

Contributing to the web of FAIR data and the uptake of AI (eosc.eu)

How AI is revolutionizing education (weforum.org)

Npuls: Ethical and effective use of AI and data (npuls.nl)

IMPACT

Education

AI-enabled data management can bring huge advantages to education, developing more personalised learning content, supporting teachers in the assessment process and supporting education by automating administrative tasks.

Research

Next to how AI is transforming how research is being done, augmented data management can automate many repetitive data management tasks in enriching metadata, quality checking, and developing and enabling more content-aware data management solutions for researchers while preserving the value of the data.

Operations

Augmented data management only works effectively on quality data. To prevent augmented data management systems from being trained with low-quality data, data managers need to be semantically skilled (on metadata, semantic vocabularies, and semantic thesauri) to ensure that high-quality data is used.

TREND #5

Emergence of DNA-based data storage to preserve data for a very long time

Public Values

	Autonomy	Privacy
	Justice	Sustainability | Integrity | Accountability
	Humanity	

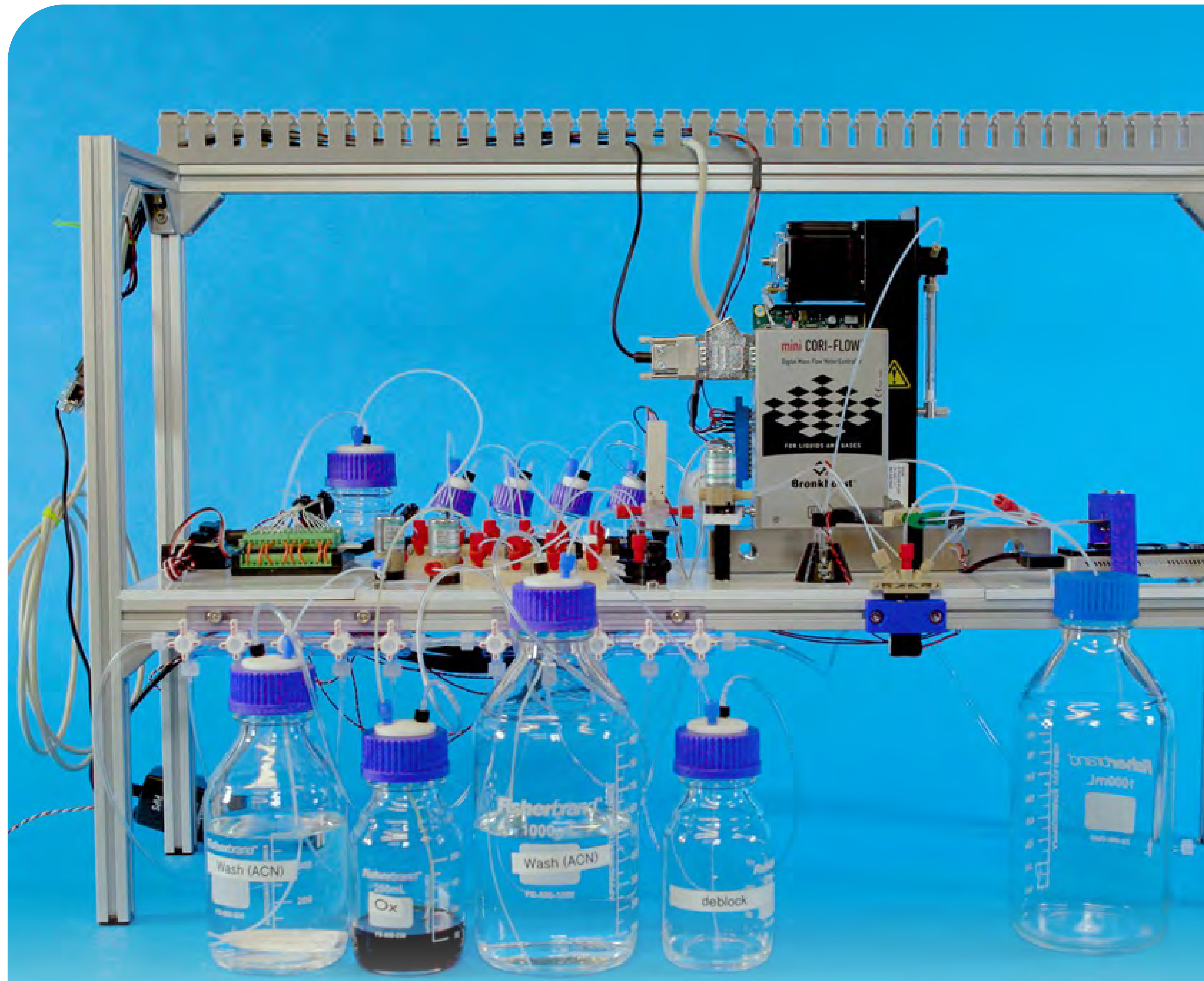
Maturity WATCH PLAN ACT

Drivers

Biotechnology; Automation & AI; Climate change & global warming; Energy supply & demand; Clean water demand; Biodiversity; Raw material scarcity

Today's storage solutions (like hard disk drives and tapes) have scaled extensively over the years; however, these types of storage media are reaching the physical limits of data storage densities. A new and promising alternative is using DNA for storing binary data in synthesised strands of DNA.

This storage solution – which will take years of R&D to be operational - could have a transformational impact on data storage infrastructures, offering potential advantages in data density, encrypted data storage, data durability, long-term data retention, and sustainability. In the meantime, R&D is focused on e.g. workable access speeds the industry needs to develop suitable standards for DNA data storage to facilitate its future deployment.



Microsoft and University of Washington demonstrate first fully automated DNA data storage. Image Microsoft (news.microsoft.com)

SIGNALS

Data synthesis companies enter the market

Twist Bioscience is a public biotechnology company established in 2013 based that manufactures synthetic DNA and DNA products for customers (twistbioscience.com)

CATALOG has created the world's first commercially viable device for DNA storage and computation (catalogdna.com)

First specifications released

The DNA Data Storage Alliance released the first two specifications: Sector Zero and Sector One (dnastoragealliance.org)

"Data storage capacity of DNA per gram is around 200 million gigabytes, which is millions of times higher than magnetic tape storage densities."

- **Tom de Greef**, TU/e

Research and industry leaders are organising themselves

The DNA Data Storage Alliance established in October 2020 (dnastoragealliance.org)

The DNA Data Storage Alliance joined the Storage Networking Industry Association (SNIA) as a Technology Affiliate in 2022 (snia.org)

Institutes are experimenting with DNA Data Storage

Researchers from the University of Washington and Microsoft have demonstrated the first fully automated system to store and retrieve data in manufactured DNA (washington.edu)

Beeld en Geluid stores iconic fragments of EK'88 in DNA (nieuws.beeldengeluid.nl)

Sound & Vision (Beeld & geluid) stores iconic fragment of European Championship '88 in DNA (nieuws.beeldengeluid.nl)

IMPACT

Education

Although DNA-based data storage has no direct impact on education yet, it could become a new educational topic, or a new way for students to experiment with data storage.

Research

In research fields where data needs to be preserved for extended periods, or potentially forever due to data importance (for example, National Archive data or endangered languages), future DNA data storage solutions seem to offer long-term possibilities for preservation.

Operations

- DNA data storage could introduce an infrastructural change in how organisations will store, manage, and preserve data in the long term. This would require new skills and industry standards.
- New companies could emerge specialised in data-oriented DNA synthesis and sequencing.

Digital Trust

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Introduction

Trust is the foundation of all digital interactions. It is the confidence that people, systems, and technologies will act reliably, securely, and with integrity. In the digital world, trust means believing that personal data will be protected, systems will work as designed, and technologies will uphold ethical and secure practices. As digital ecosystems become more complex, maintaining and earning that trust becomes not just a technical challenge, but a strategic priority.

A shift is taking place in the way that digital identities and the verifiable credentials of individuals, organisations, and objects (physical and digital) are handled. The European Union (EU) is leading this transformation with the Digital Europe Program (DIGITAL). At the heart of this transformation is the European Union Digital Identity (EUDI) Wallet initiative, which seeks to give citizens enhanced and secure control over their digital identities. In an age where misinformation, disinformation, and identity abuse are widespread, storing digital identities and credentials in digital wallets can help improve accountability, safeguard ownership, and reduce the misuse of personal data. By 2027, every EU citizen will have access to an initial version of a digital wallet. This wallet can be used to store and share personal details. This information will relate to both online and offline public and private services across the EU.

The EUDI Wallet will be applicable in many aspects of modern life, and it will have implications for how people use and access key identification information. For instance, it will be possible to store a digital version of an individual's driving licence, thus eliminating the need for someone to always have a physical copy on their person. Besides identification information, the EUDI Wallet will provide a seamless recognition of qualifications and provide authorisation across the EU, simplifying education admissions, credentials management, student transfers, job applications, and talent mobility. At the same time, fraud will be reduced, while secure and cryptographically protected identities and credentials will be facilitated. This will help to reduce forgery and increase trust in qualifications.

The future of digital trust will give people more control over their own data, by embracing conceptual models such as Self-Sovereign Identity (SSI), along with the use of digital wallets to share their identities and credentials. The success of these initiatives will have a significant impact on citizens as well as public and private organisations. Digital trust assures that the identities and data of people and organisations are handled securely, that digital interactions are reliable, and that their privacy, in terms of their identity and data, is protected. New types of trust networks will create a digital world that is more secure, fair, and trustworthy for everyone.

Contributors
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TREND #1

Trusted digital recognitions are emerging

Public Values

Autonomy	Personal empowerment
Justice	Transparencey | Equity | Inclusion | Integrity
Humanity	

Maturity WATCH PLAN **ACT**

Drivers
Individualisation & Empowerment; Cybersecurity & Trust; Digital Transformation

European frameworks (eIDAS 2.0 and MiCA Regulation) are reshaping the digital landscape with two new concepts: Verifiable Credentials (VCs) and digital assets. Both will enable a shift towards trusted digital recognition of physical and digital objects by 2030.

VCs are tamper-proof digital attestations (diplomas or qualifications) issued by trusted institutions or organisations for individuals to store in their digital wallets.

Digital assets as tokens, including non-fungible tokens (NFTs), represent digital value, access, or ownership. As it is designed to be transferable: once a token leaves your wallet, its associated rights move too, making them suitable for (value) exchange, single-use recognition, or participation in initiatives.

Aspect	Verifiable Credential	Token/Digital Asset
Function	Reusable proof of achievement or skills, identity, or status	Transferable value, access, or participation
Reusability	Yes, holder can present it multiple times	No, it moves with ownership
Privacy	User-controlled, selective disclosure	Often public, depends on token design
Verification	Via digital signature and open standards (e.g. W3C, OpenID4VC)	Via blockchain consensus and smart contracts

SURF

SIGNALS

European regulation

eIDAS 2.0 Regulation (eur-lex.europa.eu)

Markets in Crypto-Assets (MiCA) Regulation (eur-lex.europa.eu)

Nederlandse overheid - Toekomstverkenning Digitalisering 2030 (rijksoverheid.nl)

Education, skills & lifelong learning

SELFIE for work-based learning (education.ec.europa.eu)

Digital credentials & lifelong learning (unesdoc.unesco.org)

Union of Skills (2024) (commission.europa.eu)

Frameworks

Verifiable Credentials & Digital Identity (2024) - Verifiable Credentials Data Model 2.0 (w3.org)

OpenID for Verifiable Presentations and Credentials (OpenID4VC) (2024) (openid.net)

European Digital Identity Wallet – Architecture and Reference Framework (2024) (eu-digital-identity-wallet.github.io)

Digital assets and tokens

Asset tokenization in financial markets: the next generation of value exchange (2025) (reports.weforum.org)

“Trust technologies like verifiable credentials are the new invisible handshake of the digital age—empowering people and organisations to prove who they are and what they know, instantly and securely, at every interaction.”

- **Adam Eunson**, COO, AuvoDigital

IMPACT

Education

- Learners gain greater control over their learning and career journeys with digital wallets, allowing them to manage and share trusted, verifiable achievements across contexts and borders. This shift enhances mobility, autonomy, and visibility.
- Educational institutions adopt new roles as issuers and validators within decentralised recognition networks, where formal credentials and purpose-driven tokens co-exist. This transformation supports modular learning pathways, personalised recognition, and broader stakeholder engagement, from employers to societal partners.

Research

- Decentralised reputation models and token-based systems enable more transparent, collaborative ecosystems and new ways of crediting contributions. At a systemic level, eIDAS 2.0 and MiCA provide the legal foundation that enables interoperable, learner-centred ecosystems to emerge and scale.
- A future-ready education and research landscape, where trust, flexibility, and recognition are embedded, positioning individuals and institutions to thrive in a digitally connected world.

Operations

Streamlined processes, reduced administrative tasks, and automated processing of credentials will be realised thanks to interoperable and trustworthy data exchange.

TREND #2

More decentralisation of data ownership enabled by SSI solutions

Public Values

Autonomy	Freedom of choice | Independence | Privacy
Justice	Inclusion | Equity | Integrity
Humanity	Social cohesion | Meaningful contact | Well-being | Safety | Personal development | Respect

Maturity WATCH **PLAN** ACT

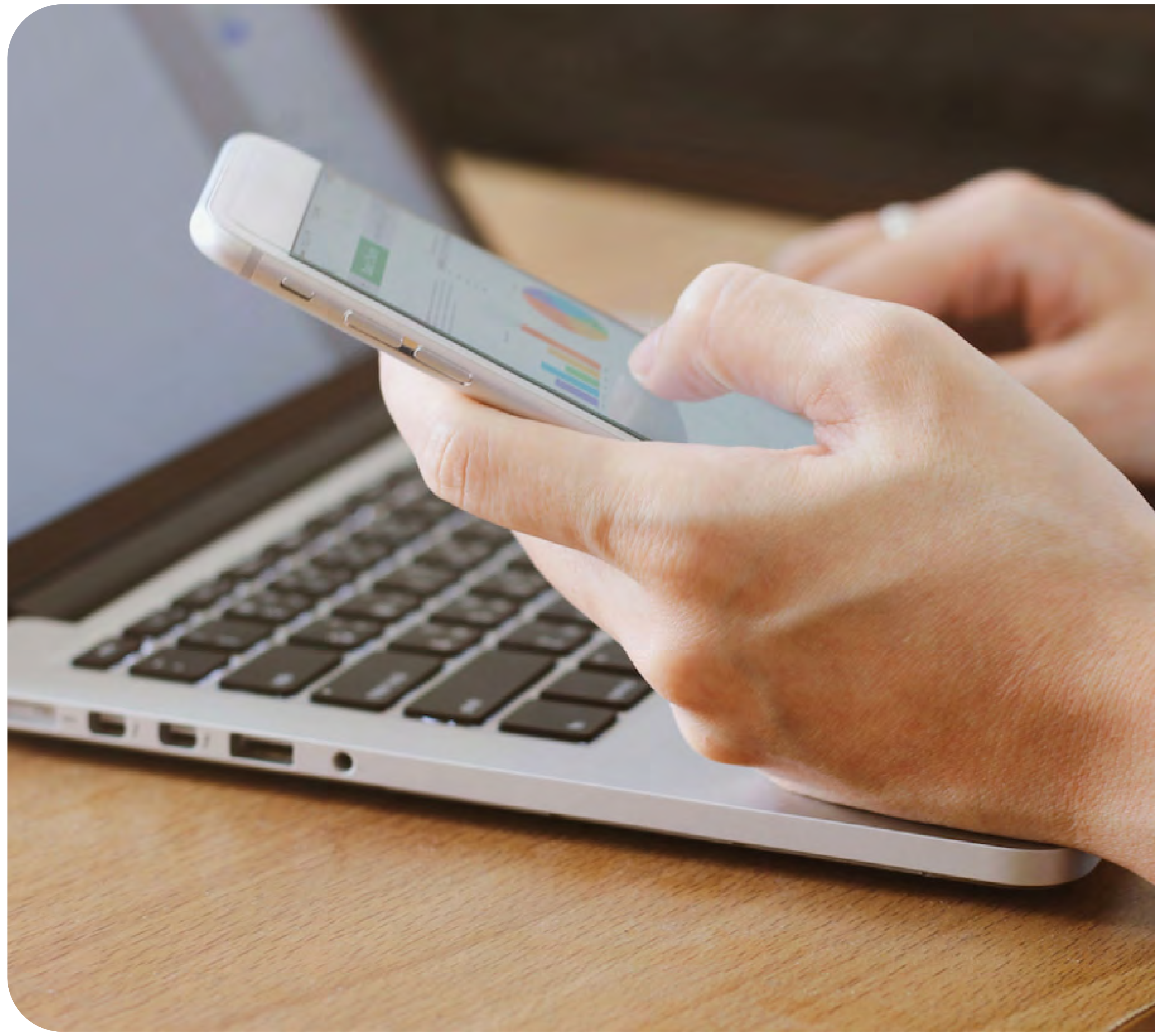
Drivers

Individualisation & Empowerment; Cybersecurity & Trust; Digital Transformation; Community Dynamics and Social Cohesion

The increasing value of personal data has led to misuse by many actors in society, ranging from big tech to data brokers and even governments.

This has prompted a counter movement focused on user empowerment and data rights protection. In the digital trust and identity domain, this movement toward data decentralisation and related individual control is commonly referred to as Self-Sovereign Identity (SSI).

The core principles of SSI include data portability, data minimisation, and access to personal data. Fundamentally, SSI seeks to empower individuals and protect data rights, with the forthcoming EUDI Wallet being a typical SSI solution.



SIGNALS

The path to Self-Sovereign Identity (lifewithalacrity.com)

Higher Education and Scientific Research Act (NL) (wetten.overheid.nl)

Data by the Source (digitaleoverheid.nl)

eIDAS 2.0 Regulation - framework for digital identity and authentication (digital-strategy.ec.europa.eu)

A digital ID and personal digital wallet for EU citizens, residents and businesses (ec.europa.eu)

IMPACT

Education

Educational institutions issue credentials that require data storage for validation. Linking these credentials to individuals necessitates personal information, creating a challenge in designing processes that balance privacy and usability while promoting autonomous decision-making.

Research

The shift towards Self-Sovereign Identity (SSI) is transforming personal data management. It challenges researchers to adopt good practice and regulate systems that adhere to human rights and legal standards, are technically feasible and promote interdisciplinary research with significant social and policy impact.

Operations

- Overly simple user flows can lead to unconscious decisions and unintended data sharing, while excessive complexity can hinder usability. A balanced approach is essential. Tools based on Self-Sovereign Identity (SSI) principles can empower users to exercise their rights while meeting GDPR requirements.
- Empowering users reduces institutional control over issued credentials. Institutions must verify identities or wallets before issuing credentials, enabling users to share them across various sectors.

TREND #3

Emergence of organisational wallets

Public Values

Autonomy	Privacy
Justice	Integrity
Humanity	Safety

Maturity WATCH **PLAN** ACT

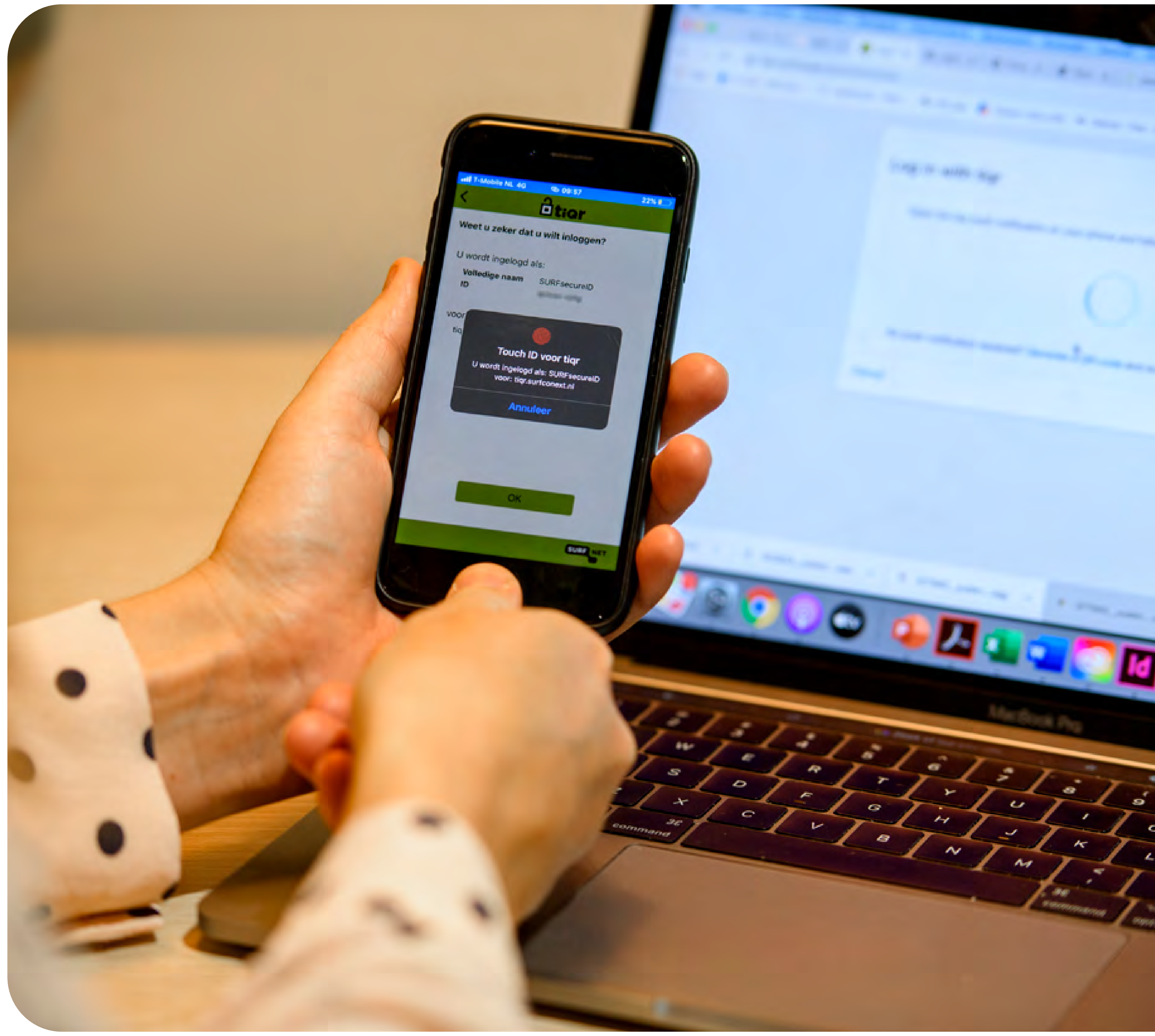
Drivers

Individualisation & Empowerment; Cybersecurity & Trust; Digital Transformation

Trust and interoperability issues have hampered business interactions across Europe. Announced in 2025, the European Business Wallet (EBW) initiative targets these inefficiencies with a unified, cross-border digital identity solution for organisations.

Organisational wallets are digital web-based wallets that provide secure digital identification, streamline data sharing, and facilitate legally valid notifications for companies and other legal entities. Unlike personal wallets, organisational wallets support multi-user access and role-based permissions (such as power of attorney).

One-click recognition of organisational identity, status, and attributes can prevent fraud (like fake websites or phishing) and compliance costs, as well as accelerate cross-border collaboration. Organisational wallets must address the complexities of legal entity identity, such as credential lifecycle management, international standards, and integration with business registers.



SIGNALS

Policy

EU Architecture and Reference Framework (ARF) (github.com)

European Business Wallet: digital identity, secure data exchange and legal notifications for simple, digital business (ec.europa.eu)

Use cases and experiments

Exploration of EU Digital Identity Wallets for legal entities with Company Passport and iSHARE (coe-dsc.nl)

EU large scale pilots with wallets for businesses (digital-strategy.ec.europa.eu)

"As the European Union moves toward full implementation of the EU Digital Identity Wallet (EUDI), businesses must prepare for a digital transformation in how identities are verified, customers are onboarded, and e-signatures are done."

- **Signicat** (signicat.com)

IMPACT

Education

- Educators and students should benefit from a significant reduction in administrative delays with international exchanges/mobility programs such as Erasmus+, and cross-border teaching or study opportunities.
- Secure, verified institutional credentials enable quick and trusted confirmation of enrolment, qualifications, and affiliations for internships, further studies, or collaborations.
- Reduced exposure to phishing and fraudulent communications enhances trust and digital safety in academic correspondence and protects personal and institutional information.

Research

- Reduced risk of impersonation or fraudulent collaboration requests safeguards intellectual property and project research credibility.
- Verified institutional identities should accelerate the establishment of cross-border collaborations, joint funding applications, and consortium agreements.

Operations

- Instant verification of institutional identity will enable faster execution of information exchange in European public-private partnerships and research collaborations, reducing administrative workload.
- Role-based digital access and trusted official communications strengthen security by reducing phishing risks, ensuring legal validity, and it also lowers compliance costs through secure, verified information exchange.
- Integration with internal systems streamlines credential checks and approvals, improving efficiency and optimising processes, although initial investment in staff training and technological infrastructure will be required.

TREND #4

Push for transparent supply chains with digital product passports

Public Values

Autonomy	Freedom of choice | Independence | Privacy
Justice	Inclusion | Equity
Humanity	Social cohesion | Meaningful contact | Well-being | Safety | Personal development | Respect

Maturity WATCH **PLAN** ACT

Drivers

Compliance and Regulation; Cybersecurity & Trust; Digital Transformation

The EU Ecodesign for Sustainable Products Regulation (ESPR) came into effect in mid-2024. This regulation mandates companies to disclose information regarding the origin of their products and their environmental impact. This mandatory implementation of digital product passports (DPPs) ensures that product data is authentic, reliable, and compliant.

Implementing DPPs will be challenging, and production and product data must be verified and accessible via a data carrier. Legislative developments will impact standardisation and DPP service providers.

While acts are being finalised, European standardisation bodies are developing the standards for DPPs for adoption by the beginning of 2026.

SIGNALS

Ecodesign for Sustainable Products Regulation (commission.europa.eu)

Centre of Excellence for Digital Product Passports (coe-dpp.nl)

Data Sharing – Digital Product Passport (tno.nl)

Position paper of Fides (formerly Dutch Blockchain Coalition) about trusted DPPs (fides.community)

"Digital Product Passports will become the main reporting vehicle for all product related compliance information in the European Union. Companies that go beyond compliance and adopt the DPP at the center of their supply chain information ecosystems will see significant additional benefits."

- **Yvo Hunink**, Founder of Regen Studio and co-writer of the position paper on trusted Digital Product Passports

Use cases & pilots

Demonstration of functioning DPPs in different sectors (cirpass2.eu)

Digital product passports: Lessons from an early adopter (British womenswear brand Nobody's Child) (voguebusiness.com)

IMPACT

Education

- Different schools and universities are already discussing the possibilities of using DPPs, the associated challenges with using DPPs, and are working on prototypes.
- Students are and can research sustainability effects, suitable business models, and the technical (in)capabilities involved with the deployment of DPPs.

Research

DPPs can also be relevant for research and datasets, especially in areas related to sustainability, IT, product lifecycle analysis, and supply chain transparency.

Operations

- Educational institutions can minimise their environmental impact and enhance procurement and campus management.
- Although not required to comply with the Corporate Sustainability Reporting Directive (CSRD), many institutions are proactively selecting sustainable products and partners.
- The DPP will improve procurement, increase transparency, and enhance real estate management, enabling campuses to make informed, sustainable choices.

TREND #5

Digital Trust Frameworks: from hierarchical to distributed trust

Public Values

Autonomy	Freedom of choice | Personal empowerment | Independence | Privacy
Justice	Inclusion | Equity | Integrity
Humanity	Social cohesion | Meaningful contact | Well-being | Safety

Maturity WATCH PLAN ACT

Drivers
Individualisation & Empowerment; Cybersecurity & Trust; Digital Transformation

Much of the trust we place in credentials comes from verification by authoritative sources; we cannot rely solely on a person's own claim. This is why educational institutions are considered authoritative when issuing diplomas and credentials. Institutions must verify that the individual attended courses or examinations, and the institution itself must be verifiably accredited.

Current trust frameworks that support this system are largely hierarchical. New standards, such as OpenID Federation, enable non-hierarchical trust, complementing existing identity federations and allowing for more independent collaborations.

However, this does not eliminate the need for trust. Authorities are still required for accrediting institutions and credentials. Additionally, when processes demand a high level of trust, further technical checks and organisational rules and regulations are necessary.

SIGNALS

OpenID Global Standards

OpenID Federation 1.0 specification (openid.net)

OpenID API specification for the issuance of verifiable credentials (openid.net)

Identity federations in practice

OpenID Connect Federation: How to build multilateral federations using OIDC (indico.geant.org)

Identity federations and inter-federation eduGAIN (wiki.geant.org)

EduGAIN OIDC pilot (indico.cern.ch)

IMPACT

Education

The role of institutions in the education data ecosystem is evolving, and requests for data and access to tools come from both within and outside of the ecosystem. Therefore, establishing trust in credential authenticity will become more challenging.

Research

The EU Digital Identity framework’s influence on the adoption of digital wallets in research and education, and its effects on trust frameworks, is subject to ongoing research.

Operations

Institutions must determine how credentials can be reliably attributed to individuals. This requires identity verification at enrolment, during assessments and perhaps even attendance.

More info about Digital Trust? Visit surf.nl

Cybersecurity

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1. Emerging dual-use of AI in cybersecurity
2. More accessible privacy-enhancing technologies to share data
3. Rising pressure to prepare for post-quantum cryptography
4. Emergence of measures for secure Internet of Things
5. The growing need for security protocols to work in the cloud

Introduction

The field of cybersecurity has advanced significantly since computer programmer Bob Thomas created the Creeper virus in 1971. Although this virus, which targeted the Advanced Research Projects Agency Network (ARPANET), was not a malicious virus, it marked an important moment in cybersecurity history. Over 50 years later, cyber attacks have grown increasingly malicious and become a significant threat to society.

Technologies, such as Artificial Intelligence (AI) and Internet of Things (IoT), bring new challenges and risks that must be addressed to maintain robust cybersecurity. For example, although AI can help improve defences against cyber attacks, it can also increase the threat by enabling automated malware.

While these digital technologies expose organisations to new threats, they are also becoming increasingly essential for organisations to manage and protect themselves. For instance, quantum computing will enable the implementation of complex and potentially very secure cybersecurity protocols. Such technologies offer significant opportunities for both individuals and organisations.

Despite these technological advancements, it remains crucial to stay vigilant about potential threats. Understanding the tools and techniques used by cybercriminals and knowing how to secure yourself and your organisation is essential for maintaining (cyber)resilience. In recent years, incidents within the education sector have highlighted the significant damage that can result from a seemingly harmless click by a so-called patient zero.

An understanding of how technologies can and could potentially shape the future of cybersecurity is essential. Therefore, this chapter has been included in the SURF Tech Trends to explain how new threats are emerging and to highlight the opportunities arising from technologies that have become integral to daily life. As society grows increasingly reliant on digital systems, cybersecurity and cyber resilience have become vital components of organisational strategy and operations. Organisations must focus on protecting (sensitive) data, complying with evolving policies and regulations (such as the EU Cyber Resilience Act), addressing the vulnerability of IoT devices to malicious attacks or unauthorised control, and mitigating emerging threats.

Contributors
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TREND #1

Emerging dual-use of AI in cybersecurity

Public Values

Autonomy	Privacy
Justice	Integrity | Accountability | Transparency
Humanity	Safety

Maturity WATCH PLAN **ACT**

Drivers

Automation & AI; Cybersecurity & trust; Engineering advances & computation; Value of knowledge & skills; Weaponisation of knowledge; Digital transformation

AI is transforming cybersecurity by improving real-time threat detection and efficient responses against these threats. AI models can analyse large datasets and data streams, identify anomalies, and predict attacks, making them a critical tool for security operations.

However, cybercriminals are also exploiting AI to improve their attacks. Techniques like AI-driven phishing, deepfakes, and automated vulnerability scanning are making cyberattacks more convincing and scalable. Rising concerns are developments on the deployment of GenAI to generate malware with minimal input and adversarial machine learning. Attackers are manipulating data to deceive AI models – such as those used for cyber defence – causing the models to overlook threats.

SURF

SIGNALS

Rise of offensive AI capabilities

Cybercriminals are leveraging large language models to craft context-specific phishing content and social engineering scripts

- **Phishing and social engineering in the age of LLMs** (link.springer.com)
- **Back to the hype: an update on how cybercriminals are using GenAI** (ibm.com)
- **With generative AI, social engineering gets more dangerous—and harder to spot** (ibm.com)
- **Could cyberattacks 'turn the lights off' in Europe?** (knowbe4.com)

AI-generated deepfakes are increasingly used in identity fraud and disinformation campaigns

- **How deepfakes, disinformation and AI amplify insurance fraud** (swissre.com)
- **A pro-Russia disinformation campaign is using free AI tools to fuel a 'content explosion'** (wired.com)
- **The dark side of AI: how deepfakes and disinformation are becoming a billion-dollar business risk** (forbes.com)

> ***"You can see that AI can help both attackers and defenders in cybersecurity. But the main focus remains on getting the basics right, with AI as a tool."***
>
> **- Jeroen van der Ham - de Vos**, University of Twente

Open source generative models are enabling low-resource actors to create evasive malware and automate attacks

- **Prediction for open source security in 2025: AI, state actors and supply chains** (openssf.org)
- **OpenAI confirms threat actors use ChatGPT to write malware** (bleepingcomputer.com)
- **How generative AI is changing how cybercrime gangs work** (bugcrowd.com)

SIGNALS

Defensive AI integration in cybersecurity operations

AI-powered Security Operations Centres (SOCs) use machine learning to automate threat detection, reduce alert fatigue, and speed up incident response

- **IBM Security, cost of a data breach report** (cloudfront.net)
- **Microsoft Security Copilot insights** (microsoft.com)

Behavioural analytics and predictive AI models identify anomalies and pre-empt threats before they escalate into attacks (of any scale)

- **Transforming SOCs with AI: From Reactive to Proactive Security** (cloudsecurityalliance.org)

Network & Extended Detection and Response (NXR/XDR) platforms integrate AI to provide real-time attack correlation, autonomous triage, and adaptive defence

- **Microsoft - What is extended detection and response (XDR)?** (microsoft.com)
- **Vectra.ai** (vectra.ai)

Mitigating adversarial AI risks

Cyber defenders use adversarial training and robust model tuning to harden AI systems against manipulation and input poisoning.

- **NIST AI risk management framework** (nist.gov)
- **MITRE ATLAS Framework** (atlas.mitre.org)

AI red teaming and model auditing are increasingly adopted to identify vulnerabilities in machine learning pipelines before attackers exploit them.

- **Anthropic: challenges in red teaming** (anthropic.com)
- **Microsoft Red Team** (learn.microsoft.com)

Threat intelligence platforms now incorporate adversarial AI detection modules to flag synthetic media, spoofed behaviour, and tampered datasets

- **Recorded Future** (recordedfuture)
- **Darktrace** (darktrace.com)
- **TNO and Jungle AI collaborate to detect cyberattack on wind turbine and improve detection capabilities** (tno.nl)

IMPACT

Education

AI tools offer the potential to secure online learning environments through anomaly detection and behavioural analytics. However, the misuse of AI can undermine educational integrity through automated cheating, deepfakes, or phishing. Securing AI in education requires balancing innovation with ethical and regulatory safeguards.

Research

Research institutions benefit from AI for advanced threat modelling, data protection, and network monitoring. However, open access policies and collaborative research environments also increase exposure to AI-driven threats. Robust model governance and adversarial resilience are key to maintaining research integrity.

Operations

As institutions digitalise, integrating AI into cybersecurity infrastructure enhances real-time response and reduces reliance on manual oversight. Yet, AI systems themselves are then becoming high-value targets. Institutions must build secure AI pipelines and invest in threat-informed AI deployment strategies to ensure long-term operational security.

TREND #2

More accessible privacy-enhancing technologies to share data

Public Values

Autonomy	Privacy
Justice	Integrity | Equity | Transparency | Accountability
Humanity	

Maturity WATCH PLAN **ACT**

Drivers

Compliance & regulation: Cybersecurity & trust; Automation & AI; Individualisation & empowerment; Digital transformation; Value of knowledge & skills

Privacy-enhancing technologies (PETs) protect sensitive information while enabling secure data processing and sharing. The adoption of PETs – such as differential privacy, synthetic data sets to resemble real sensitive data, federated learning, and homomorphic encryption – is being driven by growing data demands in education and research due to the sensitivity of data.

The recent availability of sector-specific solutions has made PETs more accessible, promising to unlock privacy-focused multi-party data sharing and analytics through research initiatives and private/public collaborations.

Embedding PETs into IT architectures will complement traditional security-by-design approaches with data-centric controls, reducing organisational vulnerability exposure, and defending against unauthorised access.

SIGNALS

Growth of synthetic data solutions

Information systems audit and control association (ISACA) (isaca.org)

Researchers at Erasmus University are being encouraged to use AI-driven synthetic data generated by Syntho Engine (2023) (syntho.ai)

Utrecht University has developed the MetaSyn platform for anonymised and FAIR data publishing (uu.nl)

Dienst Uitvoering Onderwijs (DUO) has shared synthetic datasets with Dutch researchers to train research models and help improve the education system (duo.nl)

TNO PET Lab aims to facilitate and spread the use of PETs in innovation (tno.nl)

Federated and secure data analytics piloting

SPATIAL (TU Delft) set to integrate PETS to achieve trustworthy, transparent, and explainable AI solutions for cybersecurity (spatial-h2020.eu)

Amsterdam University Medical Centre applies Federated Analytics to collaboratively develop predictive models for ICU outcomes (amc.nl)

In the Netherlands, the Social Insurance Bank (SVB) and the Employee Insurance Agency (UWV) successfully explore Multi-Party Computation (MPC) at the National Innovation Centre for Privacy-Enhancing Technologies (NICPET) (tno.nl)

PETs in cross-border data sharing

Calls for Federated Infrastructure for intensive care units data across Europe (doi.org)

EU Safe-DEED consortium project set to offer PETs for data marketplaces

- eurecat.org
- tudelft.nl)

Dutch HERACLES project lays foundation for secure private-public data sharing in healthcare sector (tno.nl)

IMPACT

Education

As education digitises, PETs will be crucial for securing student and staff data in online learning environments. Using cryptographic techniques and federated learning, PETs address privacy and security concerns in learning analytics, mitigating risks, and fostering trust amongst students and teachers in adaptive, data-driven, or personalised education systems.

Research

PETs empower researchers with secure access to sensitive or distributed datasets, mitigating privacy, reputation, and strategic risks associated with data sharing. While these technologies promise greater confidence in innovative research, they also increase pressure on institutions to facilitate them with supporting IT infrastructure.

Operations

As educational institutions adopt emerging (AI, edge computing) and maturing (cloud computing) technologies, the need for robust digital trust and data-centric security is intensifying. PETs will become essential towards achieving reliable and transparent security solutions, determining future IT security and regulatory compliance. PETs maturity and interoperability will support sector-wide implementation.

TREND #3

Rising pressure to prepare for post-quantum cryptography

Public Values

Autonomy	Privacy
Justice	Integrity | Accountability | Sustainability
Humanity	Safety

Maturity WATCH PLAN **ACT**

Drivers

Engineering advances & computation; Cybersecurity & trust; Automation & AI; Compliance & regulation; Critical infrastructure; Digital transformation

Once quantum computers reach sufficient scale, traditional cryptographic systems, which are used in digital signatures and secure communications, will be extremely vulnerable to attack.

Many of our current infrastructures lack crypto-agility, which slows transitions to robust cryptographic systems and leaves them exposed to Store Now-Decrypt Later (SNDL) threats. Most organisations are or will be exposed to these decryption threats, and their data (communication) protection readiness hinges on adopting Post-Quantum Cryptography (PQC).

Currently, the US agency NIST has released standards for PQC encryption and is encouraging system administrators to begin transitioning as soon as possible. In addition, European initiatives such as the European Quantum Communication Infrastructure (EuroQCI) seek to build secure communication networks using quantum key distribution (QKD), enabling and accelerating the distribution of cryptographic keys.

SIGNALS

Post-quantum cryptography standardisation

NIST releases first 3 finalised post-quantum encryption standards (nist.gov)

NIST standardises quantum-safe cryptography methods (cwi.nl)

"Store now, decrypt later" strategy

State actors are already collecting encrypted data for future decryption with quantum computers, as part of the "store now, decrypt later" approach (enisa.europa.eu)

National government's quantum security initiatives

The Dutch National Cybersecurity Centre (NCSC) and AIVD are leading efforts to prepare organisations for quantum threats, advising on mapping encryption use and transitioning to quantum-safe technologies (ncsc.nl)

Next steps National Cyber Security Centre (UK): Preparing for Post-Quantum Cryptography (ncsc.gov.uk)

EuroQCI project: building quantum-secure communications

The European Quantum Communication Infrastructure (EuroQCI) project aims to establish a secure communication network across Europe using quantum key distribution (QKD), ensuring long-term protection against quantum threats (digital-strategy.ec.europa.eu)

Support for crypto-agility

PQC Handbook - Evaluate and plan for a seamless migration to post-quantum cryptographic systems (aivd.nl)

IMPACT

Education

- Post-quantum security breaches are possible due to open IT environments, dependence on third-party cloud providers, and the long retention of confidential data.
- Identities could be compromised, with the exposure of gradebooks, assessments, or personal info.
- Archived teaching content, communications, or certification records could be forged or altered.

Research

- “Store now, decrypt later” is a significant threat to research confidentiality. Data such as genetic records and AI models intercepted today could be decrypted years later, exposing proprietary or sensitive findings.
- Research partners may hesitate to share data or collaborate if quantum-insecure systems are in use, leading to a breakdown in trust-based collaboration.
- Universities involved in patentable or commercially relevant research could lose a competitive advantage in the event of intellectual property theft.
- Failure to secure data may lead to funding body restrictions or non-compliance with ethical and legal requirements.

Operations

The emerging risk of quantum computers eventually breaking today’s encryption algorithms is already prompting “store now, decrypt later” tactics by state-affiliated actors, targeting data with long-term sensitivity. Therefore, key PQC infrastructure must be established. Without early PQC action in terms of policy and infrastructure funding, institutions risk long-term data exposure and eroded trust.

TREND #4

Emergence of measures for secure Internet of Things

Public Values

Autonomy	Privacy
Justice	Accountability | Integrity
Humanity	Safety

Maturity WATCH PLAN **ACT**

Drivers

Connectivity & interaction; Cybersecurity & trust; Digital transformation; Compliance & regulation; Critical infrastructure; Individualisation & empowerment

The Internet of Things (IoT) is here to stay, and it is revolutionising industries by improving efficiency and providing more insights. Yet, it faces significant security challenges and risks related to, for example, identification, authentication, and ownership of 'smart' devices, such as autonomous drones.

Over the last decade, IoT developers and vendors have neglected their responsibility for security updates throughout the product lifetime, creating cybersecurity gaps within organisations.

To mitigate such risks, security solutions, such as endpoint protection, are being developed. In addition, new legislation, like the Cyber Resilience Act, will force IoT developers and vendors to include security updates for any product's lifetime.

SIGNALS

IoT devices are being integrated into day-to-day practices

IoT devices can be found and are increasing across all verticals and supply chains, in their integration in day-to-day practices, be it in the hospital, the factory, or at home (demandsage.com)

The EU Cyber Resilience Act (CRA), effective 2024 (digital-strategy.ec.europa.eu)

IoT security has its own specific security

A review of multi-factor authentication in the Internet of Healthcare Things (doi.org)

UTwente opened an IoT Cyberlab (utwente.nl)

Edge AI: connecting cloud and devices for safe, sustainable AI (doiotfieldlab.tudelftcampus.nl)

Practical actions and guidelines

Tips from the Dutch National Cybersecurity Centre (ncsc.nl)

Guidelines for Securing the Internet of Things (enisa.europa.eu)

IMPACT

Education

Professional degrees like system engineering integrate IoT and its security aspects into the curriculum. However, the application of IoT in educational methods focuses less on digital technology, such as providing instant feedback. Enabling personalised learning remains limited.

Research

- The secure implementation of IoT can also contribute to the collection of data for scientific research (e.g. via devices and wearables).
- IoT and the security of IoT is being investigated in a wide variety of applications with higher education research institutions. This includes, for example, privacy-preserving and secure protocols for healthcare wearables (IoMedicalT), smart traffic management systems, and developing models that detect and classify IoT attacks.

Operations

IoT is often overlooked by IT security operations, despite the significant increase of its attack surface area. It is therefore important that IT security operations regain control of their hidden IoT assets, facilitate the use of secure IoT, as well as educate their employees and students about the security risks associated with IoT interactions (awareness). Institutions are advised to isolate IoT networks, use dedicated servers, and implement governance frameworks to ensure secure IoT adoption.

TREND #5

The growing need for security protocols to work in the cloud

Public Values

Autonomy	Privacy
Justice	Integrity | Accountability | Transparency
Humanity	Safety

Maturity WATCH PLAN **ACT**

Drivers

Automation & AI; Engineering advances & computation; Cybersecurity & trust; Digital transformation; Service-oriented & value-based economies; Value of knowledge & skills

Cloud computing offers unprecedented scalability, flexibility, and cost efficiency; however, the widespread adoption of cloud services introduces significant cybersecurity challenges. These challenges stem from shared provider-user responsibilities, an expanded attack surface, reliance on third-party vendors, and a lack of transparency in software and hardware.

Additionally, AI integration complicates security and privacy concerns. Hybrid cloud setups require robust security practices, like zero-trust architectures, continuous monitoring, and strong encryption.

SIGNALS

European and national alternatives for cloud services

Start Next Cloud pilot: seventy researchers across five Dutch universities (communities.surf.nl)

Rotterdam, Utrecht University, and Tilburg University will collaborate (voxweb.nl)

Dutch government committed to Dutch sovereign cloud for sensitive information

- security.nl
- open.overheid.nl)

EU FED Cloud which complies with relevant EU regulations such as the Data Act, AI Act, GDPR, eIDAS, DORA, and EUCS (eufedcloud.eu)

EOSC EU Node (open-science-cloud.ec.europa.eu)

European legal developments

NIS2 directive into force, including in the higher education sector (business.gov.nl)

EU regulation Cyber Resilience Act (CRA) (eur-lex.europa.eu)

IMPACT

Education

- Other ways of working with cloud computing technology evolve, such as switching between cloud providers and/or solutions, including addressing cybersecurity aspects. It is expected that the importance of data sovereignty and sovereignty in general will become more integrated into curricula.
- Revisions in IT education curricula could help to address the critical skills of cybersecurity professionals.

Research

- Due to a shortage of cybersecurity professionals, a lack of skilled personnel can leave research environments exposed to cyber threats, potentially affecting the integrity of research workflows and outcomes. To mitigate this, cybersecurity awareness training for researchers could be investigated.
- Shared responsibilities can lead to data breaches or loss, particularly if researchers are unaware of security protocols.
- Researchers must navigate various regulations regarding data protection and privacy, which can be complicated by cloud environment.

Operations

- As cloud adoption continues to rise, careful planning and enhanced security measures are essential for institutions to protect sensitive data, ensure compliance, and maintain resilience in an evolving threat landscape. There will also be a large impact due to (data) migrations and the associated steps, such as preparation, awareness, and costs. The adoption of open-source software (OSS) is also expected to increase.
- While hybrid clouds offer flexibility, they necessitate advanced security practices, which may be challenging for some research institutions to implement effectively.

More info about Cybersecurity? Visit surf.nl

Cloud Computing

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1. Growing investments in the European cloud infrastructure & sovereignty
2. More AI-driven hardware in data centres to manage workloads in the cloud
3. Bringing computing resources closer to the 'edge'
4. Growing need for automated cloud and edge resource management
5. Towards cloud native services and application design for research

Introduction

At the core of the digital infrastructure are two distinct, yet complementary, distributed computing frameworks. On one hand, cloud computing – the core focus of this chapter - provides vast, on-demand access to scalable processing power and data storage via the network, through private and public cloud providers. Cloud computing allows organisations and individuals to pay on demand instead of investing in their own costly infrastructure. On the other hand, edge computing pushes computing functions closer to where local data is generated – at the network's edge. Edge computers enable real-time responsiveness to the local data, reduce network traffic, maintain functionality during disconnections from central systems, and ensure that sensitive data can remain on the local device. Edge computing has developed rapidly due to the explosive growth of the IoT-devices (Internet of Things) loaded with large amounts and large varieties of data-producing sensors in e.g. cars, healthcare devices, public infrastructure, and manufacturing machines. Once viewed as separate approaches, these two frameworks are increasingly converging into a unified framework known as the computing continuum. This continuum seamlessly connects the smallest sensor in a peripheral device to a supercomputer in a central data centre, facilitating a variety of data processing capabilities.

The primary catalyst driving the computing continuum is the relentless advance of artificial intelligence (AI). For optimal operation of today's AI systems and the demands, there are two principal requirements. First, it needs massive, centralised high-performance computing

(HPC) resources for AI model training and large-scale and complex data analysis. Second, to ensure low latency during operation, decentralised processing is necessary to run these AI models, or their compact versions, in real-world applications, including, for example, synchronising with the cloud for further big data analysis.

The current cloud computing landscape is significantly influenced by strategic global competition. Hyperscalers (large technology companies that provide cloud computing services on a massive scale) are at the forefront of this dynamic. Hyperscalers such as Amazon Web Services (AWS), Google Cloud, Oracle Cloud Infrastructure (OCI), and Microsoft Azure deliver powerful services and have highly dominant market positions in regions like the US and Europe.

Countermeasures in Europe are evolving to strengthen Europe's digital sovereignty in the cloud sector. In 2025, the European Commission proposes the Cloud and AI Development Act, intending to at least triple the EU's data centre capacity within the next 5 to 7 years. These kinds of (policy) developments will lead to expanded European cloud infrastructures – both private and public – to meet the needs of EU businesses and public administrations who favour sovereign cloud services including European data residency. However, European-level collaboration is paramount for this ambition whereby initiatives like Gaia-X and European Open Science Cloud (EOSC) offer lessons learned.

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TREND #1

Growing investments in the European cloud infrastructure & sovereignty

Public Values

Autonomy	Freedom of choice | Independence | Privacy
Justice	Transparency | Sustainability | Accountability
Humanity	Safety

Maturity WATCH PLAN **ACT**

Drivers

Geopolitics & (digital) sovereignty; Compliance & regulation; Cybersecurity & trust; Automation & AI; Digital transformation; Global trade & tariffs

GenAI has influenced the cloud market considerably: half of the increase in global (public) cloud service revenues since the launch of ChatGPT (late 2022) is driven by GenAI. In Europe specifically, GenAI-specific services such as GPU-as-a-Service (GPUaaS) and GenAI Platform-as-a-Service (PaaS) are demonstrating exceptionally high growth rates over the last few years. The main beneficiaries of this European market growth have been the US companies Amazon, Microsoft, and Google, which together now account for 70% of the regional market in terms of revenues. Europe is experiencing a strong and ongoing push for digital sovereignty, aiming to reduce reliance on US-based cloud providers and ensure greater control over sensitive data. This is the reason why major global cloud providers are making significant European investments to address digital sovereignty concerns. As a result, European cloud providers' market share remains relatively constant at around 15% of the European cloud market despite the European ambitions and investments.

SIGNALS

Cloud integration in academia

Hyperscalers, like AWS and Microsoft, launch dedicated EU sovereign cloud offerings to address data residency and regulatory requirements. European Open Science Cloud (EOSC) and Gaia-X provide federated environments aligned with EU values.

AWS Unveils Independent European Governance and Operations for European Sovereign Cloud (infoq.com)

Announcing comprehensive sovereign solutions empowering European organisations (blogs.microsoft.com)

GÉANT Innovation Programme funds a Digital Research Environment (DRE) initiative to create integrated, cloud-based research platforms (connect.geant.org)

European Open Science Cloud (EOSC) develops a federated, trusted environment enabling researchers across Europe to share, access, and reuse data and services for open science (research-and-innovation.ec.europa.eu)

Size of the cloud market

Cloud market jumped to $330 billion in 2024 – GenAI is now driving half of the growth (srgresearch.com)

European cloud providers' local market share now holds steady at 15% (srgresearch.com)

The future of cloud in 2029: the journey from technology to business necessity (gartner.com)

2024 enterprise trends: cloud meets AI (redhat.com)

Cloud market share 2024 - AWS, Azure, GCP growth fueled by AI (holori.com)

Global cloud infrastructure market share 2024 (statista.com)

Amazon and Microsoft Stay Ahead in Global Cloud Market (statista.com)

AWS Remains $330bn Cloud Market Leader, Driven by AI Growth (technologymagazine.com)

Cloud Market Jumped to $330 billion in 2024 (srgresearch.com)

European cloud providers grow but lose market share to US titans (techrepublic.com)

Europe's cloud customers eyeing exit from US hyperscalers (theregister.com)

SIGNALS

European cloud infrastructure expansion

The development of a national Gaia-X testbed in the Netherlands continues, expanding the ecosystem of trusted, sovereign cloud options

Test environment for cloud services: Structura-X (tno.nl)

European cloud computing

- **Platforms** (european-alternatives.eu)
- **Policies** (digital-strategy.ec.europa.eu)
- **The cloud sovereignty nexus: How the European Union seeks to reverse strategic dependencies** (onlinelibrary.wiley.com)

Digital sovereignty in Europe: navigating the challenges of the digital era (pppescp.com)

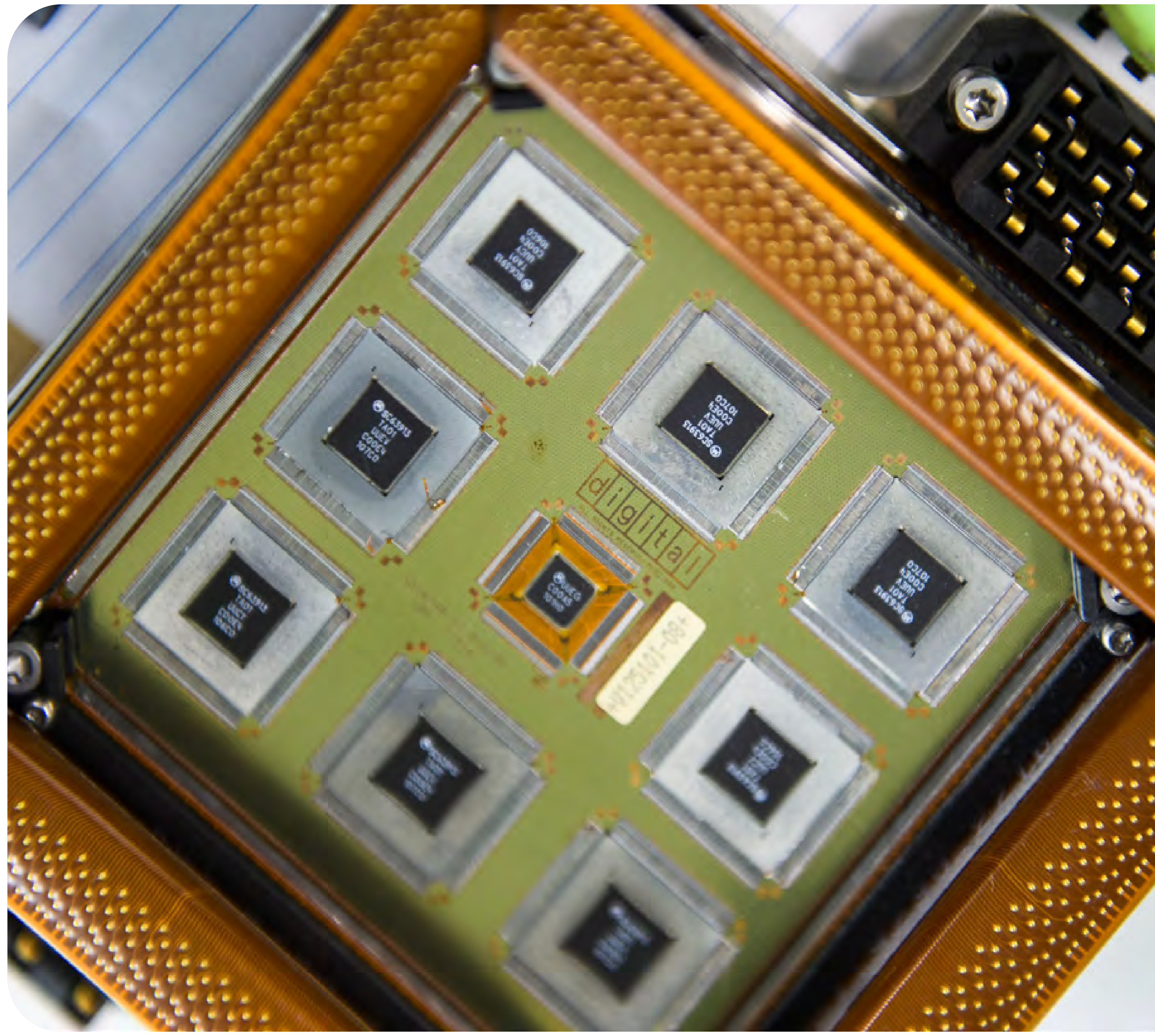
Designing the European processor (sipearl.com)

"By 2030, 75% of European businesses should use cloud-edge technologies for their activities."

– European Commission

Next Euro HPC chip coming next year will be in 2026 EU exascale system (hpcwire.com)

SiPearl raises €90 million in initial closing of Series A to launch Rhea (eib.org)



IMPACT

Education

- More institutions are adopting cloud-first policies, offering students much-needed exposure to and experience with real-world infrastructure.
- A diverse training portfolio is required for students in cloud computing and high-performance computing (HPC) to meet the rising demand for scalable AI infrastructure and navigate European digital sovereignty initiatives.

Research

- Access to powerful cloud resources on demand will accelerate the timeframe towards key research discoveries and outcomes.
- Researchers require enhanced support and training to maximise their use of cloud resources through initiatives. The hyperscalers provide tailored programmes and expert assistance, for example, AWS's Open Data and Azure for Research.

Operations

- Data centres are being upgraded and federated clouds integrated to meet increasing compute demands.
- Technical support is essential to ensure that facilities on institutional campuses operate without interruption, providing reliable maintenance and troubleshooting for high-performance computing (HPC) and cloud infrastructure.

TREND #2

More AI-driven hardware in data centres to manage workloads in the cloud

Public Values

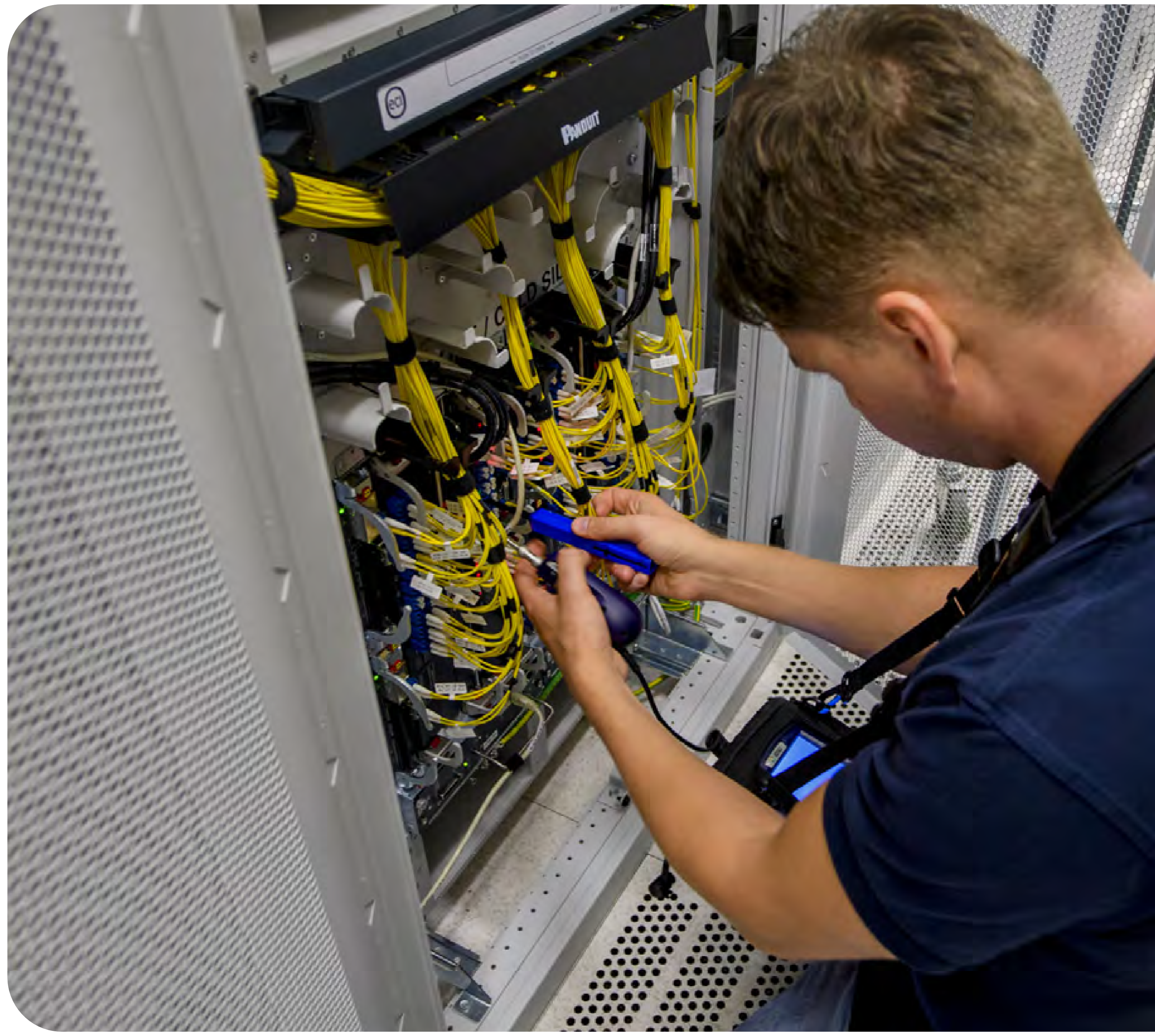
Autonomy	Independence
Justice	Sustainability | Equity | Integrity | Accountability
Humanity	Safety

Maturity WATCH PLAN **ACT**

Drivers

Automation & AI; Engineering advances & computation; Digital transformation; Connectivity & interaction; Energy supply & demand; Service-oriented & value-based economies

To support intensive workloads that are anticipated for cloud computing, cloud providers and heavy users like research institutions are investing heavily in specialised hardware. This goes beyond standard CPUs (with AMD outselling Intel in the data centre segment recently) to include powerful accelerators such as Graphical Processing Units (GPUs), which are the workhorses for AI training and whereby Nvidia's data centre GPU market share is 98%. Hyperscalers are developing specific hardware like AI chips to deliver high-performance, cost-efficient cloud services. This hardware evolution requires additional innovations in infrastructure to manage the immense power density.



SURF

SIGNALS

GPU and supercomputer upgrades

LUMI supercomputer in Finland delivers up to 380 petaflops using green energy (csc.fi)

Nvidia's new Spectrum-XGS aims to turn multiple data centers into 'one gigantic GPU' (datacenterdynamics.com)

"NVIDIA's Blackwell Ultra GPUs, along with custom accelerators from Google and Amazon, drove the data center IT component market to 44% year-over-year growth in 2Q 2025."

– Dell'Oro Group report

Custom AI hardware and efficiency

AWS Trainium, Google TPUs, and Microsoft FPGA-based services offer cost-effective alternatives (cloudexpat.com)

AI chips are driving cloud innovation through better performance-per-dollar metrics (amd.com)

Energy-aware operation of HPC systems in Germany (frontiersin.org)

Harnessing data centre heat into reusable energy: a sustainability game changer (hpcwire.com)

IMPACT

Education

Students need to gain exposure to advanced computing environments and AI-capable hardware. This can be achieved through dedicated compulsory and elective modules/courses, as well as project work, where the utilisation of new computing paradigms is a requirement.

Research

Thanks to the integration of advanced AI model training and cloud computing services, researchers will have faster and more feasible access to computing resources that are applicable across several disciplines.

Operations

At the research institute and university level, shared infrastructure serves to reduce costs. In addition, the deployment of liquid cooling systems for computational infrastructure will improve energy efficiency and help with the sustainability of these computational resources.

TREND #3

Bringing computing resources closer to the ‘edge’

Public Values

Autonomy	Independence | Privacy | Freedom of choice
Justice	Accountability | Integrity | Inclusion
Humanity	Safety

Maturity WATCH **PLAN** ACT

Drivers

Connectivity & interaction; Engineering advances & computation; Cybersecurity & trust; Compliance & regulation; Digital transformation

The rise of AI, IoT (Internet of Things), and future 6G networks is pushing computation away from a purely centralised model. This architectural shift involves moving data processing to the network edge to reduce latency, conserve bandwidth, and protect privacy. In practice, this means AI models need to run on-site on specialised hardware for real-time edge computing tasks such as field robotics (where a high degree of autonomy is required) or patient monitoring.

Concurrently, society is increasingly relying on and expecting complex, multimodal workflows that combine text, images, and sensor data. These workflows demand new, distributed architectures that seamlessly integrate edge devices for data collection and processing, cloud platforms for large-scale storage, and HPC backends for intensive AI model training and advanced data analysis.

SIGNALS

Edge for low latency AI

Implementing NVIDIA Jetson in field robotics and smart medical devices (industrialautomation.nl)

The FNS programme (6G Future Network Services) has developed AI-native 6G network to enable dynamic edge-cloud orchestration (tudelft.nl)

EC's next generation Internet of Things (digital-strategy.ec.europa.eu)

"Cloud-edge integration allows organisations like enterprises and research institutes to enhance their IT infrastructures with low-latency processing and real-time decision-making capabilities."

– EU Commission/Technopolis

Multimodal AI pipelines

AI4EU has fostered distributed AI services and federated learning platforms (ai4europe.eu)

Edge AI is being used for on-device inference, with cloud/HPC backends then employed for AI model training and coordination (sciencedirect.com)

Empowering edge intelligence: a comprehensive survey on on-device AI models (dl.acm.org)

Study on the economic potential of far edge computing in the future smart Internet of Things (op.europa.eu)

The global edge computing market size was estimated at USD 23.65 billion in 2024 and is expected to reach USD 327.79 billion in 2033, growing at a CAGR of 33.0% from 2025 to 2033 (grandviewresearch.com)

Hype Cycle for Edge Computing, 2024 (gartner.com)

The European cloud, edge and IoT continuum preliminary market analysis (zenodo.org)

IMPACT

Education

Students and staff alike need to be exposed to edge AI and network-driven architectures. This can be achieved through revision of existing modules/courses or the creation of focused content.

Research

The architectural shift will enable new experimental approaches in robotics, medicine, and environmental monitoring.

Operations

Architecture shifts are set to drive investment in IoT, network infrastructure, and local compute.

TREND #4

Growing need for automated cloud and edge resource management

Public Values

Autonomy	Privacy | Independence
Justice	Sustainability | Accountability | Equity | Integrity | Transparency
Humanity	Safety

Maturity WATCH **PLAN** ACT

Drivers

Automation & AI; Engineering advances & computation; Digital transformation; Service-oriented & value-based economies; Digital transformation; Energy supply & demand

The proliferation of AI is creating new paradigms in cloud resource management, as AI-driven automation (AIOps) becomes essential. Cloud providers are now embedding AI assistants into their platforms to automate complex tasks, such as resource provisioning - selecting and deploying computing resources for optimal application performance - and performance tuning.

In addition, the massive energy footprint of AI workloads is accelerating the push towards green computing, with a focus on sustainable data centres and intelligent workload scheduling. To manage the unpredictable costs, institutions are adopting FinOps (Financial Operations), which is the practice of financial governance that unites IT, finance, and research faculties to optimise cloud spending and maximise value.

SIGNALS

Cloud automation (AIOps)

AWS and Azure have introduced AI assistants for infrastructure usage and monitoring:

AWS AI assistant for accelerating software development and leveraging companies' internal data (aws.amazon.com)

Operate everywhere with Azure AI management and security (techcommunity.microsoft.com)

FinOps practices are being adopted to curb cloud budget overruns and track usage

FinOps Foundation (finops.org)

Cloud Strategy at the EU: Cloud computing (digital-strategy.ec.europa.eu)

Embracing cloud governance within the context of FinOps (ijfmr.com)

"FinOps is a framework and cultural practice which maximises the business value of cloud and technology, enables timely data-driven decision making, and creates financial accountability through collaboration between engineering, finance, and business teams."

– FinOps Foundation

IMPACT

Education

As students engage with AI-driven cloud and DevOps tools, they will need focused skills in AIOps, FinOps, and sustainable computing to learn how to manage automation, costs, and environmental impact effectively.

Research

The rise of AI-driven cloud management and DevOps practices enables researchers to accelerate experimentation and scale workloads efficiently, but also demands greater focus on cost management, sustainability, and cross-disciplinary collaboration.

Operations

- These new paradigms and practices are helping institutions to manage IT complexity and to meet sustainability goals.
- Although the integration of AI-driven cloud tools and DevOps practices enhances efficiency and scalability, new strategies for financial governance, sustainability, and cross-departmental coordination may need to be considered.

TREND #5

Towards cloud native services and application design for research

Public Values

Autonomy	Freedom of choice | Independence
Justice	Sustainability | Integrity, Transparency | Accountability
Humanity	

Maturity WATCH PLAN ACT

Drivers

Automation & AI; Connectivity & interaction; Digital transformation; Service-oriented & value-based economies; Value of knowledge & skills

The adoption of cloud technologies is transforming how research software is developed and used. Research IT is shifting towards cloud-native development, where applications are built as scalable microservices and consumed via application programming interfaces (APIs).

This approach, which includes containerising workflows with tools like Docker and orchestrating them with Kubernetes, is making academic software more robust and reproducible.

Practices like Infrastructure as Code (IaC) and Continuous Integration/Continuous Delivery (CI/CD) pipelines are becoming the standard, thus allowing scientists to share the exact configurations used for different experiments and support reproducibility. This modernisation not only accelerates scientific discovery but also improves the longevity and reusability of research software, aligning it with industry-grade practices.

SIGNALS

Cloud-native design and tools

Kubernetes, Terraform, and GitLab CI/CD are being used in academic and research projects:

CERN: processing petabytes of data more efficiently with kubernetes (kubernetes.io)

A grid site reimagined: building a fully cloud-native ATLAS Tier 2 on kubernetes (inspirehep.net)

The use of infrastructure as code in regulated companies (ispe.org)

"Infrastructure as Code provides several advantages toward reproducibility in computer science. ... IaC allows researchers to define and control their infrastructure accurately in a format that can be easily stored, versioned, and shared, making it easy to reproduce experiments and obtain the same results at each execution."

- Frontiers in Computer Science

IMPACT

Education

Cloud technologies in research software enhance education by providing students access to robust, reproducible tools that promote collaboration and innovation; however, students can maximise the potential by gaining hands-on skills in DevOps and cloud-native development.

Research

The adoption of cloud-native development supporting FAIR software practices profoundly enhances the efficiency and reproducibility of research, enabling scientists to scale experiments and accelerate discoveries and share methodologies more effectively.

Operations

The transition to cloud technologies and microservices in research software enhances cross-disciplinary collaboration and optimises IT service delivery, while also streamlining resource allocation and reducing software deployment time. However, a critical shortage of skills is hampering adoption.

More info about Cloud Computing? Visit surf.nl

Computing

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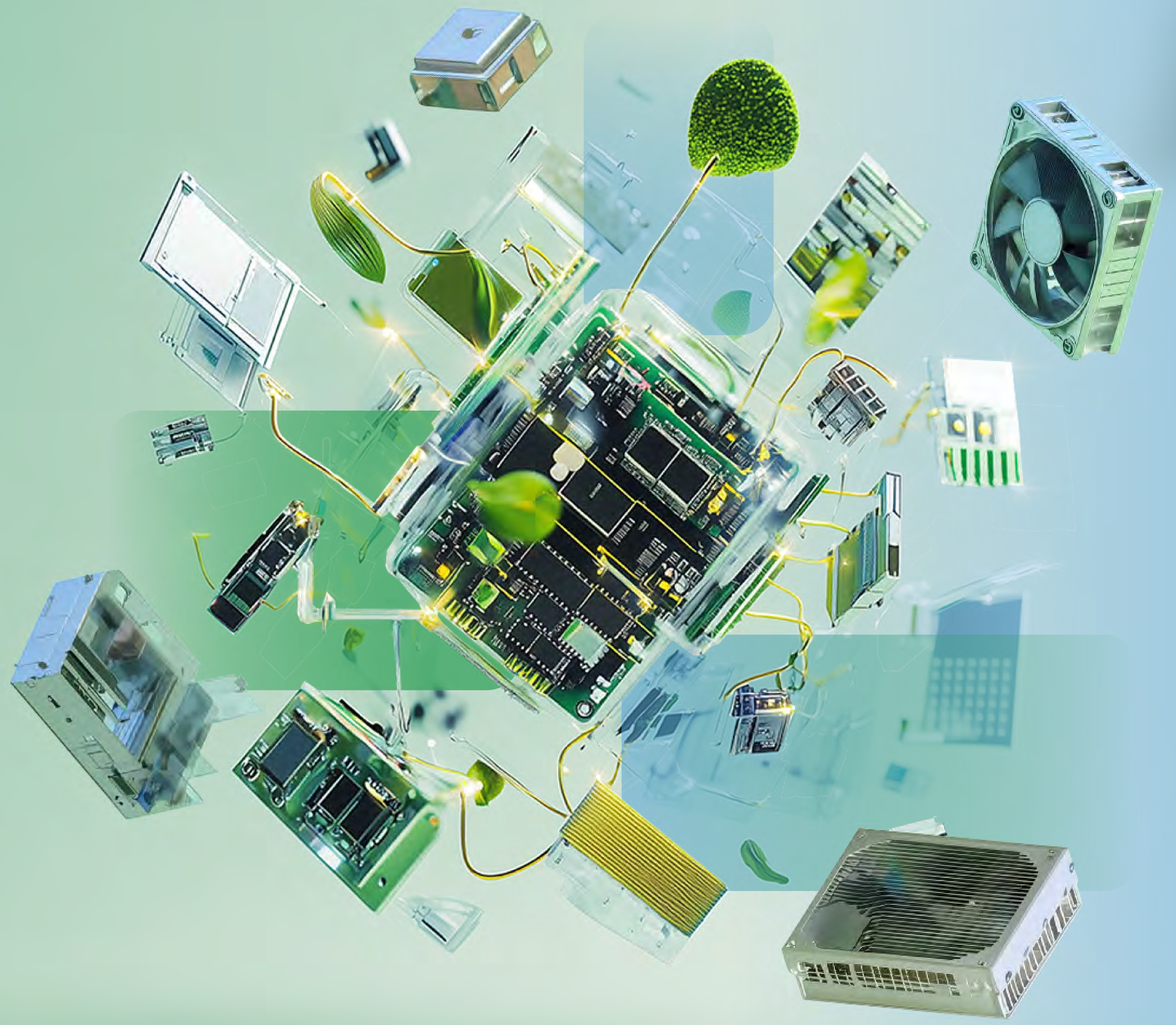

Introduction

Society is increasingly relying on advanced computing capabilities to support the transition towards renewable energy systems, develop personalised medicine, utilise digital twins, and predict the impacts of climate change. This involves leveraging the state-of-the-art digital infrastructure ecosystem through collaborative, connected platforms, services, and products that enable analysis and virtual experimentation. Exascale computing platforms play a crucial role in processing information at scales previously unimaginable.

Within this landscape, computing is reaching a pivotal point where the combination of data, AI, cloud, and quantum-enabled supercomputing will play a more significant role in our ability to process information. This critical shift is driven by rapid advancements in AI, with a surge in demand for computational power that exceeds the limits of classical methods. Further, Moore's Law is slowing down, as silicon-based transistors approach physical limits. This drives the exploration of emerging technologies and paradigms, as well as their impact on computing for science, research and education.

At the same time, computing facilities are under pressure due to the large energy footprint required for data processing and infrastructure cooling. This is pushing the boundaries of traditional approaches and encouraging efforts towards more resilient and energy-efficient infrastructures.

Globally, there is a growing emphasis on advanced computing ecosystems as strategic assets for science, innovation, and growth,

along with ongoing advocacy for the required long-term investment. Computing, data and digital infrastructures are gaining more recognition at international forums, providing pathways for knowledge and sustainable societal development. The European Union, Asia, Africa, America, and other geopolitical regions have initiated public dialogues and launched projects to strengthen their computing ecosystems, recognising their impact on research, the economy, and society.

In the Netherlands, NWO (the Dutch research council), in collaboration with SURF, published a report highlighting the computational needs for accelerated scientific discovery. Alongside NWO, more researchers and research communities are emphasising the growing importance and demands of computing for scientific research across all disciplines.

Concurrently, the ICT Research Platform Netherlands has underscored the need for long-term strategic investments in the Netherlands, compared to international benchmarks, particularly in relation to Europe's mission towards digital sovereignty, knowledge, and economic competitiveness.

All these developments are co-evolving, influencing technology, policy, business models, and capital allocation, with implications for geopolitics, global talent competition, and economic and scientific impact. This chapter focuses on technological shifts in computing and their potential effects on research and education ecosystems.

Contributors
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TREND #1

Increasing need for heterogeneous and hybrid computing platforms

Public Values

Autonomy	Independence | Freedom of choice | Privacy
Justice	Sustainability | Integrity | Accountability | Equity
Humanity	

Maturity WATCH PLAN **ACT**

Drivers

Engineering advances & computation; Digital transformation; Energy supply & demand;

The demands of modern computing applications have effectively challenged the era of classical approaches. Modern large-scale computing environments are increasingly becoming modular, integrating a wide range of specialisations such as hybrid quantum systems, cloud platforms, ASICs, GPUs, edge IoT devices, and storage, enabling the execution of complex tasks. The slowdown of Moore's Law, coupled with the growing demands of AI-driven design, necessitates specialised solutions for improved outcomes. Although the landscape remains fragmented, tools that facilitate orchestration across heterogeneous environments are becoming more widespread and valuable in mainstream scientific computing. We envision a lot of innovation in the software layers of the digital infrastructure stack for the coming decades.

SURF

SIGNALS

Hyperscale clouds design custom accelerators

AWS launches second-generation Trainium2 and Inferentia3 chips to reduce AI training costs (semianalysis.com)

Microsoft Azure introduces the Maia 100 AI accelerator and Athena CPU for its data centres (semianalysis.com)

Consumer Systems-on-a-chip integrate CPU + GPU + NPU

Apple's M3 Ultra features 32 CPU cores, 80 GPU cores, and an enhanced Neural Processor Engine (apple.com)

Qualcomm Snapdragon X Elite for Copilot+ PCs ships with a 45 TOPS NPU (qualcomm.com)

Converging software ecosystems

Intel oneAPI 2024 LTS unifies compilers across CPU, GPU and FPGA targets (intel.com)

Khronos releases SYCL Rev 9 with back-ends for CUDA, HIP and oneAPI (khronos.org)

> *"The classic computing approach, using program-flow simulations to model different functions, has become outdated, and the rise of AI and data-driven methods has accelerated the exposure of the cracks in the classic approach."*
>
> - **Manolis Sifalakis**, Innatera

Emergence of AI Driven design

AI-dedicated large-scale computing systems start to enter the market to improve efficiency and reduce cost compared to GPUs

- **Cerebras starts building six data centres with its wafer-scale AI hardware in North America and Europe from 2024 to 2025** (cerebras.ai)
- **Meta introduces next-generation AI infrastructure with custom-made AI hardware in 2024** (about.fb.com)
- **Tesla's wafer-scale Dojo AI hardware is in production to support large-scale training for autonomous driving in 2024** (tomshardware.com)

AI-dedicated hardware with emerging technologies is starting to transfer from academia to industry

- **SpiNNcloud introduces first commercial neuromorphic AI HPC in late 2024 using digital neuromorphic technology developed in the human brain project** (theregister.com)
- **In-memory computing technology starts to materialise into AI hardware products with start-up companies like Synthara and Axelera AI** (synthara.ai)
- **Innatera secures $21M in investments with plan to drive analogue neuromorphic AI to 1 billion devices by 2030** (unite.ai)

IMPACT

Education

Curricula are likely to increasingly embed specialised hardware concepts alongside conventional architectures. Students are therefore likely to engage further with a variety of accelerators dedicated to certain tasks in cloud lab environments. Lectures, labs, and projects will train students to deploy and optimise workloads on specialised accelerators. This shift is likely to drive academic programs to evolve beyond foundational programming courses towards more advanced parallel and heterogeneous computing paradigms. As a result, curricula will have to increasingly incorporate models such as CUDA, HIP, SYCL, or OpenCL.

Research

Scientific applications are likely to run more often on heterogeneous systems, such as "GPU for dense linear algebra, FPGA for bit-level genomics, or neural processing unit (NPU) for inference," within a single cluster job. This shortens iteration cycles, enables larger parameter sweeps, and lowers energy budgets. Hardware-software co-design is set to become a fertile ground, inspiring resource-efficient algorithms and spurring rapid innovation in chip architectures. However, new scheduling policies and heterogeneous-aware middleware from campus HPC centres are needed as a result.

Operations

Operation teams might need to assess designs that combine different components while balancing power and cooling needs. Furthermore, facility layouts, monitoring tools, and support staff skills will need to adapt to efficiently manage mixed-architecture racks and the fast-evolving generations of accelerators.

TREND #2

Trade-offs in accuracy with approximate computing

Public Values

Autonomy		
Justice	Sustainability | Accountability | Equity	
Humanity	Safety	

Maturity WATCH PLAN **ACT**

Drivers

Energy supply & demand; Automation & AI; Engineering advances & Computation

There are computer applications that do not require high (computational) accuracy and precision, or work with information that already contains uncertainty. Think of applications like neural networks, signal processing, and localisation and mapping for which an approximate result is sufficient to meet both the requirements and design goals in the computer architecture.

Design goals can be traded, such as performance, power, and energy efficiency. Techniques available for approximate computing include quantisation, rounding, truncation, and reduction of the number of bits.

Approximate computing is also achieved at the software level with dedicated algorithms, and at the hardware level by using approximate hardware, or via a combination of both. Therefore, approximate computing is gaining more traction, leading to trade-offs in accuracy in exchange for other improvements in computational objectives.

SURF

SIGNALS

Reducing energy consumption using the approximate computing paradigm

Approximate computing-based accelerators to reduce energy consumption have been demonstrated through scientific research (ieeexplore.ieee.org) and projects (textarossa.eu)

Joint approximations across different subsystems have been explored to improve the energy efficiency of smart camera systems (ieeexplore.ieee.org)

AI Accelerators with approximate computing

IBM integrates approximate computing techniques in AI accelerators (research.ibm.com)

Approximate DRAM devices have been used to reduce the energy consumption and evaluation latency of DNN (arxiv.org)

Approximation used in combination with Dynamic Voltage Scaling

Dynamic error detection and correction is used for Dynamic Voltage Scaling in ARM Razor, that tunes the supply voltage by monitoring the error rate during operation (documentation-service.arm.com)

Aggressive voltage underscaling can be used in high-performance DNN accelerators while maintaining the required classification accuracy (ieeexplore.ieee.org)

"Approximate computing can significantly reduce the energy and computational cost of several applications, including machine learning, video processing, and data analytics."

- **Alberto Bosio**, University of Lyon

IMPACT

Education

Computer science is mostly based on determinism and exact computation. Students need to be trained to deal with approximated and not 'exactly correct' results. Concepts like error management and computation accuracy within known boundaries are likely to emerge both in theory and in practical sessions.

Research

The approximate computing paradigm is reasonably mature. Optimisation based on approximate computing might be beneficial for specific applications such as neural networks and could boost the performance of several research application domains, such as in the medical sciences.

Operations

Generally, the use of approximate software routines does not require an update of IT infrastructure. Larger benefits could come from the use of approximated hardware, but the changes of the infrastructure required must be contrasted with the resulting benefit. Such evaluation should be done individually on a case-by-case basis.

TREND #3

Growing emphasis on neuromorphic (brain-inspired) computing

Public Values

Autonomy		
Justice	Sustainability | Equity | Accountability | Integrity	
Humanity	Safety	

Maturity WATCH **PLAN** ACT

Drivers

Automation & AI; Engineering advances & computation; Energy supply & demand; Raw material scarcity; Clean water demand; Critical infrastructure

Neuromorphic computing is a computing paradigm inspired by the human brain. Just as the brain both processes and stores information, neuromorphic computers combine data storage and processing in one device, drastically reducing the energy needed for data transfer. This facilitates faster information processing and smoother handling of complex tasks like pattern recognition. It's less energy-intensive than digital systems.

Developments in neuromorphic computing are timely as modern data centres consume massive amounts of energy. Integrating neuromorphic processors in data centres could cut the energy needed for AI-processing up to 1000-fold.

SURF

SIGNALS

Potential to cut the required energy for AI-processing by 10 to 1000 times

The Netherlands bets on brain inspired computing for a greener future (computerweekly.com)

Kösters et al. (2023). **Benchmarking energy consumption and latency for neuromorphic computing in condensed matter and particle physics,** APL Machine Learning 1, pp. 16-101 (arxiv.org)

Intel builds worlds largest neuromorphic system to enable more sustainable AI (newsroom.intel.com)

Whitepaper Neuromorphic computing (2024) calls for the development of an open ecosystem and improved coordination in the Netherlands (ru.nl)

Startups commercialising neuromorphic compute

- axelera.ai
- innatera.com
- **Hoursec** (yesdelft.com)
- imchip.ai
- cimplic.com

Neuromorphic supercomputers

- spinncloud.com
- **DeepSouth** (westernsydney.edu.au)
- **Darwin Monkey** (globaltimes.cn)

IMPACT

Education

Several universities in the Netherlands are already expanding their educational programs to include neuromorphic computing and engineering and deepen the fundamental knowledge to educate the next generation of leaders. Furthermore, thanks to its energy efficiency, neuromorphic computing has the potential to make AI-based innovations, such as personalised teaching bots, locally available in the classroom.

Research

In 2024, neuromorphic supercomputers made their debut in HPC (Spinnaker 2 (Germany), Intel's Halapoint (US), DeepSouth (Australia), Darwin Monkey (China)), thus reaching over one billion artificial neurons. The ability to understand which applications benefit most from which neuromorphic hardware is still largely open, with calls for extensive benchmarking. Moreover, current neuromorphic systems operate still far above the energy efficiency of the human brain, calling for foundational discoveries to compute as efficiently and functional as the human brain.

TREND #4

Integrating photonics for accelerated information processing

Public Values

Autonomy	Independence	
Justice	Sustainibility | Equity	
Humanity	Safety | Well-being	

Maturity WATCH **PLAN** ACT

Drivers

Automation & AI; Engineering advances & computation; Energy supply & demand; clean water demand; critical infrastructure

Photonics has already played a pivotal role in the internet cables that carry data globally and serve as a fundamental technology for data transmission within data centres.

Recently, photonics has attracted significant attention for computing applications. The same principles that benefit communication – low latency, energy efficiency, and the capacity to process data on the fly – are now being explored to overcome the limitations of electronic computing (such as energy consumption, latency, and bandwidth). This will benefit applications such as in the acceleration of neural networks, data centre workloads, and edge AI.

SURF

SIGNALS

Integrated use of photonics in the data centres

Integrated photonics is gradually making its way into the realm of supercomputing (marvell.com)

Running large-scale matrix multiplication with an energy advantage of O(1000x)

In contrast to electronics, photonic systems can naturally exploit parallelism, making them well-suited for real-time processing at scale (arxiv.org)

LUMAI offers a promising advancement in AI acceleration (lumai.ai)

Photonics in the knowledge and innovation agenda for key enabling technologies

(kia-st.nl)

"The tremendous parallelism offered by photonics, with each beam in space representing individual computations, may illuminate the future of computing."

- **Patty Stabile**, TU Eindhoven

IMPACT

Education

If optical computing continues to mature as a foundational technology for data processing and communication, education will inevitably need to evolve accordingly. The traditional focus on electronic-based computation in engineering curricula will no longer suffice to prepare students for the hybrid electronic and photonic systems of the future. At institutions such as TU Eindhoven, where an elective course on optical computing has already been introduced, this evolution has commenced. While still optional, such courses represent an early integration of photonics into the broader computing curriculum.

Research

The integration of optical computing into digital infrastructure promises significant advancements in research capabilities, enhancing the quality of infrastructure, computational tools, and processing power. Optical systems might enable faster, more energy-efficient data centres and clusters, which are vital for data-intensive fields such as climate science, genomics, particle physics, and AI. A hybrid electronic-photonic approach enhances simulation performance and energy efficiency, allowing researchers to address difficult-to-tackle challenges, such as high-resolution brain simulations or chemical modelling.

Operations

Photonic integration also enhances data centre operations by promoting sustainability. Optical components consume less energy, produce less heat, and reduce cooling needs, leading to lower costs and higher workload density. In addition, the decrease in energy requirements can lead to less stress for local or regional power networks.

TREND #5

Exploring biological systems for computing

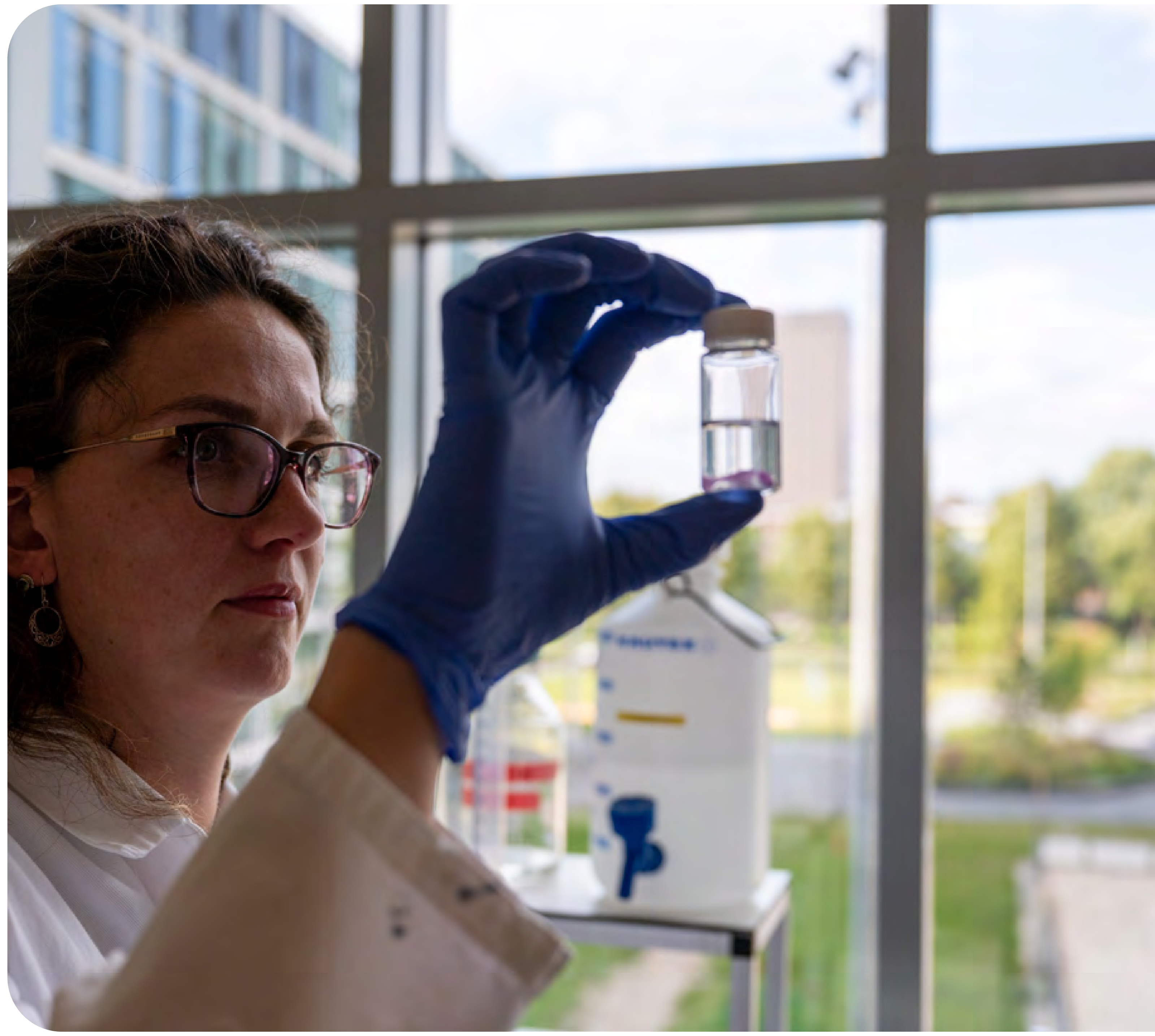
Public Values

Autonomy	Privacy
Justice	Integrity | Sustainability | Equality
Humanity	Well-being | Safety

Maturity WATCH PLAN ACT

Drivers
Engineering advances & computation; biotechnology; Automation & AI; Energy supply & demand

Living matter also performs computation. Recent years have featured a rise in the exploration of the inherent information processing capabilities of biological material as a foundation for computing systems. Biocomputing is the use of biological components, such as DNA, proteins, and cells, to perform calculations, similar to a traditional computer, but on a molecular scale. This technique offers an entirely new way of encoding and processing information, yielding some improved capabilities compared to traditional architectures, such as massive parallelism and energy efficiency. Although still an experimental field with technical challenges to be overcome (e.g., speed, scalability), research related to biocomputing is expected to continue, with this approach getting closer to real-world applications, especially in healthcare, in the next decades.



SIGNALS

Early commercialisation by companies

The company FinalSpark is offering cloud-accessible computing services using real organoids through a platform (Neuroplatform) (finalspark.com)

The start-up Cortical Labs launched a biological computer made of human brain cells (abc.net.au)

“There are promising applications of biomolecular computing in healthcare, for example; Since biomolecular computers work with molecular inputs, they could easily measure biomarker profiles and make decisions about whether there is a certain disease state or not. [...] The main bottleneck is that currently speed is very limited, even if computing operations can be massively parallelised”

- **Tom de Greef**, TU Eindhoven

R&D milestones modifying biological processes to perform computing-like routines

Synthetic biology used to build genetic circuits, equivalent to logic circuits in conventional computers (news.mit.edu)

Researchers developed a software package that facilitates the design of digital logic circuits in molecular computing (dl.acm.org)

Researchers genetically modified a strain of E. coli for computation (nature.com)

Researchers outlined a vision for biocomputers powered by human brain cells and presented a roadmap for organoid intelligence (frontiersin.org)

A biocomputing system made of living human brain cells performed speech recognition starting from audio clips (nature.com)

Researchers achieved repeated data operations (storing, retrieving, computing, erasing, and rewriting) using DNA (nature.com)

Researchers designed the first programmable DNA computer (nature.com)

IMPACT

Education

Cross-disciplinary talent skilled in both computing and biology is likely to increase in demand. This necessitates the development of new or extension of existing curricula for students in scientific disciplines benefitting from biocomputing to acquire this hybrid skillset. Computers using biological circuits may also emerge as hands-on teaching tools to illustrate the principles governing biocomputing.

Research

Once the current efficiency and scalability issues are overcome, researchers might be able to access local and/or national IT infrastructure working following the principles of biocomputing. This will be beneficial to a variety of research use cases in different scientific areas, such as drug discovery, disease diagnosis, and ecology.

Operations

The shift towards biocomputing might necessitate IT infrastructure upgrades and require (research support) organisations to re-evaluate operational processes to handle biocomputers. This requires staff skilled in working with biological systems and/or possible reliance on external parties/organisations specialised in working with biocomputers.

Connectivity

Authors
Rogier van de Wetering (Open Universiteit), **Mike Klaassen** (Breda University of Applied Sciences), **Frans Panken** (SURF), **Peter Boers** (SURF)

Introduction

In today's rapidly evolving digital world, connectivity serves as the essential foundation for innovation, productivity, and societal progress. As the demand for real-time data, low-latency services, and always-on access continues to rise, the networks that underpin our digital lives are undergoing a profound transformation. Connectivity is no longer just about being online—it is about the quality, intelligence, and sovereignty of the connections that power our homes, cities, businesses, and governments.

This chapter explores three key dimensions of the current transformation in connectivity: Access Networks, Intelligent Networks, and the growing significance of Digital Autonomy in a geopolitically fragmented world.

The journey of connectivity begins at the edge—with Access Networks. These networks form the critical "last mile" between users and the broader internet. Wireless technologies like Wi-Fi, Bluetooth, Zigbee, and cellular networks (4G, 5G) are essential enablers of modern digital environments, from smart campuses to industrial IoT deployments. When paired with global fiber infrastructure, these wireless protocols enable seamless end-to-end data pathways that are foundational for scalable and secure digital ecosystems. Harmonizing these networks on a global scale ensures not only efficiency and interoperability but also opens new possibilities for innovation and inclusivity across regions.

Beyond raw network access, connectivity is being revolutionized by intelligence. Intelligent networks are transforming how operators manage, optimize, and evolve their infrastructures. The shift from manual processes to software-driven orchestration is enabling greater automation, real-time analytics, and responsiveness to dynamic user needs. AI-powered operations (AI/Ops), digital twins for network simulation, and integration with cloud-native environments are now critical to managing the growing complexity of digital services. These intelligent networks also help address ecological challenges by embedding energy efficiency into both hardware and software, enabling sustainable scale.

Finally, the strategic importance of connectivity is rising in the realm of digital autonomy. As global tensions reshape alliances and supply chains, nations are rushing to secure control over their digital infrastructures. Investments in submarine cables, fiber, satellite systems, and alternative data routes reflect a broader desire for continuity and resilience. At the same time, Big Tech's dominance in global data flows raises complex questions around sovereignty and cybersecurity. The future of our digital connectivity landscape will be shaped by the convergence of ubiquitous access, intelligent network management, and strengthened connectivity resilience.

TREND #1

Fixed wireless access

Public Values

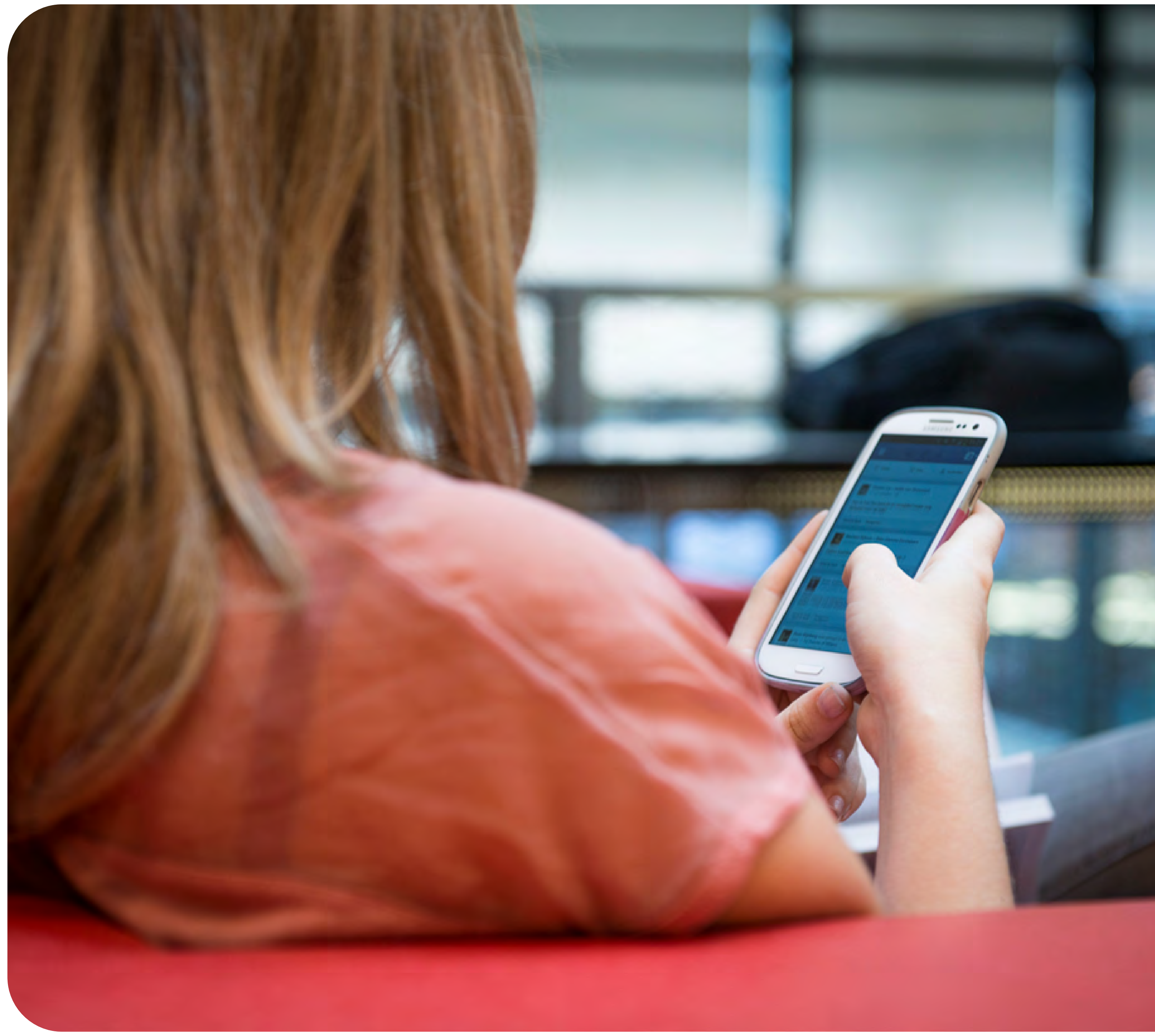
Autonomy	Freedom of choice | Independence | Privacy
Justice	Equity | Inclusion| Integrity | Sustainability
Humanity	Well-being

Maturity WATCH PLAN **ACT**

Drivers
Globalisation; Connectivity & interaction; Concentration of wealth & economic inequality

Fixed Wireless Access (FWA) is an alternative to wired access to the internet, particularly in areas where fiber or copper infrastructure is too expensive or logistically difficult to deploy. Modems and routers for FWA are commercially available in the Netherlands and some Dutch mobile operators offer an all-you-can-eat mobile subscription plan that together serves as a connection to the wired infrastructure. In addition, the recent developments in the 5G standards will enable non-terrestrial networks (comprised of various satellites) to integrate with the 5G networks on the earth surface. This will increase the support across mobile handsets and chipsets and improve performance. It may serve as an alternative to the products and services of mobile operators.

The use case for institutes of research and education includes research activities in rural areas and/or internet access for a branch office with no stringent network requirements that is in an area with no fixed network infrastructure.



SIGNALS

Ecosystem collaboration drives innovation (ericsson.com)

5G FWA and its impact on fixed broadband: the trends and strategies driving momentum (gsmaintelligence.com)

TNO - 5G-EMERGE: Satellite-enhanced media delivery at the edge (publications.tno.nl)

"FWA adoption is driven by demand for high-speed alternatives to fixed broadband and national initiatives aimed at reaching underserved areas and supporting smart city ambitions."

- **Ericsson Mobility Report**, June 2025

IMPACT

Education & Research

A 5G router could be considered that supports Wi-Fi with WPA2-enterprise (or solve this through the Wi-Fi deployment in the branch office) such that students, staff and researchers can connect to the network via eduroam as they are used to in other locations.

Operations

In the case an organisation thinks about opening a small remotely located branch office that does not require stringent network requirements (e.g. no exams) it should consider a FWA solution for connecting that office to the internet.

TREND #2

The battle for airwaves

Public Values

Autonomy	Freedom of choice | Independence
Justice	Equity | Inclusion | Sustainability
Humanity	Well-being

Maturity WATCH **PLAN** ACT

Drivers

Connectivity & interaction; Compliancy & regulation; Digital transformation; Globalisation

Frequencies for mobile communications are a limited natural resource. Harmonization of frequencies across the world realizes that network operators, equipment vendors and others leverage global economies of scale such that smartphones and laptops can connect everywhere in the world to the network in the same manner.

In 2021 the EC assigned the lower part of the 6 GHz band to Wi-Fi. As a result, we can use Wi-Fi 6e and Wi-Fi 7 in the Netherlands. The current debate is on the upper part of the 6GHz band. Some regions such as USA, Canada, Brazil, and South-Korea assigned this frequency band to indoor Wi-Fi usage and are considering outdoor usage. Other countries such as China have allocated the complete (or only the upper part of the) 6 GHz band to 5G/6G services.

Wi-Fi requires at least 320 MHz of the upper 6 GHz band for making proper design plans in the near future. The EC is currently engaged in making policy recommendations on how to best organize the future use of this band in Europe. Some countries such as France and Germany opt for assigning the upper 6 GHz band to 5G/6G.

SIGNALS

Public consultation on the draft RSPG report on 6G strategic vision (radio-spectrum-policy-group.ec.europa.eu)

Upper 6 GHz band - Overview of current and potential future use in The Netherlands (repository.tno.nl)

Wi-Fi Alliance - 6 GHz Wi-Fi®: powering sustainable connections (wi-fi.org)

RCR Wireless - Europe's 6 GHz spectrum tug-of-war (analyst angle) (rcrwireless.com)

"The EU's decision on the upper 6 GHz band will directly affect progress on the Digital Decade 2030 goals — bridging the digital divide, enabling smart cities, and ensuring Europe remains competitive in global technology leadership."

- **Adlane Fellah**, RCR Wireless

IMPACT

Education & Research

Benefits of the usage of the 6 GHz band include the enabling of faster, lower latency, and more reliable connections used by students and researchers for e.g. digital classrooms, video conferencing, and online learning.

Operations

Wi-Fi professionals require at least 320 MHz of the upper 6 GHz band to make a proper Wi-Fi design in the 6 GHz band at a medium to large building of an institution. If this capacity is not available, the risks include encountering similar problems as experienced in the past with the 2.4 GHz band, resulting in unstable connections and applications that operate sub optimally. By the end of 2025 the Ministry of Economic affairs ends their plan for and integrated vision for the upper 6 GHz band. Consider persuading them to allocate at least 320 MHz of the upper 6GHz band to Wi-Fi.

TREND #3

AI/Ops, digital twinning and the emergence of the LLM in network operations

Public Values

Autonomy	Privacy | Freedom of choice | Independence
Justice	Accountability | Inclusion | Equity | Transparency | Integrity
Humanity	Safety

Maturity WATCH **PLAN** ACT

Drivers
Automation & AI; Connectivity & interaction

Generative AI (GenAI) has become a transformative tool across many businesses including the networking sector. AI agents such as Retrieval-Augmented Generation (RAG) are being deployed to automate tasks, enhance customer interactions, and enable intuitive data exploration. Vendors are now embedding large language models (LLMs) into Network Management Systems (NMS), allowing users to manage infrastructure through natural language interactions. This has created new business opportunities for vendors, as many customers previously turned to open-source network management tools to avoid vendor lock-in —especially in wide area networks (WANs) managed by Internet Service Providers (ISPs).

Notably, all major networking vendors have introduced AI-enhanced NMS platforms. Meanwhile, the open-source community is working to close the gap, with prototypes emerging from groups like the Network Automation Forum and National Research and Education Networks (NRENs). In the Netherlands, the Future Network Services (FNS) National Growth Fund project is exploring AI/Ops and digital twin technologies to simulate network changes before deployment. However, practical digital twin implementations remain challenging yet due to limitations in replicating hardware behavior and real-world traffic loads.

AI-driven tools can boost operational efficiency, but organisations must weigh the risks of vendor lock-in versus investing in open-source skills and flexible architectures.

SIGNALS

Development of various AI assisted network management systems

Event-driven automation: reliable, simple, adaptable data center network automation (nokia.com)

HPE acquires Juniper: Leading the convergence of AI and networking (mist.com)

Top 10 AI-powered tools every network engineer should know (blog.octanetworks.com)

Digital twins and AI in networking

Intelligently orchestrating programmable 6G networks of the Dutch national growth fund initiative 6G Future Network Services (futurenetworkservices.nl)

What AI means for networking infrastructure in 2024 (forbes.com)

Toward building a digital twin for network operations and management (ieeexplore.ieee.org)

Network orchestration of advanced networks

Shifting from single domain automation to multi-domain orchestration (itential.com)

Decentralized AI-control framework for multi-party multi-network 6G deployments (wimnet.ee.columbia.edu)

“SURF’s ambition is to have an intelligent network capable of correctly assessing incidents and fixing them in real-time by using AIOPs. As a community we should collaborate and develop the algorithms we need to run the network out in the open and make sure they are accessible to all.”

– **Peter Boers**, SURF

IMPACT

Education & Research

Higher-quality network services are crucial for various types of research and education activities that rely on data access and data exchange. For example, this would be critical for online student lessons or high-throughput data exchange to execute scientific experiments or perform scientific analysis.

Operations

- AI-driven tools can improve operational efficiency, but institutions must balance the risks of vendor lock-in with investments in open-source skills and flexible architectures for long-term sustainability.
- High-quality network services require a professional incident management approach to effectively reduce the Mean Time to Acknowledge (MTTA) and the Mean Time to Repair (MTTR) following an incident. Leveraging AI in Network Management Systems (NMS) can significantly reduce MTTA and MTTR.

TREND #4

Power usage and ecological footprint

Public Values

Autonomy	Independence
Justice	Sustainability | Accountability | Transparency | Equity
Humanity	Well-being

Maturity WATCH **PLAN** ACT

Drivers

Energy supply & demand; Connectivity & interaction; Clean water demand; Biodiversity

The energy transition has increased scrutiny on the energy efficiency of digital infrastructures. Rising energy costs and limited power grid capacity have put pressure on data centers and network operators to reduce power and cooling demands. Simultaneously, as Moore's Law slows, chip miniaturization faces physical limits, making efficiency gains from smaller nodes (e.g. 5nm to 3nm) increasingly marginal. With bandwidth demand growing at 25% annually, future performance improvements will depend on higher power input, intensifying thermal management challenges.

To address the need for energy-efficient operations, adaptive energy-saving strategies are being explored. Such strategies include approaches such as router tuning and powering down unused systems supported by standards like Energy-Efficient Ethernet and green computing practices. As traffic patterns are predictable, automated energy optimization could yield major savings.

In the Netherlands and beyond, rising power and cooling costs are prompting institutions to consider energy-efficient hardware for long-term investments. Devices with built-in power-saving capabilities could offer lower total cost of ownership over their 5–10-year lifecycle, aligning performance needs with sustainability goals.

SIGNALS

Energy saving in hardware

Saving energy on Juniper's PTX routers with PFE (packet forwarding engine) power off (community.juniper.net)

Nokia and Orange announce extreme deep-sleep energy-power-saving mode at Mobile World Congress 2024 (telecomtv.com)

Standards & green computing

What is energy efficient internet? (fs.com)

From awareness to action: Evaluating green computing engagement among IT professionals for effective policy design (journalwjarr.com)

"We have long advocated the need for ecosystem cooperation if we are to reduce our industry's environmental footprint and make our networks as energy efficient as possible."

- **Arnaud Vamparys**, CTIO, Orange Europe

IMPACT

Education

- Education programmes should be aware of the sustainability implications of data centres and large-scale data network services regarding power consumption and cooling demands.
- Prepare students for careers in green tech, smart cities, and general awareness of good sustainable computing practices.
- Integrate energy efficiency topics into network engineering, IT management, and sustainability courses.

Research

- Research groups should be aware of the sustainability implications of data centres and large-scale data network services regarding power consumption and cooling demands.
- Sustainability-oriented innovation will drive further research in low-power hardware, software-defined networking (SDN), and AI for energy optimisation.
- Actively seek out funding opportunities for grants that are aligned with climate action and sustainable development goals.

Operations

- Institutions should include sustainability parameters, like power consumption and cooling requirements, in their procurement and operations policies, alongside hardware performance needs and total cost of ownership.
- Consider the significant bandwidth growth that is expected over the next decade when making network design choices regarding service and hardware requirements.

TREND #5

Fibre optic net-works: strategic infrastructure for the knowledge economy

Public Values

Autonomy	Privacy | Independence
Justice	Integrity | Transparency | Accountability | Sustainability
Humanity	Safety | Well-being

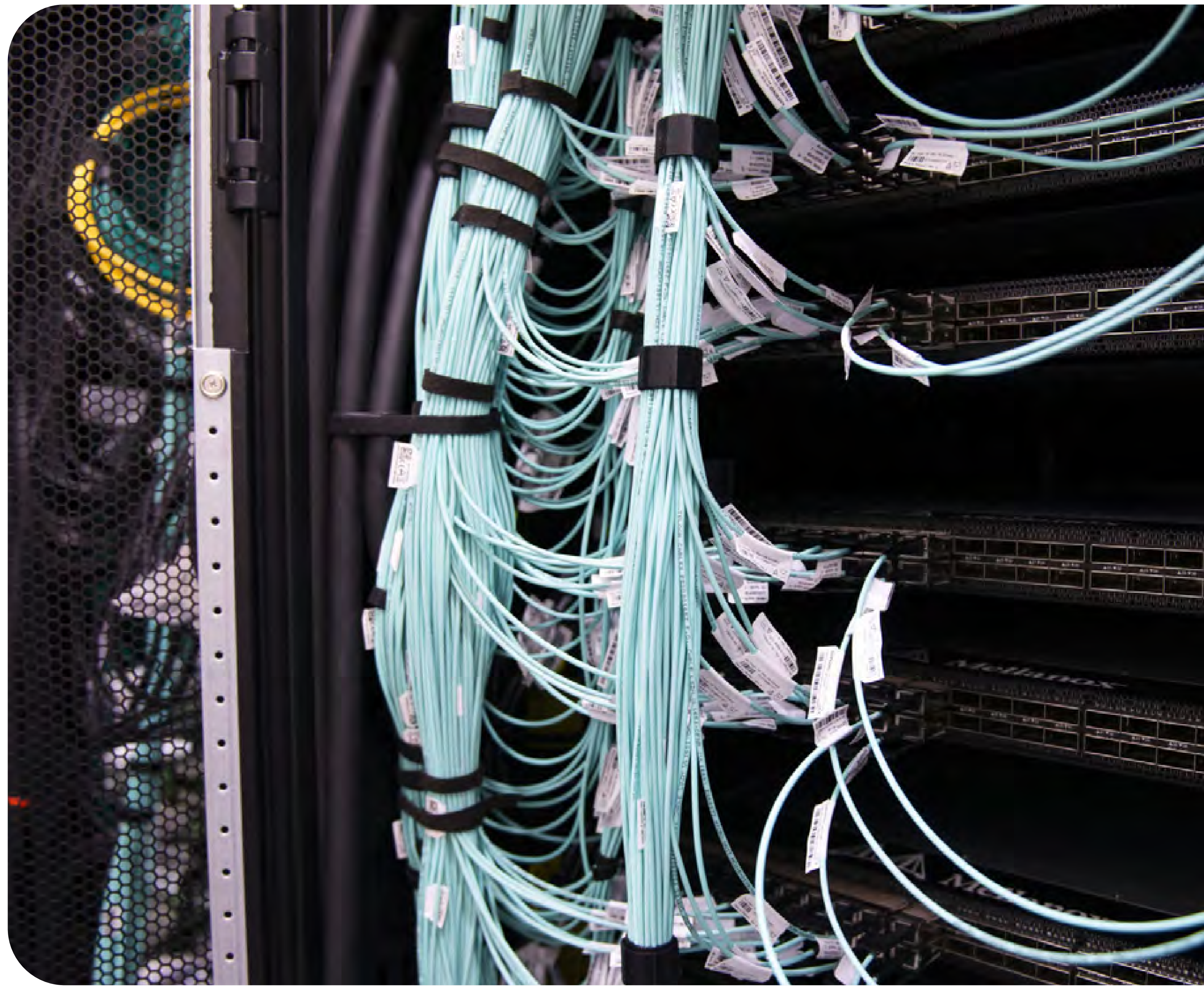
Maturity WATCH PLAN ACT

Drivers
Globalisation; Connectivity & interaction; Geopolitics & (digital) sovereignty; Critical infrastructure

Intercontinental fiber-optic networks serve as the foundation of today's global digital infrastructure, delivering high-speed, low-latency connectivity vital for economic growth and national security. Countries are rapidly expanding their fiber deployments to improve digital performance and reduce dependence on foreign-controlled infrastructure.

In addition to their traditional role, fiber networks are becoming strategic assets through the advent of fiber sensing technology. This innovation allows fiber-optic cables to detect seismic activity, monitor ocean conditions, and identify physical disturbances—enhancing both infrastructure security and environmental monitoring.

However, this also raises concerns about data privacy and unauthorized access. On a geopolitical level, there is increasing urgency to diversify global data routes, as a large portion of traffic still transits through vulnerable chokepoints like the Suez Canal. In response, nations and corporations are exploring alternative subsea paths, including routes through the arctic, made feasible by melting ice. These routes offer improved redundancy and lower latency between continents but introduce new strategic tensions. As fiber networks evolve into tools of geopolitical leverage, ensuring their resilience, sovereignty, and data protection becomes critical.



SIGNALS

Developments in fibre cable technology

NEC and NTT successfully conduct first-of-its-kind long-distance transmission experiment over 7,000km using 12-core optical fiber (subtelforum.com)

Distributed acoustic sensing in submarine optical fibers (spiedigitallibrary.org)

Nationalisation of commercial fibre infrastructure

‘Strategic’ submarine telecom cable manufacturer ASN nationalised by France (lemonde.fr)

Arctic fibre infrastructure

Built-in resilience for arctic subsea cables (nordu.net)

Arctic Fibre is a three-phase submarine cable project, planned to connect Asia, Canada and Europe through the arctic ocean (submarinenetworks.com)

Global interest in undersea cables

The geopolitics of undersea cables: underappreciated and under threat (tatic1.squarespace.com)

Whitepaper: The new geopolitics of undersea cables (hinrichfoundation.com)

IMPACT

Education

- Geopolitical tensions surrounding undersea cables could disrupt digital access services, impacting online learning and cloud-based education tools.
- Regions with weak cable infrastructure or limited alternative routes are most affected, widening the digital divide between well-connected and under-connected institutions and learners.

Research

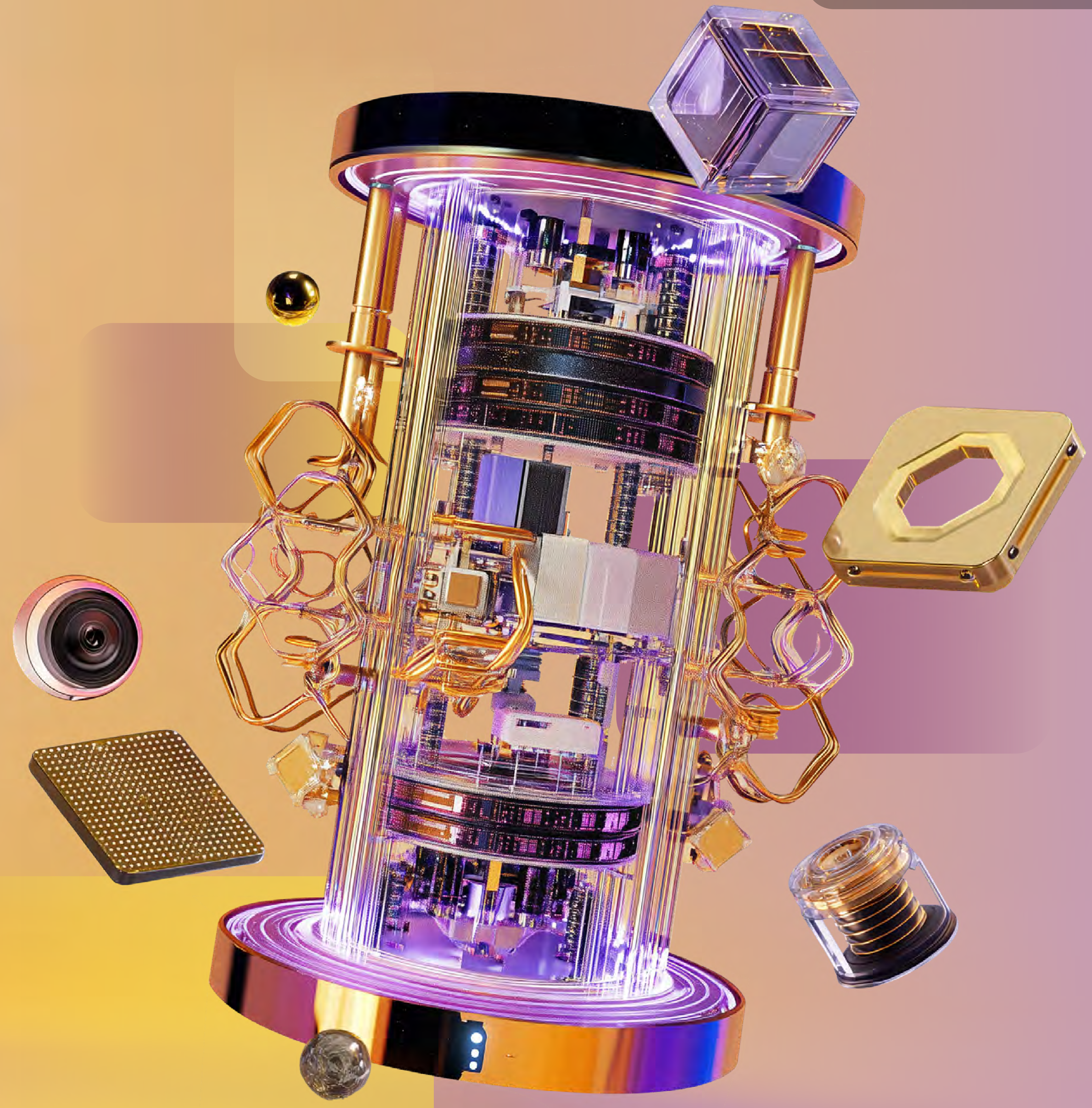
As data flows through politically sensitive regions, there is a heightened risk of surveillance, data interception and sabotage, which can impact how researchers collaborate and share sensitive information internationally.

Operations

- Investment required in redundant connectivity, local cloud services, and stronger cybersecurity to maintain operational continuity amid potential cable disruptions or surveillance risks.
- Transferring sensitive academic and student data through geopolitically sensitive routes raises the need for compliance with data protection laws, increasing legal and technical workloads.
- Current geopolitical dynamics encourage institutions to align with national priorities and enhance digital sovereignty by reducing dependence on foreign infrastructure and supporting local innovation.
- Well-connected institutions provide room for collaboration and access to knowledge, so informed value-based decision-making for investments in critical digital infrastructures remains essential at all levels.

More info about Connectivity? Visit surf.nl

Quantum Technologies



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Introduction

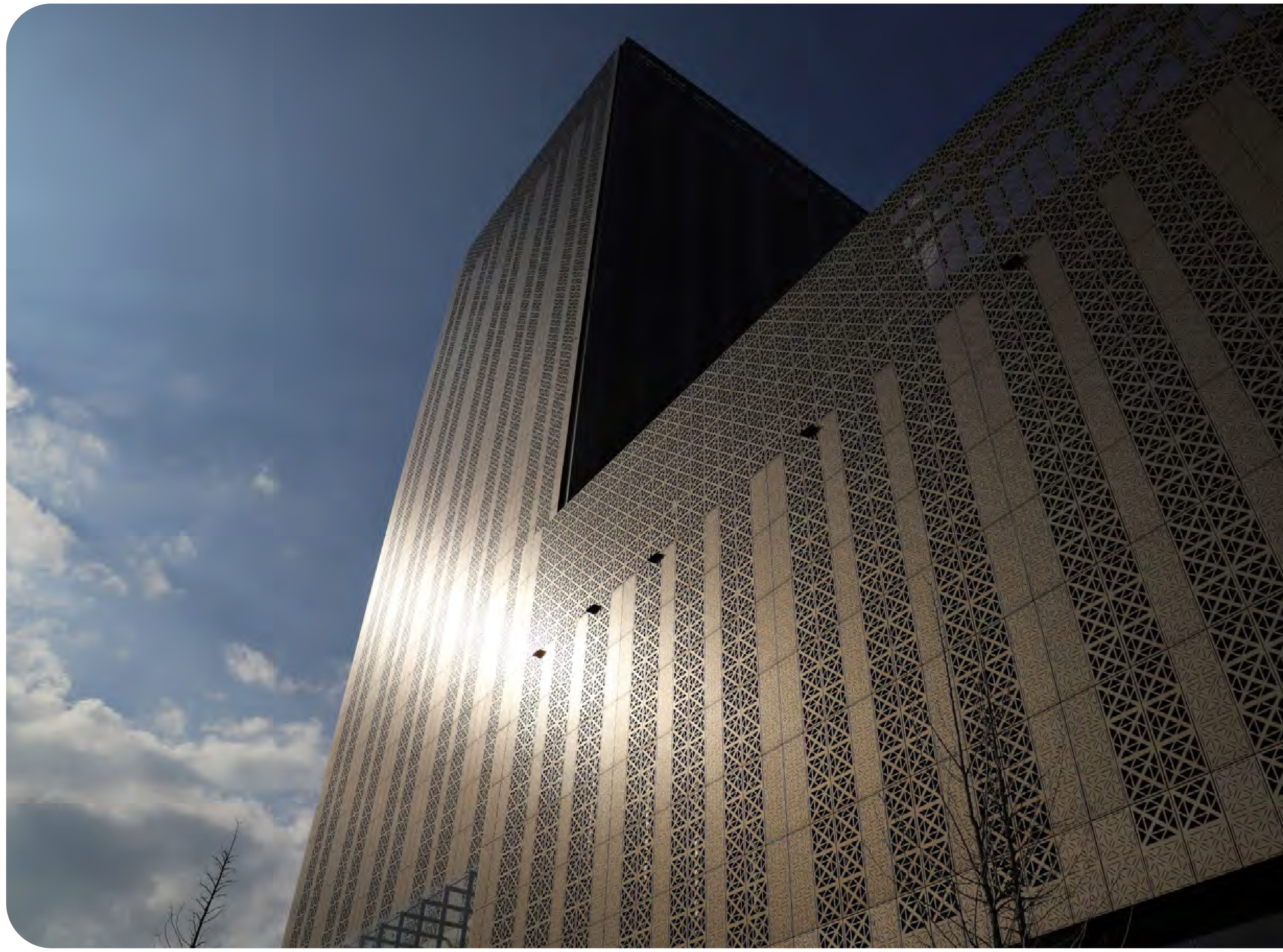
Quantum technology harnesses the principles of quantum mechanics. Quantum technology promises to revolutionise fields like materials science, medicine, and AI by enabling new simulations, order of magnitudes faster data processing, and enhanced security through quantum networking and quantum sensing.

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.

SIGNALS

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

IMPACT

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

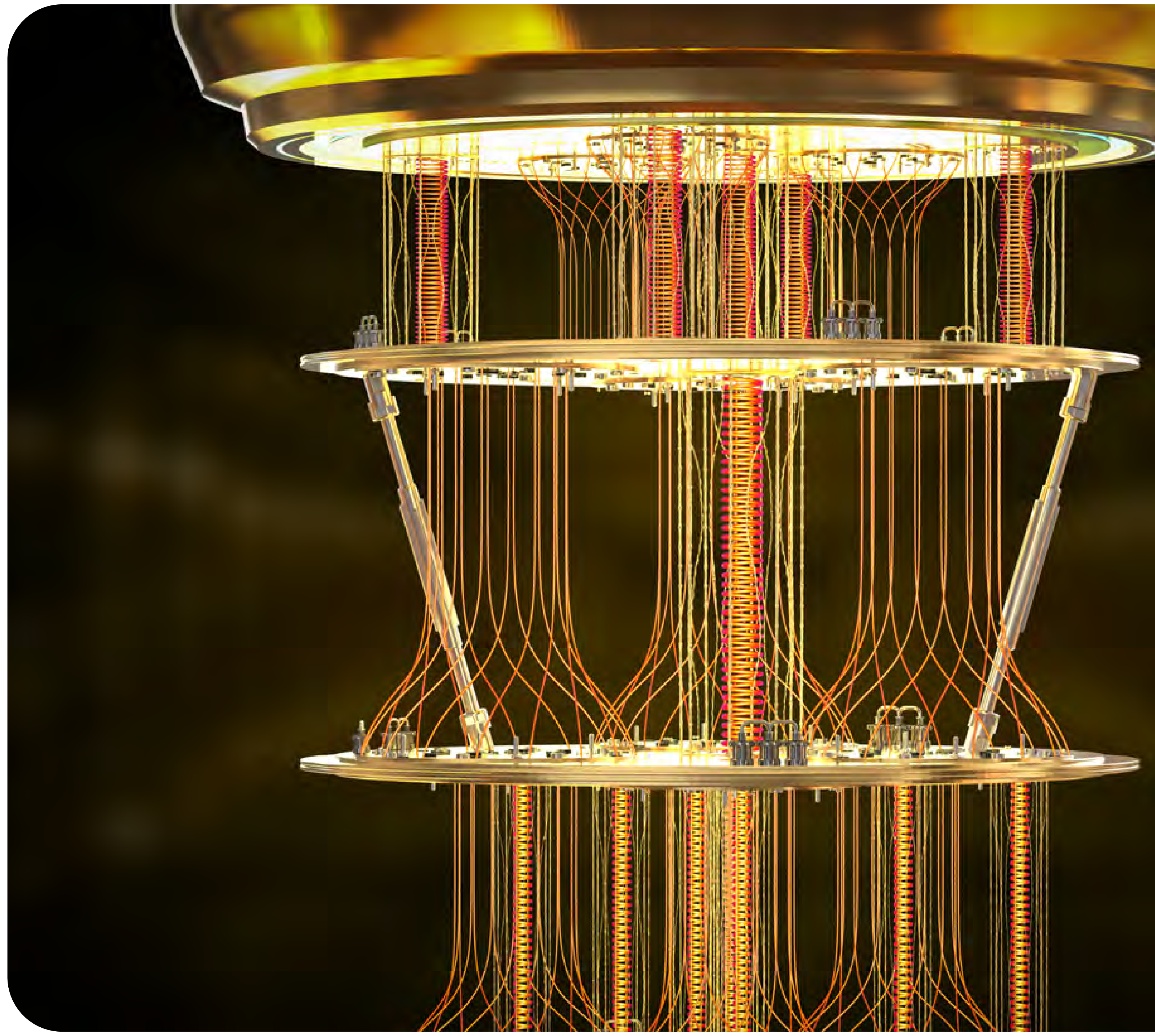
Drivers
Engineering advances & computation; Critical infrastructure

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.



SURF

SIGNALS

Roadmaps to reach FTQC

IBM roadmap (ibm.com)

Google roadmap (quantumai.google)

Alice & Bob roadmap (quantumcomputingreport.com)

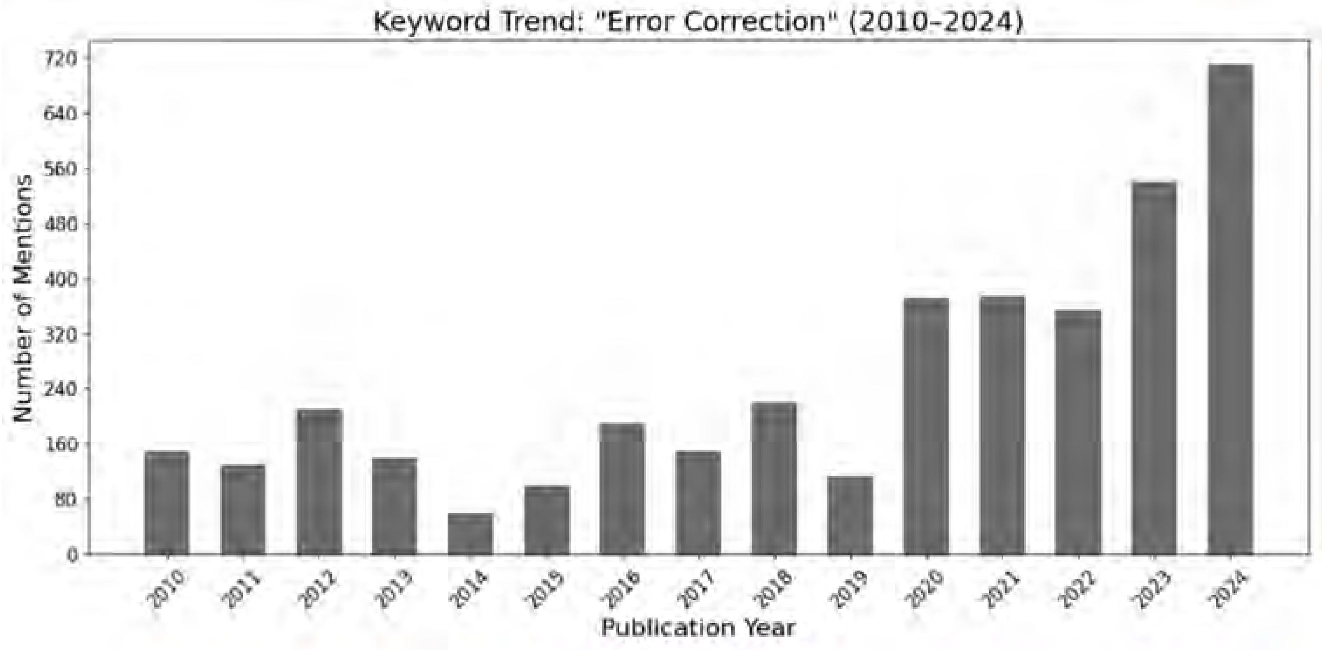
Quera roadmap (quera.com)

Quantinuum roadmap (quantinuum.com)

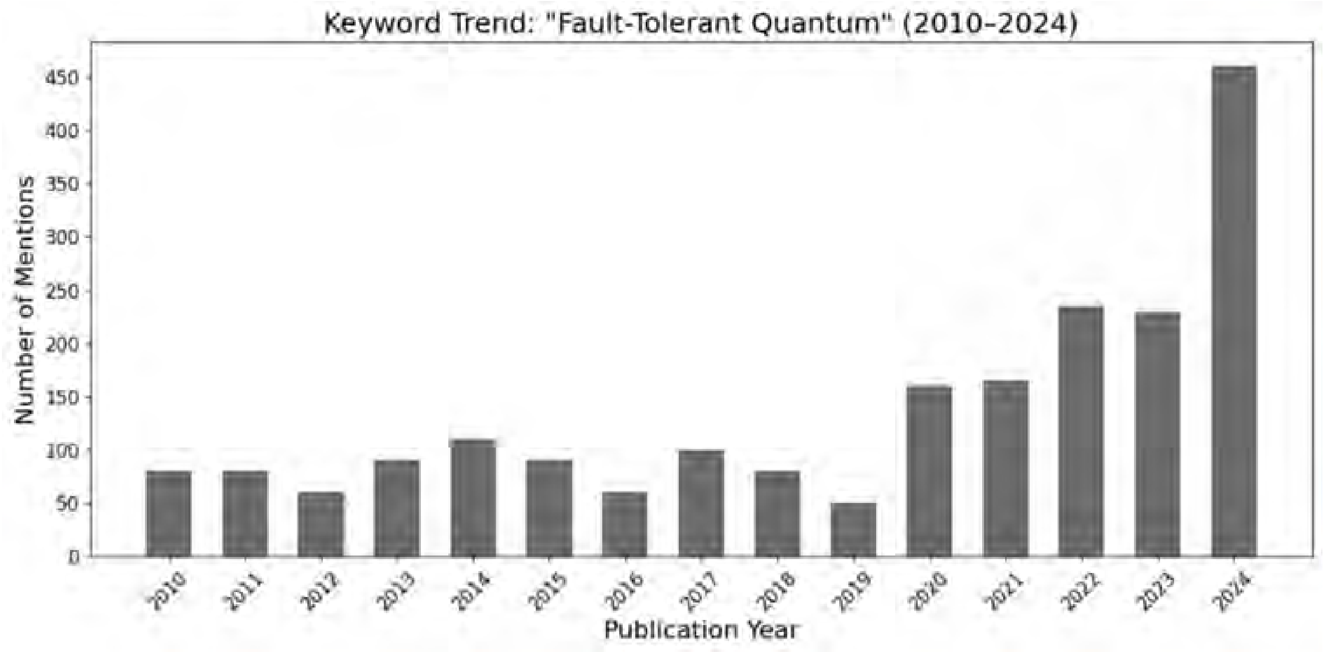
"FTQC is no longer a distant goal, it's on a defined trajectory. To fully realise its impact, we must pair this momentum with optimised algorithms, meaningful use cases, and realistic resource estimates."

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

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)

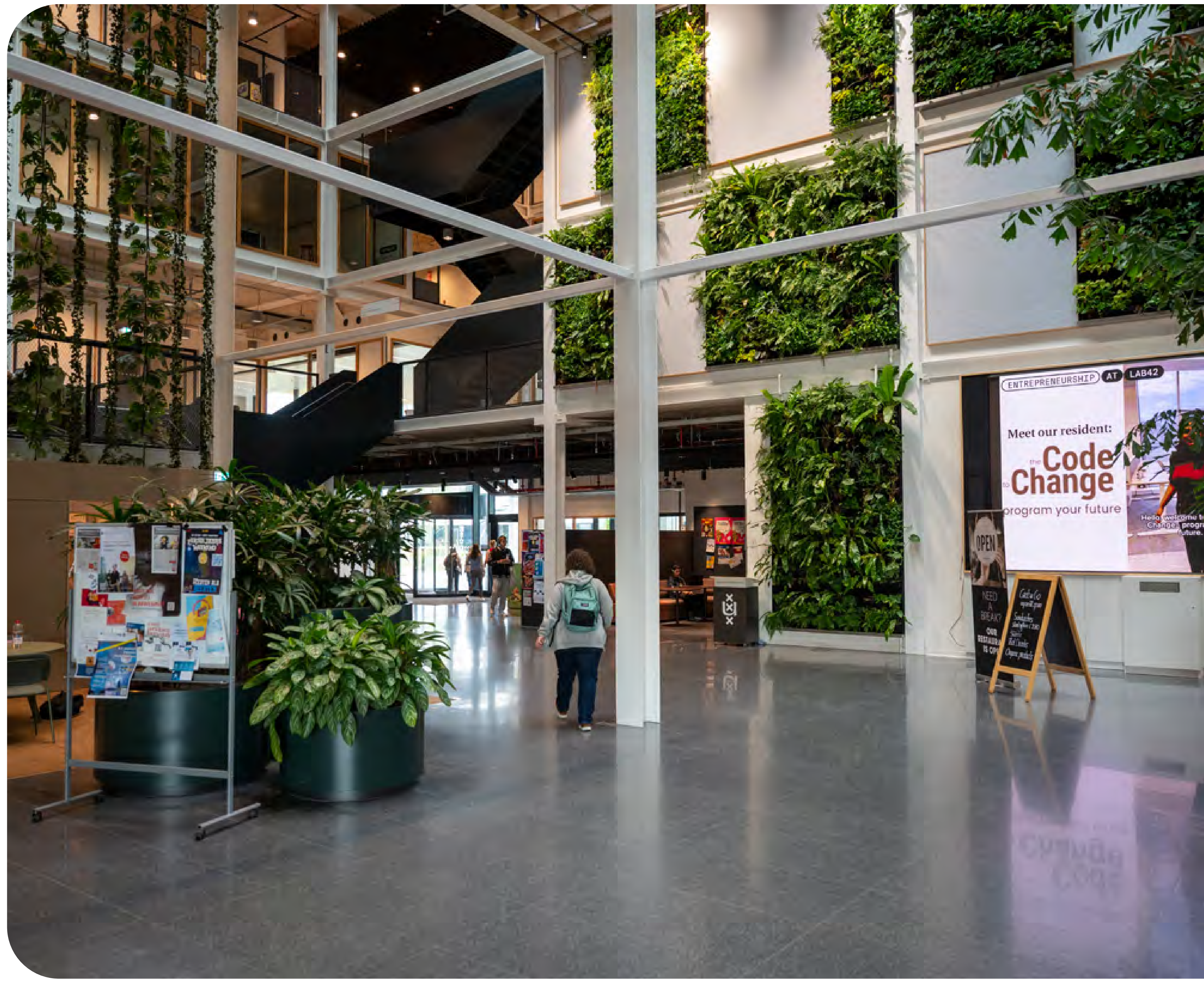
IMPACT

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

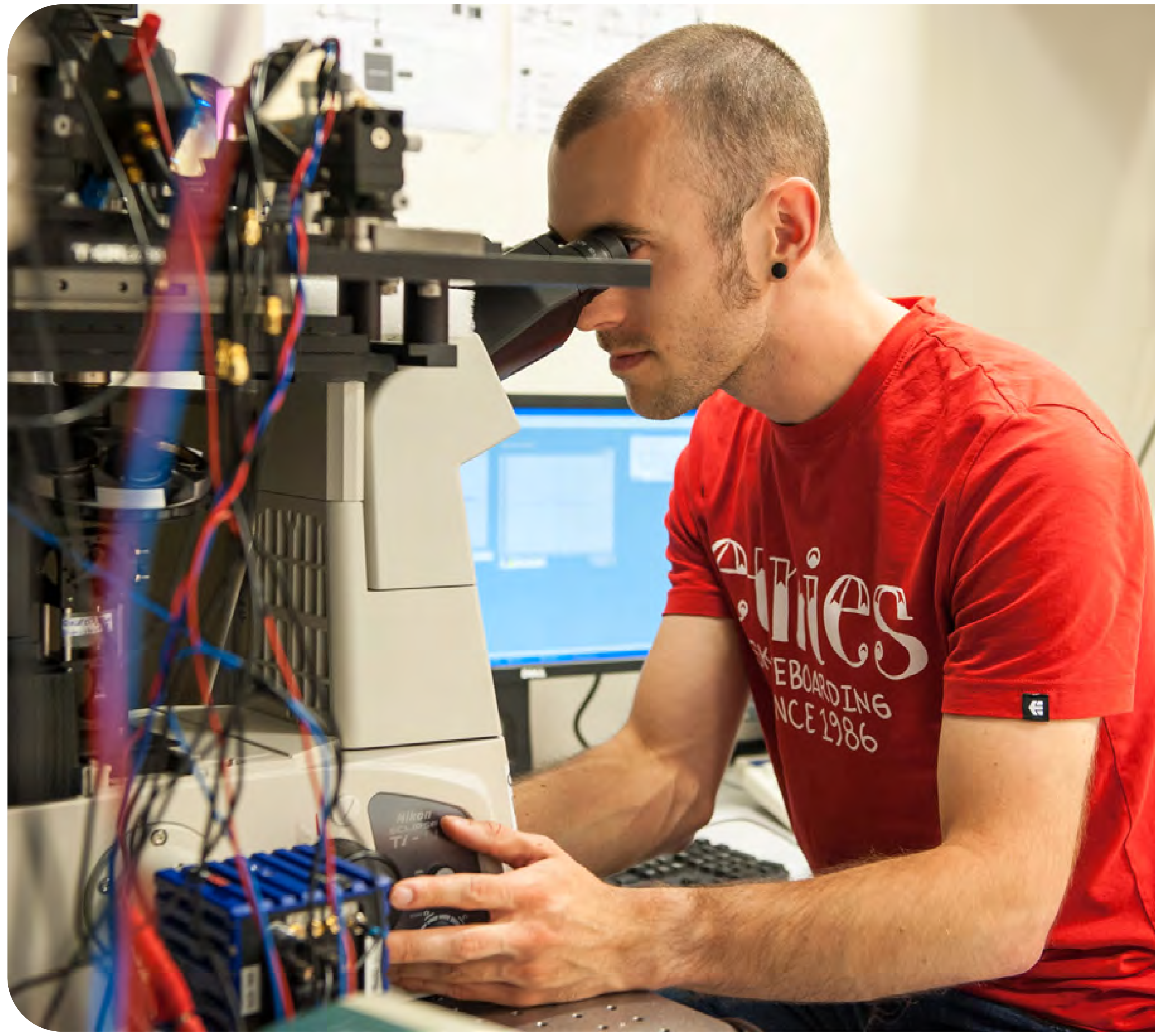
Autonomy	Pluralism
Justice	Equity | Integrity | Accessibility
Humanity	

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.

SIGNALS

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)

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, oxford ionics, Universal Quantum
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

IMPACT

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.

SURF

SIGNALS

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)

IMPACT

Education

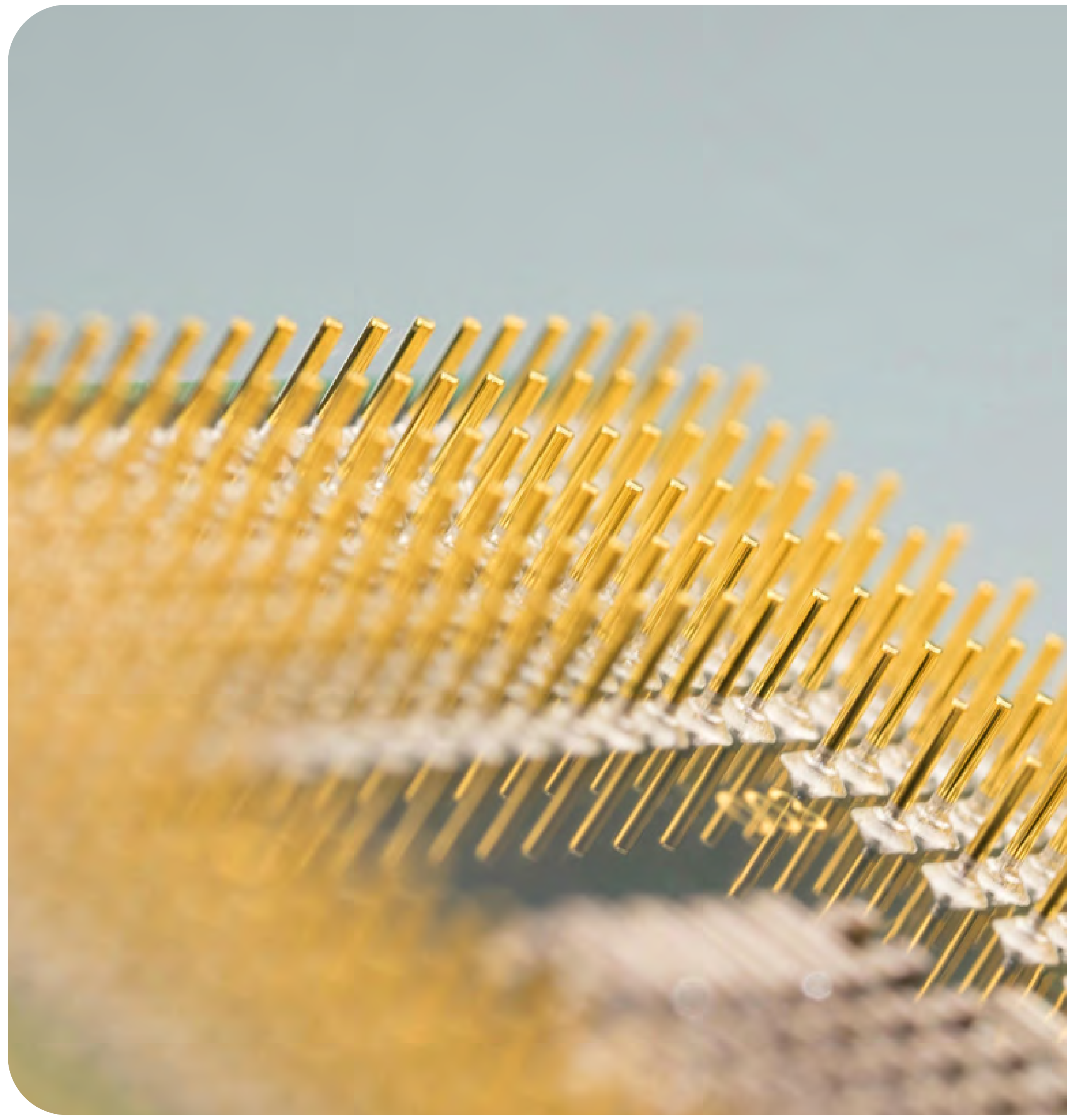
A workforce with more specific skills sets and interdisciplinary knowledge is required.

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**

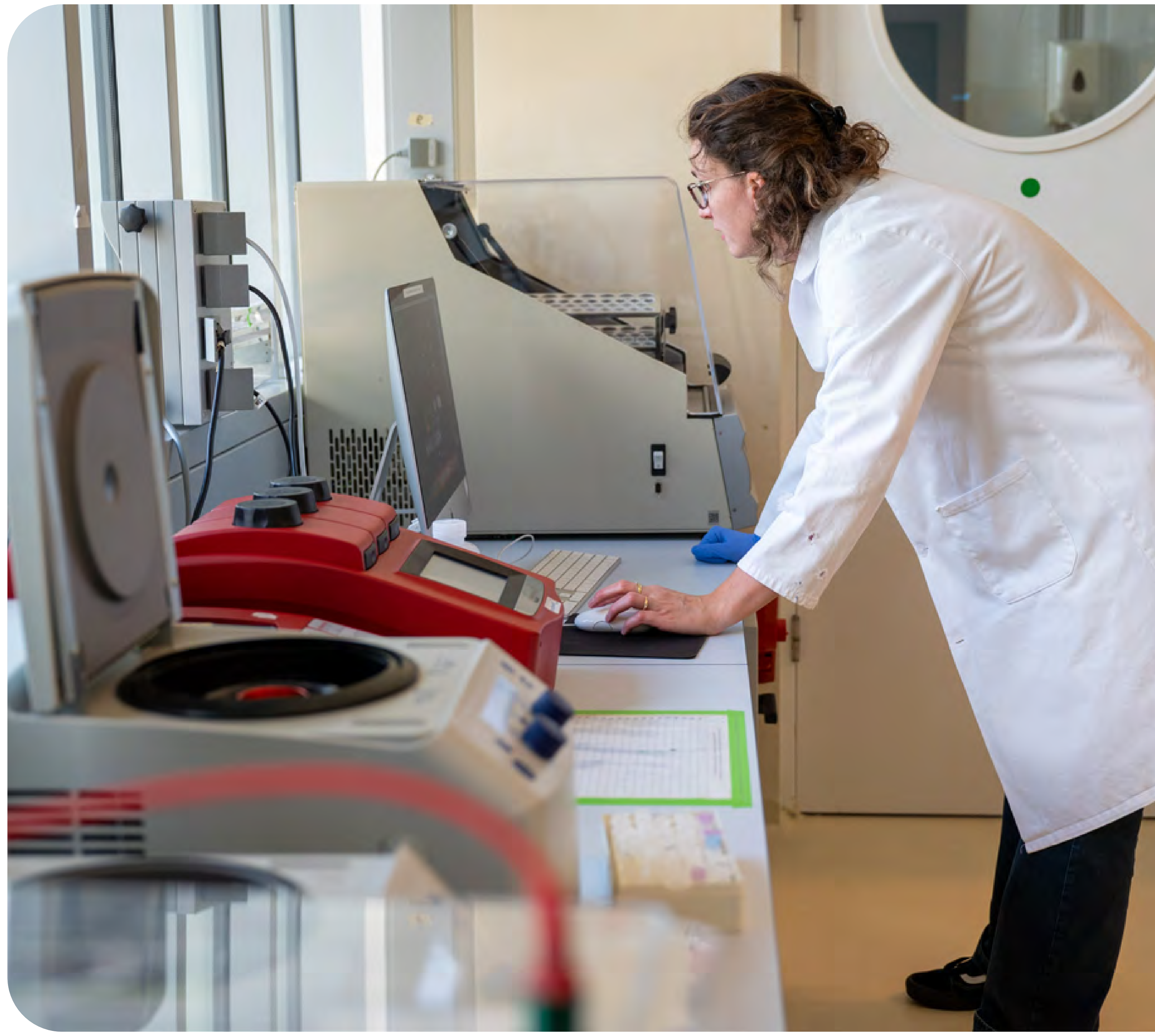
Drivers

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.



SIGNALS

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)

IMPACT

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

Wildcards

Introduction

Building upon the previous thematic chapters, this wildcard chapter offers a broader perspective by sharing a variety of emerging and potentially disruptive trends (the wildcards) to inspire the SURF cooperative.

Our society is built upon an important starting point – the human. With advancements in quantum, connectivity, and AI technologies, it's imperative to reflect on how these and other technologies will affect us as individuals. A society without healthy individuals – both physically and mentally – is one destined to underperform and feel less well connected to society and each other. Over the past 100 years, antibiotics, robotic surgery, and diagnosis technologies (such as MRI or CT scanners) have enhanced our ability to treat a multitude of physical conditions.

This trend of innovation in human healthcare continues unabated.

According to a recent study, almost 800,000 people in the Netherlands have had either a replacement hip or knee joint. Smart implant technologies will augment future hip or knee joint replacement performance, longevity, and the quality of mobility for individuals.

Technologies facilitate new experiences, and brain-computer interfaces (BCIs) – which consist of sensors to measure brain waves – will help people to interact with technologies whether to relax or in healthcare settings. Exoskeletons controlled by BCIs have been piloted, and look set to change the mobility possibilities for those with spinal cord injuries.

Smart implants and BCIs for exoskeletons focus on the physical health of the individual, but it's also imperative to consider well-being in this age of new technologies. BCIs can control technologies to enhance mobility, but they can also help those with locked-in syndrome to communicate with the world around them. Yet, as we immerse ourselves ever more in such cyber-physical technologies and the online world it's imperative that protocols are in place to promote and support proper digital well-being. The individual needs both a healthy body and a healthy mind.

In a world designed for and by humans, it's not surprising that humanity would create robotic technologies in their own image. Humanoid robots – robots that look like humans in shape and form – will be used in industrial production and work in environments too harsh for the fragile human body. Mass deployment in society is some time away, but the humanoids are coming.

For such human-focused technologies to develop and emerge in the European context, advancements in computing platforms are required. With the geopolitical landscapes constantly evolving, Europe needs chip competitiveness right at the doorstep of technological progress. Without reliable and advanced computing chips, our ability to enhance society for humanity including nature will stall.

TREND #1

Advances in brain-controlled technologies

Public Values

Autonomy	Privacy	
Justice	Accountability | Transparency | Integrity	
Humanity	Safety | Well-being	

Maturity WATCH PLAN ACT

Drivers

Compliance and Regulation; Mental health and well-being; Individualisation and Empowerment; Automation and AI; Biotechnology; Cybersecurity and trust; Digital Transformation

Controlling actions or technologies through a digital interface using thoughts has been explored for decades. As of now, these brain-computer interfaces (BCI) are expected to gradually enter the market.

Non-invasive BCIs detect brain activities via electroencephalography (EEG) sensors placed on the cranial surface, making them cost-effective and wearable. In contrast, invasive BCIs require sensor implantation on or near brain tissue and mainly serve medical purposes.

Companies in the US and China are at the forefront of market development, with applications in healthcare, entertainment, and military sectors.

Technological advancements, such as improved signal processing and multi-sensor integration, could further enhance BCI capabilities.

Societal discussions about the BCIs must be comprehensive, considering ethical concerns like privacy, autonomy, and equality.

Authors

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SURF

SIGNALS

Brain-computer interfaces further explained

The history, current state and future possibilities of the non-invasive brain computer interfaces (sciencedirect.com)

From vision to reality promises and risks of brain-computer interfaces (consilium.europa.eu)

The future of BCI: breakthroughs, education and challenges (ru.nl)

Companies and market developments

Top 10 global brain-computer interface companies in 2025 (alltechmagazine.com)

Brain-computer interface gains traction in China (chinadaily.com.cn)

Application areas and developments

Introducing brain-computer interfaces for education and research: reimagine the human-computer interactions, for better or for worse (surf.nl)

Invasive brain computer interface for motor restoration in spinal cord injury: a systematic review (sciencedirect.com)

Passive brain-computer interfaces for enhanced human-robot interaction (frontiersin.org)

A fully implanted brain computer interface for an individual with locked-in syndrome (uu.nl)

Societal and ethical aspects

The protection of mental privacy in neuroscience: societal, legal and ethical challenges (europarl.europa.eu)

Decentralising the self – ethical considerations in utilizing decentralised web technology for direct brain interfaces (link.springer.com)

Ethical considerations for the use of brain–computer interfaces for cognitive enhancement (journals.plos.org)

"Understanding the functioning and limits of BCI is required to responsibly and fruitfully harness its power."

- **Prof.dr. Anne-Marie Brouwer**, TNO Human Performance and Radboud University, Donders Institute for Brain, Cognition and Behaviour

IMPACT

Education

- The fundamentals and implications of BCIs are relevant topics to incorporate in curricula on neuro and cognitive sciences, medical sciences and healthcare, engineering and digitalisation, sociology, and ethics.
- BCIs could also be used in education programmes for learning (experiments), although capital investment may be needed for certain versions of the technology.

Research

- Brain research topics related to neurotechnologies and neurodata, experimental applications, and the societal implications, including ethical and legal aspects are natural research topics of study.
- Expected advancements in BCIs will lead to increased deployment as a research tool in the future for research activities. For instance, a researcher may use non-invasive BCI technologies for measurement and validation. Of course, such activities would be subject to ethical approval.

Operations

- BCIs and other neurotechnologies are developing fast and as they do so, they raise several pertinent societal and ethical questions.
- Institutes will need to reflect on the institutional policies and guidelines for the use of these technologies, and how neurodata can be used for education and research.

TREND #2

Cyber-physical technology calls for resilient minds

Public Values

Autonomy	Privacy
Justice	Accountability | Transparency
Humanity	Safety | Well-being

Maturity WATCH **PLAN** ACT

Drivers

Individualism and Empowerment; Mental health and Well-being; Community Dynamics and Social Cohesion; Automation and AI; Connectivity and Interaction; Cybersecurity and Trust; Ideologic Polarisation; Compliance and Regulation; Digital Transformation

Ongoing digital transformation requires an unprecedented level of cognitive adaptation from both individuals and society.

The convergence of profoundly intrusive cyber-physical technologies such as Brain-Computer Interfaces (BCI), Artificial Intelligence, and Extended Reality can and will continue to affect our mental and physical well-being. Their emergence is raising concerns over their pervasive influence, particularly in the context of applications with social media.

This new reality is motivating the need for urgent intervention measures such as digital detoxes, ethical design principles, governmental regulation and approaches for managing digital overload, all centred on protecting privacy and the psychological health of individuals and society.

By addressing mental health challenges and countering a growing appetite for our intimate data, these measures will help promote responsible, human-centred technology that preserves human values.

Ultimately, they aim to ensure technology supports – rather than undermines – our well-being and sense of self.

Authors

Mark Cole (SURF), **Alina Kadlubsky** (Open XR Europe), **Erik Knol** (Regieorgaan SIA), **Tijmen Leurs** (MBO Digitaal)

SIGNALS

Impact of digital technologies on well-being

The impact of digital technologies on well-being: main insights from the literature (oecd.org)

Well-being and brain-computer interface in use case (researchgate.net)

Digital transformation in education

Unpacking the impact of digital technologies in education: literature review and assessment framework (publications.jrc.ec.europa.eu)

AI report by the European Digital Education Hub's Squad on artificial intelligence in education (op.europa.eu)

A comprehensive review of key cyber-physical systems, and assessment of their education challenges (ieeexplore.ieee.org)

Human-centred design of digital technologies and applications

Understanding human-centred AI: a review of its defining elements and a research agenda (tandfonline.com)

Embedding human values in the design of mixed-reality technologies (ieeexplore.ieee.org)

Responsible development and uptake of XR technologies by European project XR4 HUMAN (xr4human.eu)

Report on Virtual World trends and benchmarking by European project OpenVerse which has the vision to create inclusive, open, and ethically responsible European Virtual Worlds (open-verse.eu)

IMPACT

Education

Cyber-physical technologies have the potential to transform education by enabling immersive, personalised learning experiences. Although they can improve engagement, accessibility, understanding and knowledge acquisition, they also raise novel emerging privacy and security concerns. Ensuring ethical use is essential towards harnessing their benefits, while protecting students/ trainers' rights and well-being.

Research

- BCI and other cyber-physical technologies can revolutionise research by enabling immersive data collection and new avenues for exploring the brain and human behaviour.
- Despite the enormous potential for innovative study possibilities in research, cyber-physical technologies bring with them a need for stronger cybersecurity, ethical guidelines, and advancements in our understanding of human rights.
- Future research should be driven by an interdisciplinary focus for securing these technologies and addressing privacy concerns.

Operations

- Future campus environments can be transformed by enabling immersive learning, virtual labs, and enhanced accessibility.
- The cyber-physical transformation will give rise to privacy, ethical, and security challenges for institutions, thus requiring new policies.
To maximise the benefits for the wider community, campuses must develop safeguards, ensuring safe, equitable, and ethical integration of these technologies.

TREND #3

Rise of the Humanoids

Public Values

Autonomy	Freedom of Choice | Independence
Justice	Accountability | Transparency | Integrity | Equity
Humanity	Safety | Respect | Meaningful Contact | Well-being

Maturity WATCH PLAN ACT

Drivers

Demographic shift (ageing); Mental health & well-being Automation & AI; Connectivity & interaction; Service-oriented & value-based economies; Compliance & regulation

Humanoid robots, built to resemble humans in appearance and movement, are helping to boost productivity and address labour shortages in various industries. They are highly flexible, capable of navigating complex environments, and adept at handling objects of different shapes and weights. Their human-like appearance can also make them more readily accepted in places such as hospitals, care homes, and schools.

Since the 1980s, advancements in artificial intelligence and robotics have dramatically improved their capabilities, prompting major investments from companies like Tesla, Boston Dynamics and UBTech, amongst others.

However, challenges such as high investment costs, energy efficiency, operational safety, and sophisticated software still limit their widespread use. Despite these obstacles, humanoid robots are increasingly considered for tasks that minimise risks to humans or fill workforce gaps.

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Contributors

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SURF

SIGNALS

Market developments related to humanoid robotics

Position paper of International Federation of Robotics: Humanoid robots - vision and reality (ifr.org)

Future of robotics 2035: insights from industry experts (hexagon.com)

Humanoid robots - Game changer or hype? (ipa.fraunhofer.de)

"A humanoid only becomes interesting when its form factor truly matters, for example, in (social) interaction or when their task generalisation is sufficient for them to function in the everyday human world. After all, the human world is tailored to the human form factor."

- **Dr ir Mark Vlutters**, Assistant Professor, Biomechatronics and Rehabilitation Technology, University of Twente

Reflections on technologies, innovation, and trends regarding humanoid robots

Humanoid robots like Tesla Optimus and the future of supply chains: enhancing efficiency, sustainability, and workforce dynamics (mdpi.com)

Reality is ruining the humanoid robot hype: the obstacles to scaling up humanoids that nobody is talking about (spectrum.ieee.org)

Between fascination and discomfort: the new generation of humanoid robots (ndion.de)

Do people really want humanoid robots in their homes? (spectrum.ieee.org)

Societal reflections

AI robots and humanoid AI: review, perspectives and direction (ui.adsabs.harvard.edu)

Artefacts of change: the disruptive nature of humanoid robots beyond classificatory concerns (link.springer.com)

The Robot Rights and Responsibilities scale: development and validation of a metric for understanding perceptions of robots' rights and responsibilities (tandfonline.com)

IMPACT

Education

- Across vocational, undergraduate, and graduate levels, robotics education may need to shift from siloed tracks (e.g. technology, psychology, or economy) and adopt a more inherently interdisciplinary approach. This would not just produce technical specialists, but adaptable innovators equipped to drive progress and implementation across fields for real-world applications.
- Humanoid robots themselves may eventually contribute to education, offering new forms of support for both teaching and learning.

Research

- Humanoid robotics interconnects a wide range of research domains, and as humanoids enter workplaces, research must move beyond technologies and cost savings to broader use cases: sustaining productivity, enabling collaboration, and rethinking processes and (organisational) systems.
- Research on humanoids should address not just what humanoids can do, but how they can be accepted, usable, and valuable. Humanoids are a testbed for how we connect technology, people, and society, and how we can shape the future of work, learning, and innovation.

Operations

- Institutions can support human-centred development and carefully consider the adoption of humanoid robots through collaborations with tech developers, use case organisations, and other stakeholders.
- Institutions might start to consider how they participate in the evolution of and the future of humanoid robots in the workplace, education and society as a whole.

TREND #4

Smart regenerative implants in trauma care

Public Values

Autonomy	Freedom of choice | Privacy
Justice	Transparency | Accountability | Equity | Inclusion | Integrity
Humanity	Personal development | Meaningful contact | Safety | Well-being | Respect

Maturity WATCH PLAN ACT

Drivers

Demographic Shift: Ageing; Biotechnology; Engineering Advances & Computation; Connectivity and Interaction; Automation and AI; Well-being

Trauma patients require extensive treatments and the greatest attention, with about 80,000 cases annually in the Netherlands.

For example, when a trauma patient arrives at a hospital with multiple bone fractures, ruptured blood vessels, and damaged organs, they will require multiple surgeries for internal injuries and immobilisation of broken bones with a cast or brace.

So-called smart implants are now being developed that can stimulate bone growth, help regenerate tissue, and monitor patient healing in real time. Monitoring devices can be powered by blood flow, muscle movement, or even breathing.

In addition, smart implants to restore and support skeletal and muscular tissue can be made from biodegradable materials, which are then naturally excreted by a patient; thus eliminating the need for further invasive surgery to remove the implants.

Authors
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SIGNALS

Smart implant research

Materials scientists, cell biologists, tissue engineers and medical scientists work together on the regeneration of tissue and organ function with intelligent, lifelike materials. (tue.nl)

Geometry-mediated bone formation. Geometry-driven osteo induction is enabled by high speed, high precision additive manufacturing (tue.nl)

Smart implants in healthcare to treat diseases, monitor patient recovery, and restore organ functionality are being developed by a host of organisations around the world (sciencedirect.com)

Beyond Tissue replacement: The Emerging role of smart implants in healthcare (research.umcutrecht.nl)

Biomechanics and regenerative medicine requires an interdisciplinary approach

Project Brave is seeking to develop an innovative and smart implant for ischemic or coronary heart disease (projectbrave.eu)

“Smart Implant technologies could significantly improve quality of life and give healthcare providers better insight into how to accelerate recovery and optimise treatment strategies for patients.”

– **Dr Linda Chen-Zijlstra**, Research IT consultant, Department of Biomedical Engineering, TU Eindhoven

IMPACT

Education

- Innovation in smart implant treatments requires and needs collaboration across various disciplines – medicine, biology, chemistry, physics, materials science, and engineering (including e.g. data sciences for simulations). As a result, students must cover a broader range of fields and perspectives.
- Students will be provided with the opportunity to learn together, interact more closely, and develop a deeper understanding of how different disciplines connect. Traditional education models (in e.g. medical and health) will need to evolve – becoming more flexible and allowing students to cross boundaries between fields and disciplines more easily.
- Interdisciplinary thinking for the challenges of future smart implant-based healthcare and technologies, should in the long term, broaden career development.

Research

- Considerable research on smart implants is already taking place both in universities and in research facilities at hospitals. For instance, smart bone-related implants are intended to replace the traditional inert metal-based implants currently used in treatments.
- Clinical implementation of such smart implants will need to follow a structured roadmap, while key issues such as the powering smart implants used for monitoring and understanding how native biological cells in the body interact with smart implants require further investigation.

TREND #5

A growing urge for chip sovereignty in Europe

Public Values

Autonomy	Freedom of choice | Independence
Justice	Sustainability | Transparency | Accountability | Integrity | Equity | Inclusion
Humanity	Safety

Maturity WATCH **PLAN** ACT

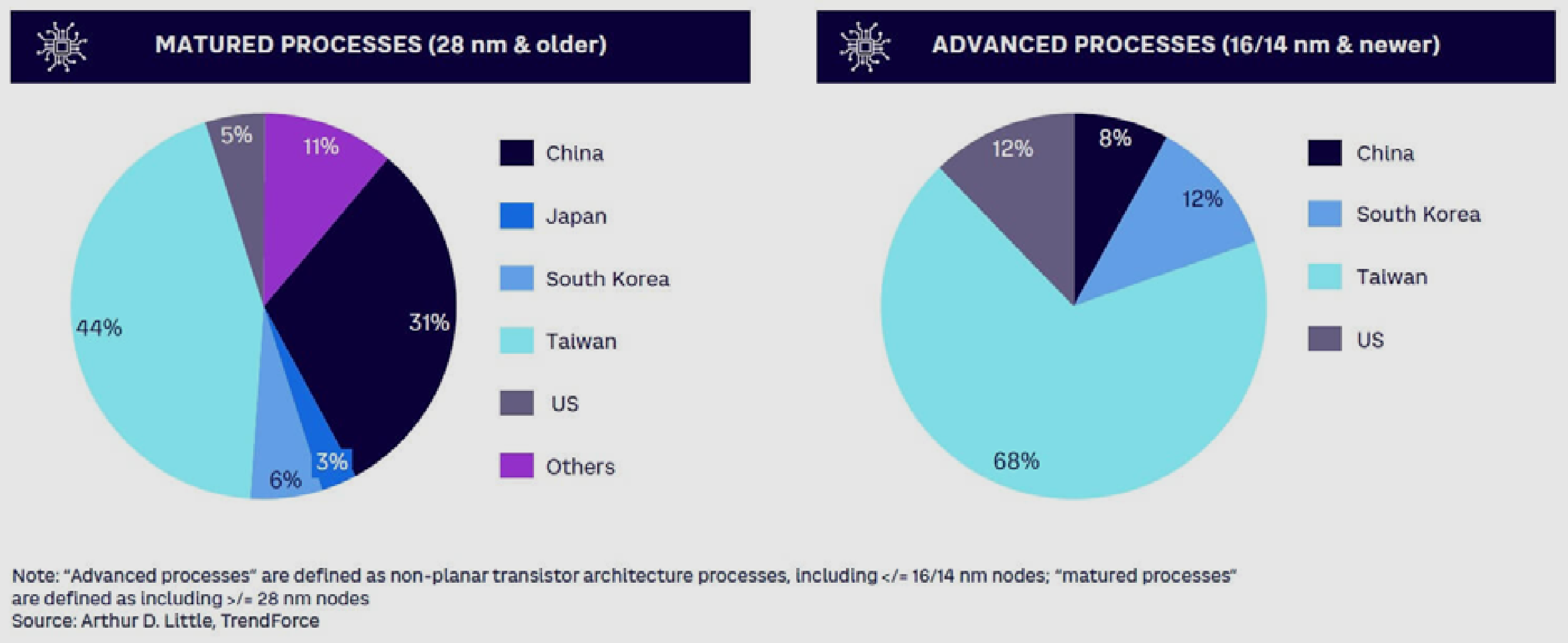
Drivers

Geopolitics & (digital) sovereignty; Compliance & regulation; Critical infrastructure; Automation & AI; Engineering advances & computation; Digital transformation; Global trade & tariffs

All devices require chips to function, and in the case of AI more specialised hardware (chips) are needed, and required, to accommodate the demand. Most of the chip manufacturing takes place in Asia, and with the current geopolitical dynamics, the supply chain for chips is under pressure. In combination with the scarcity of raw materials used for classical (and AI) chip manufacturing, have led several countries to rethink the supply chain.

One of the developments here is the European Commission's Chips Act, introduced in 2023. The ECA framework is set for revision, facilitated by broader consultation with stakeholders in late 2025, to ensure an EU-based microchip ecosystem.

Another noticeable shift is seen in research and development (R&D). More transdisciplinary research, beyond universities, takes place in collaboration with industry partners, to rethink and redesign chips by looking into the pipeline (from materials and architectures to software and memory) for more efficient and intelligent devices.



Distribution of foundry capacity by region, 2023 (adlittle.com)

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Europe's drive to make microchips

An agreement between all EU member states as they all join the Semicon Coalition to secure the continent's technological leadership

- government.nl
- advisory.eib.org

The European Commission has launched a public consultation on the current ECA to address its current shortfalls in light of significant recent changes to the industry (September 2025) (digital-strategy.ec.europa.eu)

EU Chips Act comes into force in September 2023 (ec.europa.eu)

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digital-strategy.ec.europa.eu

Investments in AI chips

ASML invests €1.3 billion in the French-based company Mistral AI (asml.com)

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fintechweekly.com

European Investment Bank (EIB) working on a new initiative to raise €70 billion by the year 2027 for AI and semiconductors (reuters.com)

"True chip sovereignty means more than fabs — it's about creating the next generation of intelligent hardware. Europe can lead in brain-inspired, energy-efficient computing."

– **Prof. Dr. Wilfred G. van der Wiel**, Director Center for Brain-Inspired Computing (BRAINS), University of Twente

Quantum Europe Strategy or European Quantum Act

Launch of the European Commission Quantum Europe Strategy on July 2, 2025 which seeks to position Europe as a global lead in quantum by the end of the decade (digital-strategy.ec.europa.eu)

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qt.eu

Europe's Quantum Leap – The new EU Strategy for quantum technologies up until the year 2030 (globsec.org)

Dutch positioning in the quantum ecosystem and alignment with the European Quantum Act (hollandhightech.nl)

SIGNALS

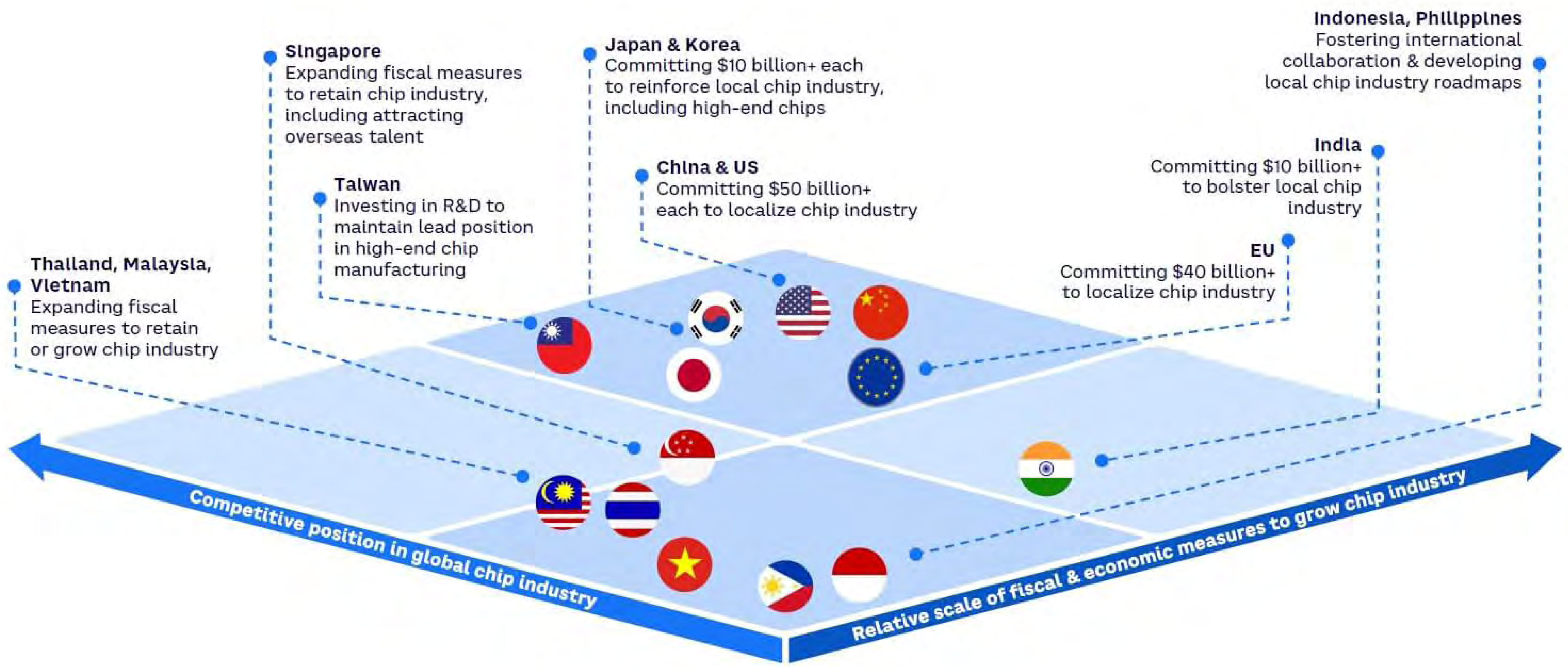
Institutional movement

Material that listens: Twente breakthrough in speech recognition (utwente.nl)

Eindhoven University of Technology is establishing a new research institute dedicated to such as semiconductor, quantum, and photonics chips that aligns with recent policy initiatives such as the ECA and the Dragi-report (tue.nl)

Launch of the Casimir Institute at Eindhoven University of Technology (tue.nl)

Fiscal measures committed vs. competitiveness in global chip industry (adlittle.com)



Source: Arthur D. Little

IMPACT

Education

- The European Chip Act will drive resilience and technological innovation in the broader chip industry within the EU. Nevertheless, it's impact on innovation will be influenced by geopolitical policies and the global technological competition.
- Talent is needed to guarantee the growth of the EU chip industry from a technological standpoint, but this talent should be made aware of the significance of EU policy and geoeconomics on the ecosystem.
- In some courses, these topics are covered implicitly. However, explicit coverage of these topics in dedicated modules that complement traditional technical modules would help to train a more balanced talent pool. This would be talent with the capability to innovate within the chip industry who are also aware of the influence of geopolitical change on their efforts.

Research

- The pursuit for digital autonomy can drive research projects in fields pertaining to the chip industry – ranging from processes to materials, and logistics to synergy with artificial intelligence, connectivity, and data management.
- Collaborate beyond universities and across Europe with researchers, industry partners and society to develop (new) use cases.
- Specialised lab facilities to accommodate new developments in chip testing, manufacturing and knowledge transfer.

Operations

- Talent development and housing will need to be prioritised and accommodated to scale the capability in the Netherlands.
- The implementation of new smart, energy-efficient IoT devices will require architectural focus for future campus scenarios.
- The transdisciplinary research projects require a trusted collaboration environment, allowing for industry partners to access knowledge.

Colophon

Driving innovation together

SURF is the cooperative association in which Dutch research universities, universities of applied sciences, vocational schools, university medical centres, and research institutions work together to provide the best IT for education and research. We develop and provide reliable, state-of-theart IT services, or purchase them centrally on favourable conditions. We collaborate on new, innovative applications of IT in education and research. And we come together to exchange knowledge, ideas and expertise. This keeps Dutch education and research at the top of the world.

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