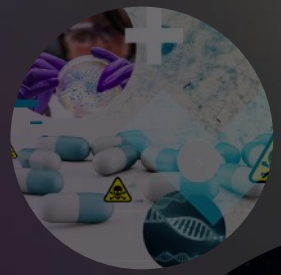
# The GESDA 2024 Science Breakthrough Radar

Geneva Science and Diplomacy Anticipator's
Annual Report on Science Trends at 5, 10 and 25 years



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# A Letter from the Chairmen

## Democratising access to knowledge about emerging science and technology

**We have to acknowledge that we are in the midst of a revolution. What's more, with the numerous and rapid advances in science, we have entered an era in which technological and social changes are occurring at an ever-accelerating pace, leading to a state of permanent disruption and reducing the sense of tranquil stability to a relic of the past.**

We all live in a world accelerated by science and technology, and there is no plausible indication that the pace of change will slow down, given the ever-increasing public and private investments and the immediate adoption of innovations by businesses and citizens that result from this acceleration.

But there is another truth: not everyone benefits enough from science and technology today. Therefore, the first path to a globally sustainable future for people, society and our planet is to rapidly democratise, as much as possible, the early understanding and early use of emerging scientific breakthroughs in 5, 10 and 25 years.

The most recent example is the surge in artificial intelligence over the past two years, with its myriad applications and no one really knowing what it will be capable of in the years to come. The Geneva Science and Diplomacy Anticipator Foundation (GESDA) was created to anticipate this frenetic pace, and its reference tool remains the Science Breakthrough Radar, the fourth edition of which you are holding in your hands.

The 2024 Radar provides an overview of emerging trends in five selected major areas of science and technology. A total of 40 emerging scientific themes and 348 breakthroughs are covered in this document, which is the result of the reflections of 2100 scientists and experts from 87 countries.

And since prioritisation is also one of the basic functions of the Radar, we have selected eight Anticipated Scientific Trends that should be on your radar: eight areas that we believe deserve increased attention because of their recent developments, their potential to transform society and their need to be anticipated because they are new or little known. They are: Eco-augmentation; Archaeology; Unconventional Computing; Neuro-augmentation; Healthspan and Lifespan Extension; the Orbital Environment; the Behavioural Science of Groups; and Synthetic Biology.

All of these fields are evolving at a breathtaking pace. This has prompted us to hold the 2024 Geneva Science and Diplomacy Anticipation Summit under the banner of "The Great Acceleration". As we explore the transformative power of accelerating scientific progress, four key areas of scientific augmentation emerge, which are also the key pillars of the 2024 Summit programme. They are: augmenting data, augmenting humans, augmenting ecosystems and augmenting knowledge itself.

The issue of technological progress also occupies the highest echelons of multilateral politics. Contacts with the UN Security Council illustrate this. During the August 2024 visit to Campus Biotech, GESDA's headquarters in Geneva, members of the Security Council learned how technological advances in artificial intelligence, quantum technologies, synthetic biology and neurotechnology will reshape the global security landscape over the next 5, 10 and 25 years.

But are current and future decision-makers, not to mention citizens, sufficiently informed and prepared to address the challenges posed by these technological advances? Are they ready to respond to this acceleration and its complex challenges?

In this context, the GESDA Foundation is launching its second product, a Knowledge Augmentation Initiative, at the 2024 Summit. This will consist of three complementary components:

- **Knowledge for Future Leaders:** an Anticipatory Leadership Initiative to train and prepare decision-makers across society for a world accelerated by science and technology. In 2025, to incubate this initiative — which is supported by the UK-based charity Wellcome — five Anticipatory Leadership Weeks will be organised with host partners in five different regions of the world.

- **Knowledge for Diplomats:** a digital tool for political intelligence — the GESDA Anticipation Observatory — that puts anticipated scientific advances into a broader context through the lenses of prosperity, peace and security, and human rights. The first pilot application, focused on neurotechnology, will be launched in October 2024.

- **Knowledge for the Public:** an interactive exhibition, the Geneva Public Portal to Anticipation, will provide citizens with an accessible entry point into a world accelerated by science and technology. The first pilot installation will be part of the Swiss Pavilion at the Osaka World Expo in 2025.

And of course, the GESDA Science Breakthrough Radar® will continue to be an essential tool underpinning all components of this second GESDA initiative, which follows the launch of the Open Quantum Institute in Spring 2024.

We hope you enjoy exploring these pages.

**Peter Brabeck-Letmathe**
Chairman of the Board of Directors
GESDA

**Patrick Aebischer**
Vice-Chairman of the Board of Directors
GESDA

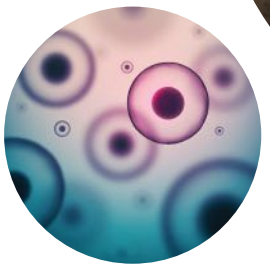
# Introductory Essay: GESDA's Approach to Science Anticipation

**Michael O. Hengartner**
Chair, GESDA Academic Forum;
President ETH Board

**In 2024, we are living in a world of revolutionary AI and post-pandemic medicine, of urgent climate science and experimental gene therapy, of hyper-connected digital societies and synthetic biological organisms.**

In only a few decades, scientific and technological advances have transformed our societies, and continue to have unanticipated consequences on how we function as individuals, how we relate to each other, and how we interact with the environment, our planet and its resources. Fuelled by rapidly growing AI capabilities, the rate of change is likely to even accelerate further — which is why it has never been more vital that we anticipate, and therefore use, the future to build the present.

Practising science anticipation emphasises the need both to anticipate science and technology, and to employ a methodology rooted in research and following its principles of peer review, academic rigour and subject-matter expertise. An anticipation rooted in science also recognises the capacity of research itself as one engine of anticipation — the capacity to make disciplined inquiries into those things we need to know but do not know yet, systematically increasing the horizons of one's current knowledge.



GESDA aims to act as an honest broker here: between the scientific community, diplomats, citizens, philanthropists and the private sector, encouraging open debates about how we wish to shape the future and what opportunities for action can be seized today. The principal tool for this is the GESDA Science Breakthrough Radar®: a detailed examination of the possibilities envisaged for the future across the natural, social and engineering sciences, as well as the humanities and philosophy. To translate the principles of science anticipation into practice, it is necessary to consider anticipation as the capacity to treat the future as a range of possibilities. This makes it possible to make decisions in the present that can influence what happens in the future. To provide useful data for meaningful debate and discussion, GESDA practises science anticipation over a 25-year prospective timeframe. By directly engaging with leading researchers embedded within their respective fields, and through the appointment of specialist GESDA Anticipation Committees, we act to anticipate research trends over the next 5, 10 and 25 years. These anticipated trends are described in the Radar's "Pulse of Science".

In addition to the detailed descriptions of science trends, we also calculate an “Anticipation Potential” score for each topic area, mapped onto our Radar visualisation. Each topic’s Anticipation Potential reflects the opinion of an extended network of subject-specific global experts regarding: the uncertainty of future science breakthroughs in a research field over the next 25 years; the transformative nature of the breakthrough for science, technology, humanity, society and our planet; and the opportunity for multilateral action in the present to ensure that a breakthrough’s potential is realised. Consequently, a field with high Anticipation Potential combines the potential of highly transformative futures with clear opportunities for action in the present.

A detailed breakdown of this methodology can be found on the GESDA Radar online platform. But it is worth pointing out that the methodology’s roots go deeper than GESDA’s innovations in science anticipation.

The Greek word for “anticipate” is προλαμβάνω (prolambano), of which the original meaning is to “seize beforehand”. From its earliest use, therefore, anticipation has combined a forward-looking attitude with the potential for deliberate action, with consideration of possible futures used as a key factor in deciding which actions to take in the present. Through this ability to combine action and purposeful anticipation, we are freed to see aspects of our future as being malleable to creative forces and novelty — as long as suitable enabling conditions exist.

Hence GESDA’s real-world goal: to create, through informed and intelligent science anticipation, conditions that enable clear sight of our possible futures and create the best chance of seizing all the opportunities they present. I earnestly believe that the GESDA Science Breakthrough Radar® will prove an invaluable tool for this task.

2.1
2.2
Human Applications of Genetic Engineering
Future Food Systems
3.3
3.4
Orbital Environment
Collective Intelligence
1.6
1.5
Solar Radiation Modification
3.6
Advances in
4.2

# About the GESDA Science Breakthrough Radar®

A Swiss foundation with global reach and a private-public partnership working from Geneva, GESDA was started in September 2019 to develop and promote anticipatory science and diplomacy for greater impact and multilateral effectiveness.

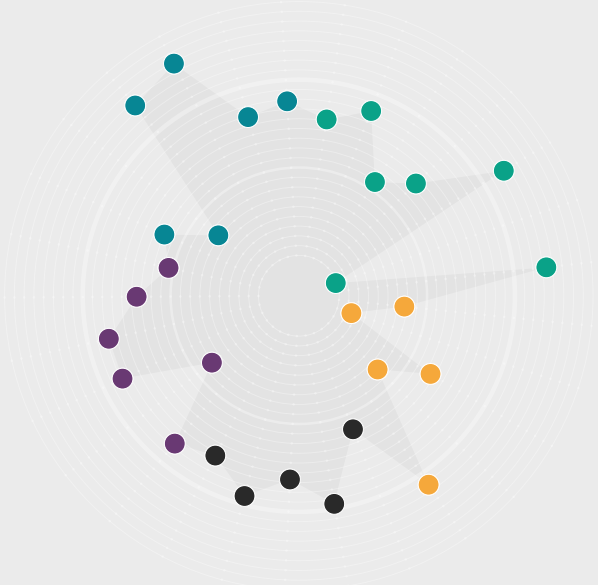
**The GESDA Science Breakthrough Radar® is:**

- A new tool for multilateralism, informed discussion and concerted action.
- A single point of entry to catch up with the unprecedented pace of progress in science and technology.
- A factual basis for eye-opening reflections on the impacts of future scientific discoveries for people, society and the planet.
- An interactive, evolving instrument.

The 2024 GESDA Science Breakthrough Radar® aims to identify emerging research and map major anticipated science advances at 5, 10 and 25 years from now. These advances will potentially have a significant impact on who we are as humans, how we are going to live together and how we can ensure the sustainability of our planet.

The trends and related breakthroughs are updated annually through sustained engagement with the global academic research community. They are distributed across five Scientific Platforms:

1. Quantum Revolution & Advanced AI
2. Human Augmentation
3. Eco-Regeneration & Geoengineering
4. Science & Diplomacy
5. Knowledge Foundations



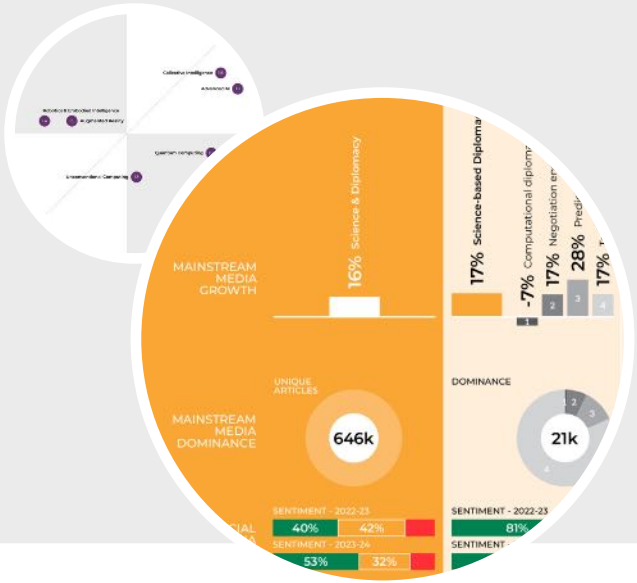
**Each Scientific Platform contains four community-based Pulses:**

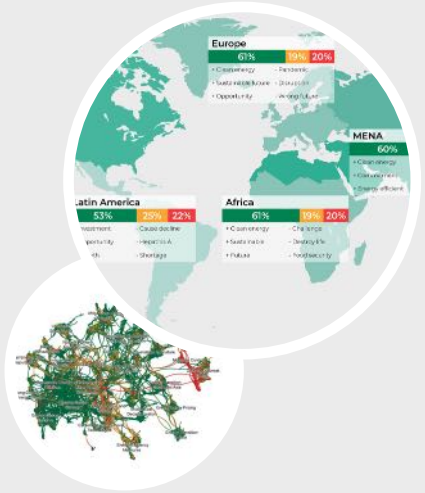
The **Pulse of Science** provides a summary of insights from leading experts in the scientific community on how research in different fields may advance over the next 5, 10 and 25 years. It describes anticipated science trends across 40 emerging scientific topics, covering a broad range of research areas in natural sciences, engineering sciences, social sciences and the humanities. These trends are not absolute predictions — they may develop in unforeseen ways — but noting their emergence makes an important contribution to debates about the future of humankind and the role that the international community can play within it.

The **Pulse of Diplomacy** provides perspectives from the global diplomatic community — heads of states and ministers, heads of international organisations, policy-makers and diplomats — on the implications of the anticipated science and technology advances described in the GESDA Science Breakthrough Radar®. Presented as selected proceedings from the annual GESDA Science and Diplomacy Anticipation Summit, the Pulse of Diplomacy describes the impact of future breakthroughs on global issues such as human rights, peace, security and prosperity.

The **Pulse of Impact**, a new addition to the GESDA Science Breakthrough Radar®, provides additional data about investments in the private sector on selected topics. Whether science and technology breakthroughs are successfully deployed from the lab into the world depends to a certain extent on — and can be accelerated by — investments from the private sector. The Pulse of Impact describes the latest data about patent filling, start-up creation and private investment in topics covered by the GESDA Science Breakthrough Radar®.

The **Pulse of Society**, finally, provides an analysis of public perception of, and debates in mainstream media and social media on, the topics of the GESDA Science Breakthrough Radar®. Extending past analyses, the data presented in this year's edition reflects an enhanced and standardised methodology which allows the description of the evolution of public sentiment over the years.



# The GESDA Pulse of Science

| SCIENTIFIC PLATFORM | HIGHLIGHTS FOR 2024 | BREAKTHROUGH BRIEFS<br>Top anticipated scientific trends in **bold** | INVITED CONTRIBUTIONS |
|---|---|---|---|
| 1 Quantum Revolution & Advanced AI | GESDA Geopolitical Lens: Anticipating the Geopolitical Impact of Advanced AI; AI Futures: Peace and War | 1.1 Advanced AI<br>1.2 Quantum Computing<br>**1.3 Unconventional Computing**<br>1.4 Robotics and Embodied Intelligence<br>1.5 Augmented Reality<br>1.6 Collective Intelligence | Artificial Cognition<br>Superconductivity |
| 2 Human Augmentation | | 2.1 Cognitive Enhancement<br>2.2 Human Applications of Genetic Engineering<br>**2.3 Healthspan Extension**<br>**2.4 Future of Consciousness**<br>2.5 Organoids<br>2.6 Advanced Therapeutics | Growing Embryo Models<br>Space Technology and Global Health |
| 3 Eco-Regeneration & Geoengineering | The 2024 Villars Anticipation Workshop: **Shaping Ecosystems: Anticipating an Age of Eco-augmentation**<br>The GESDA Philosophical Lens: Shaping the Future of Social-ecological Systems | 3.1 Decarbonisation<br>3.2 Earth Systems Modelling<br>3.3 Future Food Systems<br>**3.4 Orbital Environment**<br>3.5 Ocean Science<br>3.6 Solar Radiation Modification<br>3.7 Infectious Diseases | Fungal Pandemics |
| 4 Science & Diplomacy | | 4.1 Science-based Diplomacy<br>4.2 Advances in Science Diplomacy<br>4.3 Prediction, Foresight and Futures Literacy<br>4.4 Digital Security<br>**4.5 Behavioural Science of Groups** | The Future of Multilateralism<br>The Future of Trade |
| 5 Knowledge Foundations | GESDA Science Lens: Anticipating the Future of Research | 5.1 Complex Systems Science<br>5.2 Economics<br>5.3 Science of the Origins of Life<br>**5.4 Synthetic Biology**<br>**5.5 Archaeology** | The Future of Fusion<br>Future of Social Science and the Humanities<br>Mathematics for Humanity |

HUMAN AUGMENTATION
ECO-REGENERATION & GEOENGINEERING
SCIENCE & DIPLOMACY
KNOWLEDGE FOUNDATIONS
QUANTUM REVOLUTION & ADVANCED AI
2.4 Future of Consciousness
2.6 Advanced Therapeutics
3.2 Earth Systems Modelling
2.3 Healthspan Extension
2.5 Organoids
3.1 Decarbonisation
3.3 Future Food Systems
3.4 Orbital Environment
3.5 Ocean Science
2.1 Cognitive Enhancement
2.2 Human Applications of Genetic Engineering
1.6 Collective Intelligence
1.5 Augmented Reality
3.6 Solar Radiation Modification
3.7 Infectious Diseases
4.2 Advances in Science Diplomacy
4.1 Science-based Diplomacy
1.4 Robotics and Embodied Intelligence
1.2 Quantum Computing
1.3 Unconventional Computing
4.4 Digital Security
4.3 Prediction, Foresight and Futures Literacy
1.1 Advanced AI
5.5 Archaeology
5.1 Complex Systems Science
5.3 Science of the Origins of Life
4.5 Behavioural Science of Groups
5.4 Synthetic Biology
5.2 Economics

# Facts and Figures

**The GESDA Science Breakthrough Radar® comprises 40 topics spanning five Scientific Platforms. It presents the outcomes of four community-driven "pulses" on scientific topics — the Pulses of Science, Diplomacy, Impact and Society.**

**The Pulse of Science** details **348** anticipated breakthroughs at 5, 10 and 25 years from now. In addition, it contains three "lenses" on philosophy, geopolitics and science discussing anticipated advances from the perspective of three fundamental questions about the future of humanity, society and our planet. **2,100** scientists from **87** countries have contributed to the Pulse of Science since the Radar's creation in 2021. **706** scientists from **60** countries contributed to the Pulse of Science in the 2024 GESDA Science Breakthrough Radar®.

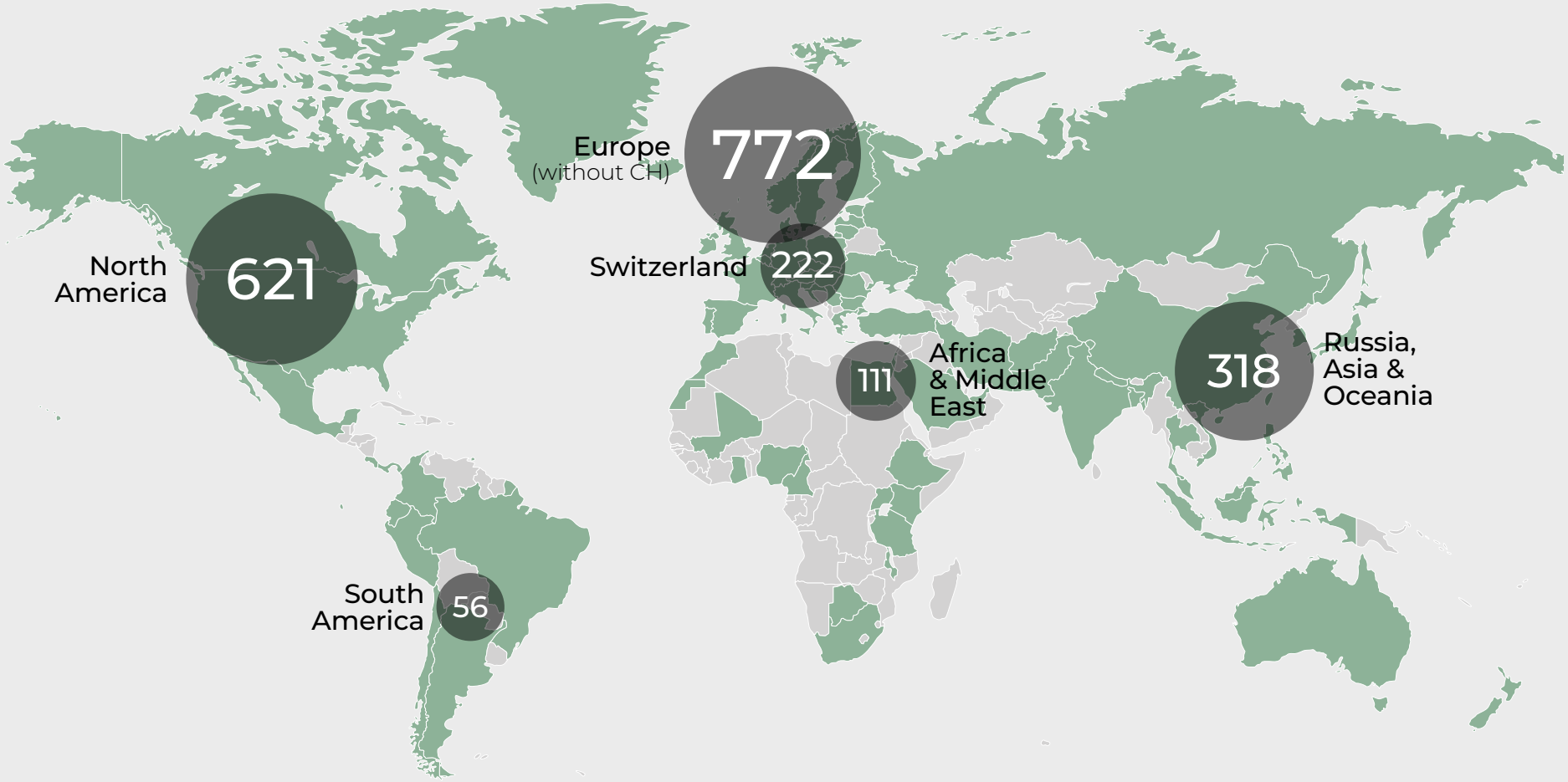
**The Pulse of Diplomacy** provides an overview of **11** topics related to anticipatory science and diplomacy as discussed at the GESDA 2023 Science and Diplomacy Anticipation Summit, building upon insights from **89** speakers and over **800** participants.

**The Pulse of Impact** includes an analysis of **30,114** companies worldwide and patents in over **50** jurisdictions.

**The Pulse of Society** includes an analysis of over **10 million** social media posts and **1.3 million** articles in mainstream media in order to capture people's opinions about the scientific topics in the five Scientific Platforms.

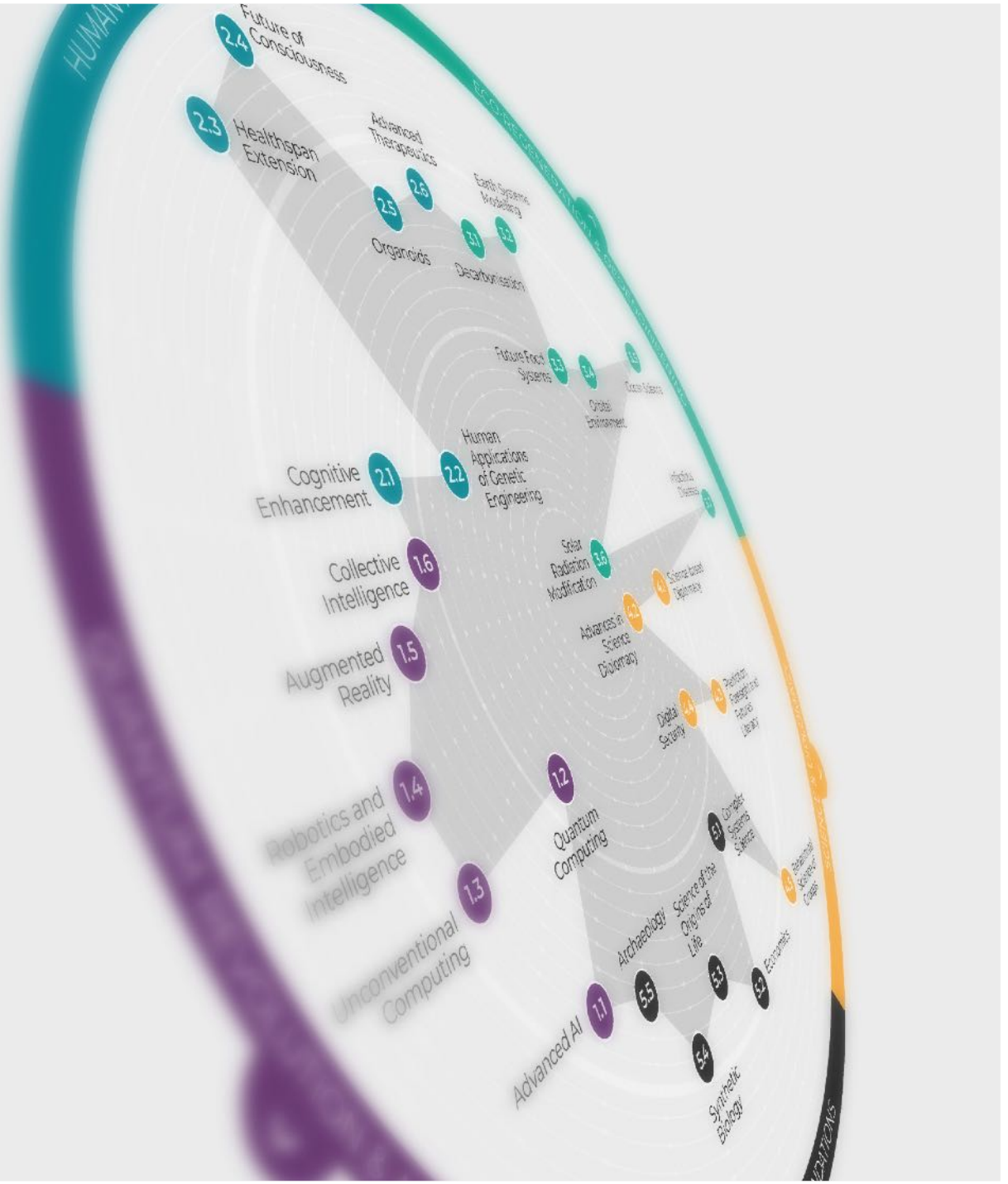
**348** anticipated breakthroughs
**2100** scientists
**87** countries

**Geographical spread of contributors to the Pulse of Science since 2021**



# Executive Summary

The 2024 edition of the GESDA Science Breakthrough Radar® includes several new developments for GESDA's work on science anticipation. Beyond working with the scientific community to ensure the Radar reflects the latest developments and trajectories in science and technology, the Pulse of Science has been expanded to include four new scientific topics: Robotics and Embodied Intelligence; the Behavioural Science of Groups; Digital Security; and Archaeology. GESDA has also renewed its approach to science anticipation, developing and refining a robust methodology that reflects the broad range and uncertainty of possible future scientific trajectories, their potential transformative effects on both science and society, and the scope for multilateral action in the present.




MORE INFORMATION:

go.gesda.global/top-trends

In spring 2024, GESDA hosted the second GESDA Villars Anticipation Workshop focussed on Eco-augmentation, following on from the inaugural Villars Anticipation Workshop on Neuro-augmentation in 2023. The success of this latest workshop, which brought together a diverse range of experts to discuss the accelerating ability of humans to deliberately use science to shape the environment, has solidified the GESDA Villars Anticipation Workshops as a key instrument for trans-disciplinary, multinational science anticipation.

Expanding upon the scientific insights included in the Radar, we again include three cross-disciplinary "lenses" through which to examine anticipated breakthroughs. These are the GESDA Philosophical Lens, this year with a focus on eco-augmentation and humanity's present and future relationship with the planet; the GESDA Geopolitical Lens, with a focus on how AI could affect the future of peace and war; and the GESDA Science Lens, through which we consider how anticipated breakthroughs themselves could affect the process of scientific discovery and knowledge creation.

Finally, this edition of the Radar integrates for the first time four community-based "**pulses**": on science, diplomacy, impact and society. **The Pulse of Science**, developed with our scientific community, reflects expert opinions on anticipated future breakthroughs in different areas of science and technology. **The Pulse of Diplomacy** highlights areas of diplomatic interest related to these possible breakthroughs, including key discussions from GESDA's 2023 Science and Diplomacy Anticipation Summit. **The Pulse of Impact** tracks private investments and company creation in relation to science breakthrough trends, and **The Pulse of Society** captures people's changing sentiment towards anticipated advances in science and innovation.

## Highlights of the 2024 Edition

### The 2024 Villars Anticipation Report on Eco-augmentation

*Platform 3: Eco-Regeneration & Geoengineering, page 144*

This report provides a record of the cutting-edge scientific advances anticipated across fields relevant to eco-augmentation, and identifies key opportunities for the future. Recent advances in synthetic biology, stem-cell biology, ecosystem sensing and artificial intelligence now make it possible, in principle, to deliberately modify ecosystems and enhance their functions: "eco-augmentation". At the second GESDA Villars Anticipation Workshop, leading researchers from different disciplines met to discuss issues pertinent to the future of eco-augmentation across three interrelated themes: reading and writing ecosystems, transitioning ecosystems and hacking (co-)evolution. Such eco-augmentation has the potential to undo some of the damage humans have done to ecosystems, to stabilise, restore or enhance ecosystem services, and to increase ecosystem robustness to avoid catastrophic collapse.

### The GESDA Philosophical Lens on Eco-augmentation

*Platform 3: Eco-Regeneration & Geoengineering, page 200*

A panel of leading philosophers, convened by GESDA, reflect on how advances anticipated by the participants of the Villars 2024 Anticipation Workshop on eco-augmentation will reshape our understanding of who we are as humans, how we live together as societies, and how we relate to the planet. This philosophical lens provides a discussion of the different relationships between human beings and nature, and our responsibility as humans in an age when the power of technology is growing exponentially.

### The GESDA Geopolitical Lens on Anticipating the Geopolitical Impact of Advanced AI

*Platform 1: Quantum Revolution & Advanced AI, pages 70 and 74*

In collaboration with the Geneva Centre for Security Policy (GCSP) and the School of International and Public Affairs (SIPA) at Columbia University, New York, the geopolitical lens discusses how artificial intelligence might reshape peace, war and security in the future. As we have entered a renewed era of geopolitical competition, new technologies will provide essential capabilities for warfare, security and peace-building. This discussion paves the way for further debates and action to promote future peaceful deployment of emerging technologies.

### The GESDA Science Lens on Anticipating the Future of Research

*Platform 5: Knowledge Foundations, page 308*

Breakthroughs in science not only have the potential to radically alter society, but also will influence how scientific research is carried out — a recent example being how AI is changing research practice across disciplines. The anticipated breakdown of traditional scientific disciplines, the generation of increasingly ambitious questions requiring larger and larger collaborative networks, the increasing reliance on advanced archival architectures for intelligent data mining and the possibility of future automated laboratories that are directed by artificially intelligent machines all have vast implications for the practice and role of research in the future. This GESDA perspective on the future of research initiates reflections on how breakthroughs anticipated by scientists will themselves influence the way science and research is practised, and what this could imply for knowledge creation in the future.

## Top 8 Anticipated Scientific Trends in the 2024 GESDA Science Breakthrough Radar®

**All change for computers**

Over the past year, our expectations of what computers are and what they can do have been reshaped by advances in artificial intelligence. But these are not the only radical changes we can expect. Today's AI systems still run on relatively conventional hardware and have significant constraints, particularly in terms of their reliance on data for training and of their heavy energy consumption. **Unconventional computing** approaches are attempting to resolve this, including computers that operate with light rather than electrons, and "neuromorphic" machines which seek to emulate the power, flexibility and efficiency of the human brain. The coming years might see an acceleration of alternative and unconventional developments.

One area which has already attracted significant attention, but which may still be under-anticipated, is quantum computing — computing with machines that encode information using the rules that govern the properties of subatomic particles, photons of light and certain other objects. In principle, this facilitates the exploitation of novel and extremely powerful computational techniques. After decades of development, experts believe that certain niche — but meaningful — applications could be realised within the next five years, with far-reaching consequences for scientific discovery and for a wide variety of industries.

**Expanding consciousness, healthspan and lifespan**

The nature of consciousness has been debated for millennia: even defining what we mean by the term has proven difficult, differing across both time and cultures. That remains an issue, but is not preventing the development of techniques and technologies that are helping us to probe our mental states and the physiological sites and neural activity associated with them. Pharmaceutical interventions and electrical stimulation are making it possible to routinely modulate consciousness. The same can also be said about cognition, our deliberate thought processes: we are gaining the ability to measure and modify the ways we think, and this **neuro-augmentation** is only set to advance in the future. Reading from and writing to the human brain could allow us to restore lost nervous function, modulate neural activity to improve mental wellbeing and improve our capacity to think and remember.

There is also a renewed interest in artificial intelligence and what this means for machine consciousness. Researchers are investigating the presence and nature of consciousness in many non-human entities, going far beyond the usual "clever animals" to include invertebrates, machines that emulate human behaviour and even organoids: proto-organs grown from human tissue — including brain tissue. Such an expansive view, if substantiated, could overturn our ideas about the nature and significance of human consciousness. That in turn would help us to better understand what an "inner life" might actually be, and how we might adjust or augment it — initially for therapeutic purposes, but perhaps later for other reasons, too.

We can also anticipate substantial changes in how we repair and enhance the functioning of our bodies, as well as our minds. New approaches to genetic modification will allow us to make extremely precise changes that offer **healthspan and lifespan extension**. The emerging fields of epigenome editing and metagenomics, which can provide a complete profile of all the diverse organisms in a given microbiome, will take this further, allowing fine-tuned optimisation of environmental and symbiotic factors. This increasing availability of genetic data from all organisms on Earth, including species that have been extinct for hundreds of thousands of years, is providing a treasure trove of information from which AI can identify new tools to combat acute challenges such as rising antibiotic resistance.

**Eco-augmentation — reshaping the environment**

This year, we have taken a close look at **eco-augmentation**: deliberate and strategic interactions with nature to develop more robust and sustainable social-ecological systems.

This topic is complex and controversial, since there are many potential benefits to eco-augmentation, ranging from environmental restoration to preserving genetic diversity to increased productivity or increasing robustness. Such interventions require us to reframe future relationships between social and ecological systems in ways that challenge the historic separation of human and natural spheres. But as environments around the world continue to undergo rapid transformation, and new insights from science and technology result in more powerful tools, the appetite for such interventions is growing.

That said, the state of our knowledge about the details of the environment and its sets of complex interactions does not match our ability to intervene. Some ecosystems are well studied, but we need to better understand and monitor their dynamics and health. By illuminating “dark spots” — entire ecosystems or biomes about which we are ignorant — and “grey spots”, for which data exists but is fragmented and disparate, we will better understand how interventions may be employed. A poorly designed or executed intervention might have effects ranging from ineffectual to disastrous — but because technologies such as synthetic biology are advancing rapidly, there is an increasing need to decide how and why we wish to deploy them.

An acute example is our ocean systems, which we know support human ecosystems but are also vulnerable to human activity, most obviously climate change. Advances in ocean science are creating astounding new discoveries, such as dark oxygen sources in the deep sea. Given how little we know currently, one of the few things we can be certain of in the future is that we will make many more such paradigm-shifting discoveries in fields including biodiversity and ecosystem services, as well as chemistry, minerals and energy sources, all of which will need to be carefully managed. Equally in need of careful attention is our **orbital environment**: advances in off-Earth manufacturing and increasing capabilities of space-based resources and infrastructure are intensifying the need to peacefully manage outer space.

**The datafication of society**

In a year when a huge proportion of the global population went to the polls to vote, the role that digital technology plays in shaping our societies was once again under scrutiny. Conflicts around the world are taking place simultaneously in the information sphere and in physical reality, while the ways in which we interact within civil society are also subject to novel and potentially transformative forces, which are, for the most part, poorly understood.

New technologies including AI, quantum computing and the internet of things promise to make the situation even more fluid in years to come: the ability to deploy convincingly faked material and "bots" capable of holding plausible online conversations, for example, pose new and intractable security risks. The boundaries of privacy are also being forced back as biometric data and detailed information about people's movements and activities becomes available at scale. These developments necessitate new ways of thinking about trust, identity and digital security — for example, providing trusted mechanisms for validating multiple aspects of a single person's identity — and new approaches to safeguarding data, including a raft of new approaches to encryption.

This plethora of online activity provides opportunity, as well as challenge, however: it supplies raw material for more detailed and accurate modelling of the **behavioural science of groups** that previously had to be estimated or assumed. Equipped with granular data about social behaviours and interactions, researchers can begin to understand how conflict, polarisation and extremism arise — and develop precisely targeted interventions to defuse dangerous situations before they ignite.

**Transformative fundamental technologies**

Some technologies have the power to significantly transform huge sectors of society, as well as being an enabling force for technology development itself across many different sectors — AI being a recent example. Other, similarly powerful technologies also present enormous opportunities — though with significant technical, ethical and social challenges.

One such field is **synthetic biology**, based on precision tools for editing and engineering genomes and other biological molecules. This enables the modification of organisms in fundamental and enduring ways, or the creation of entirely new organisms. Initial applications have targeted medicine and health, but are also starting to be used to develop new carbon-negative materials, foodstuffs and energy sources — as well as to modify ecosystems. In the future, the development of cheap, off-the-self kits for designing biology from scratch will provide huge opportunities for new applications of synthetic biology, but also raise questions of how the applications of such powerful technology will be regulated.

While synthetic biology promises to reshape our future, related technologies offer us unparalleled new insights into our past — redefining **archaeology**. Significant advances in molecular-level analysis of archaeological remains are starting to give us the ability to detail the biology and behaviours of our ancestors, as well as the prehistory of our environment, climate and societies. These will have revelatory implications for our understanding of our situations today — allowing comparisons of migration trends, for example. As DNA reading technologies improve to allow us to extract information from deeper and deeper into the past, the distinction between social and natural sciences is likely to further erode to offer unified and powerful insights into key questions about our world.

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**Martin Müller**
Executive Director Science Anticipator, GESDA

**Sophie Gilbert**
Programme Lead, GESDA Science Breakthough Radar®

MORE INFORMATION:

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# The GESDA Scientific Platforms

The GESDA Science Breakthrough Radar® anticipates frontier research in five fundamental domains, or Scientific Platforms. In this section, leading experts contribute insights that identify and explain emerging research in each of these domains, anticipating major anticipated science advances at 5, 10 and 25 years.

All citations in this section can be found in the resources tab on the digital platform using the URL or QR code below:

**radar.gesda.global**

5 KNOWLEDGE FOUNDATIONS Pages 264 – 319

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1 QUANTUM REVOLUTION & ADVANCED AI Pages 24 – 87

SCIENTIFIC PLATFORM

1

# Quantum Revolution & Advanced AI

What has been called the information age is now morphing into an age of radical innovation with information. Whether through data mining for machine learning, physics-based processing with quantum computers, copying biological information-handling, creating intelligent robots or augmenting our experience of reality, this is a time of upheaval. These innovations require attention if they are to be developed and deployed in ways that serve humanity, society and our planet. In this section, we anticipate, explain and explore the various ways in which advances in novel information technologies may evolve and impact our world.

GESDA **GEOPOLITICAL LENS** (pages 70-77)

Anticipating the Geopolitical Impact of Advanced AI
AI Futures, Peace and War

PULSE OF **SCIENCE** (pages 26-69)

Containing deep insights into anticipated advances associated with Quantum Revolution and Advanced AI over the next 5, 10 and 25 years, the GESDA Pulse of Science provides the expert opinions of leading researchers in fields related to novel forms of computing and related applications.

PULSE OF **DIPLOMACY** (pages 78-81)

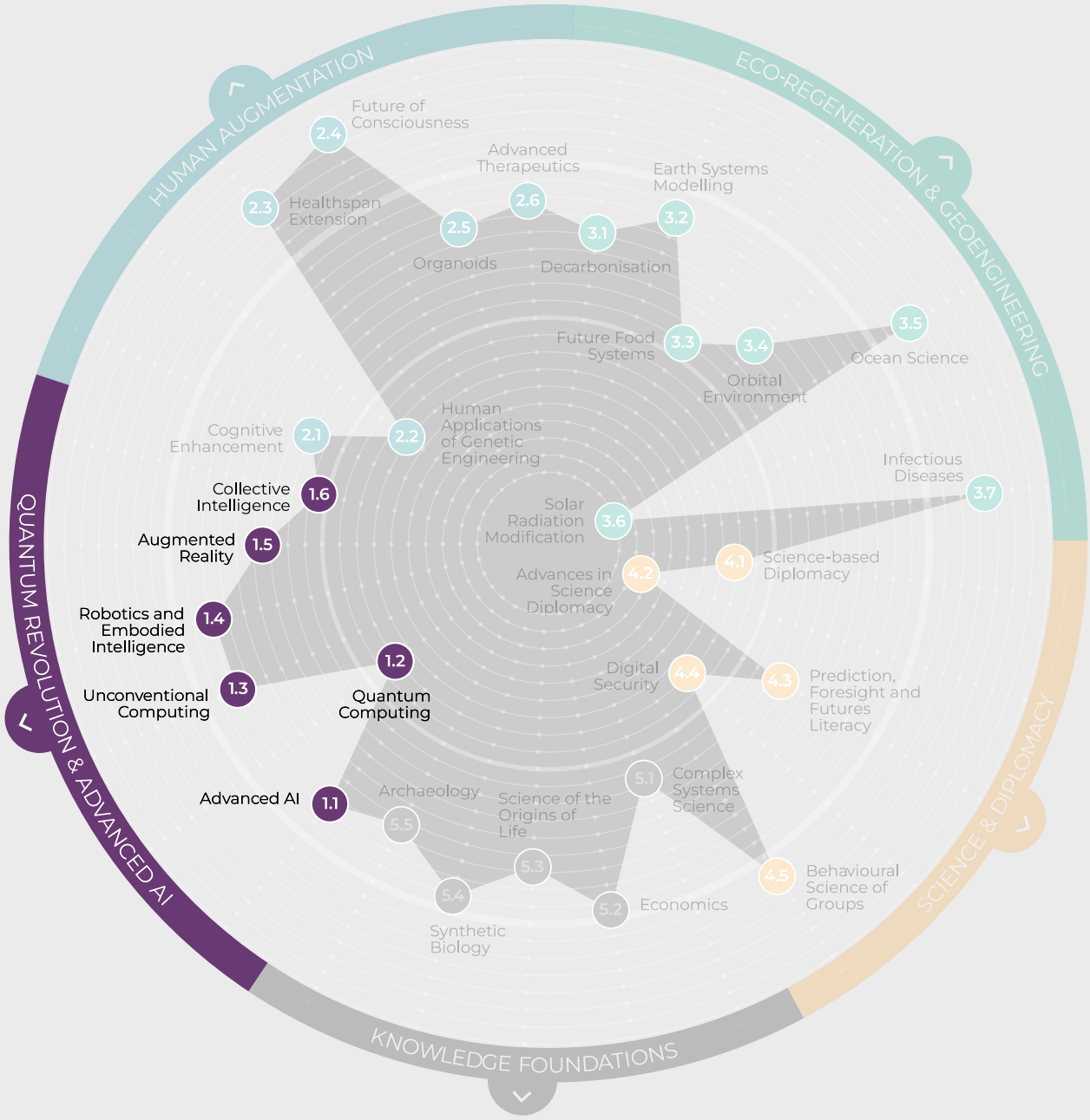
The GESDA Pulse of Diplomacy captures the latest discussions between diplomats and scientists at the 2023 GESDA Science and Anticipation Summit on topics related to quantum and other unconventional computing, robotics, collective cognition, augmented reality and human-computer interaction.

PULSE OF **IMPACT** (pages 82-83)

Current investment trends and dynamics of company creation highlight quantum computing as an increasingly important topic. The GESDA Pulse of Impact provides data detailing private-sector investment, intellectual-property activity and company creation in this area since 2000.

PULSE OF **SOCIETY** (pages 84-87)

Powered by AI, the GESDA Pulse of Society's network and dynamic sentiment analysis of both mainstream and social media reveals macro and micro trends in public opinion around the world on topics relating to non-conventional computing and emerging applications of information processing.



1.1

# Advanced AI

CHAIRS:
**Emmanuel Abbé**
Full Professor, Chair of Mathematical Data Science, Swiss Federal Institute of Technology in Lausanne (EPFL)

**Rüdiger Urbanke**
Professor of Communication and Information Theory, Swiss Federal Institute of Technology in Lausanne (EPFL)

CONTRIBUTORS:
**Blaise Agüera y Arcas, Samy Bengio, Sébastien Bubeck, Alexandre Pouget**

**Artificial intelligence (AI) aims to produce intelligence using algorithms and machines. This means, in particular, machines that are able to behave in ways we associate with human activity: perceiving and analysing our environment, taking decisions, communicating and learning. AI systems have achieved some impressive milestones in the last decade, and could prove disruptive to societal norms in the near future.**

At the core of AI lies machine learning (ML), the methodologies allowing machines to learn and make predictions autonomously by discovering patterns in data. Deep learning is an ML methodology that relies on large models called neural networks, in particular transformers. When fed large amounts of data, neural networks learn to recognise statistical patterns, which can then be used to solve a variety of tasks in areas such as vision, language or game-playing.

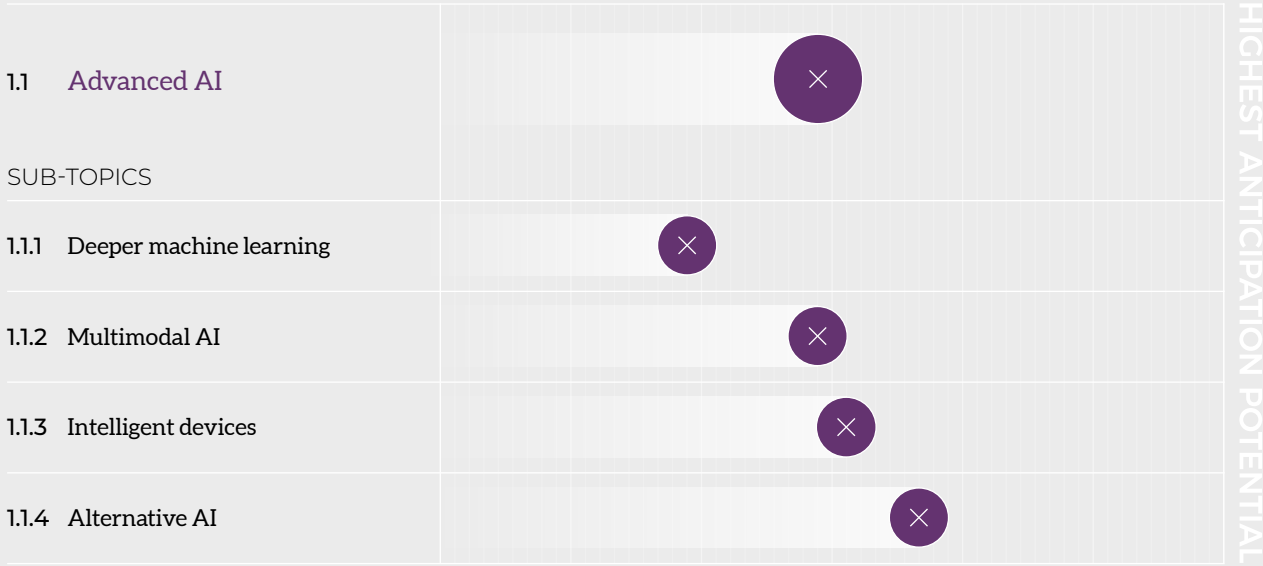
Computer vision systems powered by deep learning identified objects better than humans in 2015.[1] The following year, deep learning systems beat a Go champion and started playing complex video games.[2] Last year, AI predicted the structure of nearly every known protein known and brought chatbots with powerful linguistic capabilities to the general public.[3,4] Today, a wide range of AI tools including chatbots, image generators and coding assistants are commercially available and even integrated into search engines and office software.

This rapid progress is primarily due to the increasing availability of data and computing power. There is evidence that AI capabilities scale with model or dataset size leading many AI research labs and organisations to focus on building ever-larger systems.[5,6] However, deep learning-based AI remains prone to bias and often can't generalise what it has learned to new situations, an ability known as out-of-distribution generalisation. The inner workings of neural nets are also opaque and they are inefficient learners, requiring vast amounts of data, processing power and energy. This has led to predictions that improved approaches will be required to achieve more adaptable, efficient and trustworthy AI that can be deployed broadly across society.[7] That said, many in the field believe that continued scaling could also address these outstanding challenges to an extent that is acceptable in many applications, and that society needs to prepare for the disruptive effects of AI that can outperform humans in a wide range of tasks.

KEY TAKEAWAYS

Recent progress in AI research has already had enormous societal impact, and more is certain to follow. Advances known as **Deeper machine learning** offer significant improvements on current capabilities, leading to rapid improvements in language, coding, vision and robotic control, although bias and "hallucination" of untruths and weakness of reasoning remain a problem. Future AI systems are increasingly likely to use data from a variety of source types. Such **Multimodal AI** is already in limited use in autonomous vehicles, and will spread to a much wider set of applications. This is likely to accelerate its learning and to improve human-computer interaction, since humans are themselves multimodal. Concerns over privacy, bandwidth and safety mean that research is exploring the use of **Intelligent devices** that can process data and run AI models on smaller platforms. The challenges here are spurring innovations in chip design, training and inference protocols. There are hints that scaling, resource use and trustworthiness issues associated with current AI may hinder its full development, necessitating new methodologies for developing **Alternative AI**.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Advanced AI is already having a transformative effect on science and society, and calls for global multilateral action are consequently very high. However, because of the high maturity of areas such as deep learning and multimodal AI, the Anticipation Potential scores are relatively low. Alternative approaches such as neurosymbolic AI, causal AI and quantum machine learning are believed to be more than a decade away and have the potential to be highly transformational. This results in a higher score for the Alternative AI sub-topic.

MORE INFORMATION:

**go.gesda.global/1-1**

Advanced AI

## 1.1.1 Deeper machine learning

**Many advances in deep learning have involved humans laboriously labelling vast amounts of data for algorithms to be trained on. More recently, though, a new paradigm known as self-supervised learning has accelerated progress. This was magnified in the case of language tasks with transformers, which learn to predict "engineered labels" by completing texts based on far more data than before.[8]**

This has led to rapid improvements in AI language and coding capabilities and is also showing promise in domains like vision and robotic control.[9,10,11] So far, transformer performance scales reliably with model or dataset size, and the largest systems appear to demonstrate emergent capabilities they were not explicitly trained for, such as some creativity and limited reasoning capabilities in language.[12] They have also been applied to scientific problems such as protein folding with considerable success.[13]

Nonetheless, there is evidence that the current "scale" approach is learning mainly by memorisation, exemplified by poor performance on more complex tasks such as mathematics and logic.[14] Research has also suggested that seemingly emergent capabilities are simply the result of flawed testing.[15] And because these models are statistical in nature, they readily learn biases from training data and can confidently "hallucinate" facts that are not true.[16]

The imperative to build ever-larger models also means cutting-edge AI research is increasingly accessible only to well-funded labs possessing significant compute power. There is also interest in creating smaller models,[17] but access to data and hardware remains a key differentiator and is stoking geopolitical competition over access to AI chips.[18]

### 5-YEAR HORIZON

**Deep learning models grow in scale**

Further scaling of deep learning models leads to performance that is increasingly indistinguishable from humans in language and vision tasks. Widespread deployment by businesses reshapes significant sections of the economy, such as customer service, content generation and programming. AI agents capable of acting autonomously are deployed in low-risk areas, providing assistance to humans. Most countries adopt AI regulations to limit the potential negative impacts of AI such as bias, misinformation and privacy invasion. There is also a push to clarify copyright protections for those whose data is used to train AI.

### 10-YEAR HORIZON

**Workforce disruption necessitates radical intervention**

Deep learning systems outperform human knowledge workers in a wide range of professions. AI agents start to interact with each other, creating a new AI workforce operating alongside humans. Employment and wealth distribution policies are rethought. Progress shows whether exponential increases in model size outpace hardware improvements, prompting renewed innovation in AI methodological developments, and whether missing ingredients to improve reasoning and trustworthiness of AI emerge.

### 25-YEAR HORIZON

**Deep learning's influence is ubiquitous in daily human life**

Given current acceleration, at this timescale predictions about AI are incredibly difficult. If scaling laws hold, then AI is likely to reach superhuman capabilities in all domains, leading to runaway progress that is impossible to forecast — and potentially dangerous, requiring urgent policy decisions about AI's agency and responsibility. However, it remains possible that there are fundamental barriers that scaling alone will not resolve. In this case, efforts to build generally intelligent AI will refocus on combining it with alternative AI approaches.

## 1.1.2 Multimodal AI

**AI research has traditionally focussed on solving discrete problems that involve a single type of data, such as images, text or audio. This has led to superhuman capabilities in narrow areas like object recognition, speech recognition and game-playing. But humans and animals use multiple senses to navigate the world around them, and there is growing recognition that for AI to become more flexible it will need to work with multiple data modalities at once.**

Multimodal AI is already used in autonomous vehicles to fuse input from cameras, radar and LIDAR, and shows promise in healthcare, where a wide range of physiological signals need to be considered.[19,20] More recently, large language models repurposed to work with multiple data modalities have shown considerable promise. Photorealistic imagery and video clips can now be generated from simple text descriptions, the latest AI-powered chatbots can perform complex image analysis, and robots can combine visual input, motion data and natural-language commands to carry out complex tasks.[21,22,23]

The ability to draw correlations between different data sources can accelerate learning and help ground the knowledge encoded by language models in the realities of the physical world.[24,25] It could also transform human-computer interaction by allowing people to communicate with machines in a wide range of mediums. These approaches are data-intensive, though, and while the internet is a goldmine of text and images, finding sufficient training material for other modalities could be a challenge. Robotics is presenting a potential model for overcoming this barrier, though, with research groups pooling resources to create massive open datasets of multimodal training data.[26,27]

### 5-YEAR HORIZON

**The knowledge industry is entirely disrupted**

Multimodal AI works with both text and image data to automate a wide range of tasks in knowledge industry jobs. “Generative” AI can now produce art, images and long-form videos indistinguishable from human-made ones, disrupting the creative industries and stoking fears about misinformation. Limited data availability stymies efforts to expand into new modalities, prompting growing focus on using AI models to create synthetic data to train on.

### 10-YEAR HORIZON

**AI works with more modalities**

More efficient algorithms and a concerted effort to collect and share data expand the modalities that AI can work with. This strengthens applications to precision medicine. It also helps AI systems to develop deeper knowledge of the world around them, and a grasp of physical concepts and social dynamics. This allows AI, including intelligent robots, to work more seamlessly and safely alongside humans, boosting the use of the technology in less structured settings like retail, care and education.

### 25-YEAR HORIZON

**AI understands the world through multiple data streams**

What happens on this timescale will have a sensitive dependence on the outcomes of the next few years of AI development. However, we can predict that more general advanced AI systems will use multiple data streams to understand the world around them, in much the same way as humans. These are not limited to the five senses: at 25 years, specialist AI systems use a different set of modalities, depending on their task. Multimodal deep learning also accelerates scientific inquiry.

Advanced AI

## 1.1.3 Intelligent devices

**Massive AI models running on servers are incredibly powerful, but to make use of them, data has to be streamed back and forth via the cloud. This is not ideal for privacy-sensitive applications such as healthcare and smart homes, or safety-critical ones such as autonomous vehicles or robotics, where network lags could lead to accidents.**

Hence, running models embedded on "intelligent devices" will be imperative for many of the most promising AI applications.[28] However, smaller machines with limited power supplies are unable to support the computing and energy requirements of today's leading models. This is spurring efforts to develop more efficient chips specialised for embedded applications, and optimisation techniques that can make models smaller, more energy-efficient and faster.[29,30,31] Analogue AI chips are showing promise as a way to dramatically reduce the power required to run leading models.[32]

Training these intelligent devices will also require innovations. Federated learning is a promising approach that distributes training over many smaller devices, reducing bandwidth requirements and improving privacy.[33] Reinforcement learning, in which AI learns to perform a task by repeatedly performing actions to maximise a carefully chosen reward, will keep improving the training of robots and other automated machines. This is slow and costly, though, and collecting enough real-world training data is a challenge. New open robotics datasets can help researchers pool resources, but training models in simulations and then porting them over to devices may work better.[34]

### 5-YEAR HORIZON

**Simple AI models become ubiquitous**

The number of devices capable of running simple AI models increases dramatically. This allows companies to generate far more useful insights from sensors and machinery throughout the supply chain, leading to significant efficiency gains. On-device processing also becomes standard for privacy-sensitive consumer applications like fitness tracking, health monitoring and smart homes.

### 10-YEAR HORIZON

**Autonomous robot deployment expands**

Breakthroughs in simulation technology make it possible to train autonomous vehicles and robots far more quickly and cheaply than before, massively expanding their deployment. While state-of-the-art models remain large and centralised, the AI most people interact with on a daily basis becomes highly distributed. Both the training and running of these models is increasingly done on devices at the edge of the network.

### 25-YEAR HORIZON

**Humanity experiences ambient intelligence in the environment**

Improvements in both hardware and software mean it is now trivial to add AI to almost any device. Humanity enters the era of "ambient intelligence" in which every element of the human-made environment responds intelligently to us in an intuitive and almost undetectable way. This dramatically simplifies people's everyday lives, but raises deep questions about distinctions between human and machine agency.

## 1.1.4 Alternative AI

**Despite progress in deep learning and foundational models, recreating the kind of reasoning-driven intelligence that humans have developed may involve coupling it with other approaches. There are question marks over whether the statistical patterns these algorithms learn can ever equate to true understanding.[35] They also require vastly more data and energy to learn than humans, are notoriously bad at transferring knowledge between domains and are incapable of continuous learning. Improving the reasoning capabilities of the models and their extrapolation ability becomes a central challenge.**

Alternative approaches could solve some of these issues. Neurosymbolic AI, for instance, combines statistical learning with structured representations of prior knowledge, often inspired by cognitive science. It appears more capable of common-sense reasoning, and decisions are more readily interpretable by humans.[36] Google DeepMind recently used the approach to solve complex geometry problems at the level of human experts.[37] While deep learning focuses on finding correlations in data, Causal AI seeks to give machines a deeper understanding of cause and effect that could be crucial for general intelligence.[38] And Bayesian AI approaches use the statistics of probability to help AI better understand the uncertainty of the real world while achieving continuous learning.[39]

So far, these approaches have not achieved the same success as deep learning. Many researchers also believe that similar capabilities will emerge spontaneously as deep learning models become larger and more sophisticated. But our theoretical understanding of deep learning lags far behind the practice, making it difficult to spot potential roadblocks to progress. It is possible that some combination of these approaches may be necessary if we want to recreate the kind of general intelligence seen in humans.

### 5-YEAR HORIZON

**Deep learning continues to dominate**

The continued success of deep learning overshadows alternative approaches and diverts resources away from them. Nonetheless, theoretical advances continue and progress is made on building the software tools required to scale these approaches up. Advances in reasoning methods provide more clues about the missing ingredients behind general intelligence.

### 10-YEAR HORIZON

**Emerging scaling laws determine the future of deep learning**

The scaling laws that have governed progress in deep learning could begin to peter out, renewing interest in alternative AI approaches, especially given ethical and other concerns. This could result in a shift to hybrid systems that make use of many different AI techniques to boost explainability, efficiency and reasoning. Alternatively, further scaling of model size could cause the spontaneous emergence of these missing ingredients in deep learning models, reducing interest in alternative approaches.

### 25-YEAR HORIZON

**An entirely unpredictable era for AI achievement**

At this timescale predictions about AI are inherently unreliable. If scaling laws hold, then Alternative AI approaches are likely to become intellectual backwaters. However, if fundamental barriers to scaling arise — in particular, limited reasoning — then the most advanced AI systems are likely to be complex architectures incorporating a wide range of modules running very different kinds of algorithms. Incorporating the best of all of these approaches will make it possible to create generally intelligent AI systems that exhibit adaptability, generalisability, common sense and more advanced forms of reasoning.

1.2

# Quantum Computing

CHAIR:
**Sabrina Maniscalco**
Professor of Quantum Information and Logic, University of Helsinki; Adjunct Professor, Aalto University, Finland

CONTRIBUTORS:
**Sebastian Blatt, John Goold, Cornelius Hempel, Iordanis Kerenidis, Jungsang Kim, Pedro Lopes, Kanav Setia, Sofia Vallecorsa**

**When information is stored in the physical states of objects whose behaviour is governed by the laws of quantum physics, new and powerful forms of information processing become possible. Suitably realised and managed, this creates novel computational capabilities that have the potential to significantly impact sectors as diverse as finance,[1] materials science,[2] cryptography[3] and drug discovery.[4]**

The basic premise of quantum computing is that quantum particles such as atoms, their subatomic components and photons of light (and certain carefully-managed larger objects) can operate in "quantum superposition" states that allow them to encode information in an unprecedented manner. Today's familiar "classical" machines store and process information encoded as the binary digits (bits) 0 or 1. Quantum bits (or qubits) can not only be states 0 and 1 but can also exist in superposition states where the bit can be both 0 and 1 until observed. Leveraging quantum superposition and quantum entanglement, qubits can perform computational routines that are not possible on classical machines.

Qubits must be isolated from the large-scale classical world, otherwise the sub-atomic quantum properties that give them their unique powers are overwhelmed by classical noise. The result is errors in the computations that are extremely difficult to contain. Nonetheless, progress in isolation, noise mitigation and error correction appears to be accelerating, and quantum computing that outperforms what is reasonable and possible on a classical computer could be achieved within the next five years.[5]

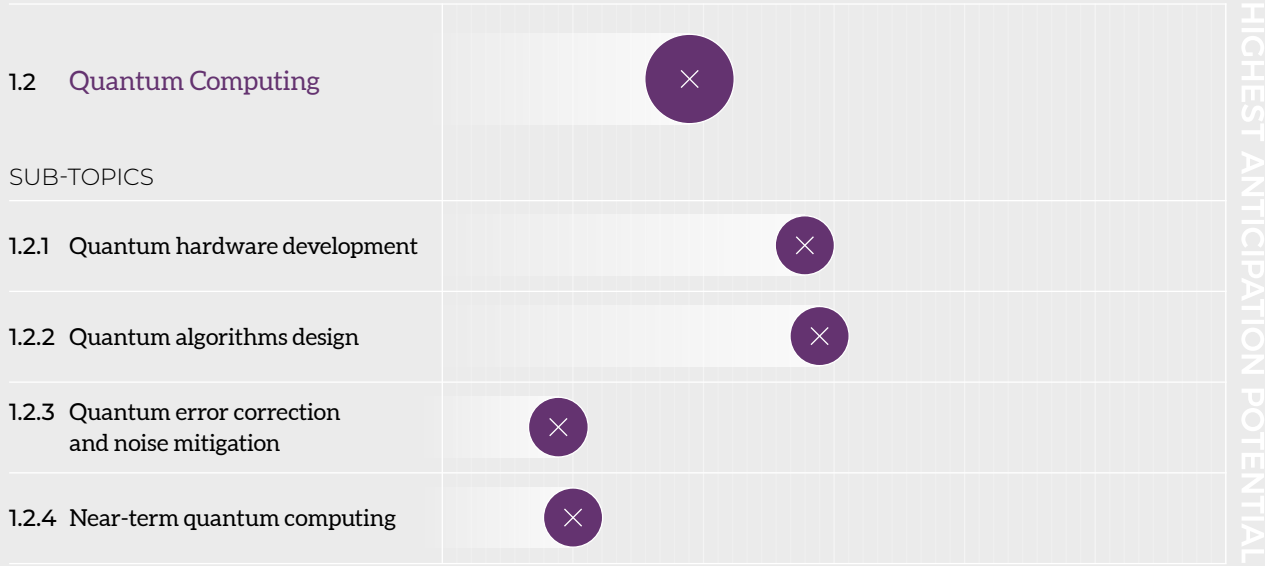
In order to fulfil all their potential as currently understood, it is likely that quantum computers will need to operate with hundreds of thousands of "physical" qubits (for information processing, these are grouped into structures known as "logical" qubits). However, useful computations are possible with far fewer qubits. This is partly because quantum computers will not simply replace or supersede classical machines, but will provide a novel set of capabilities that can supplement classical capabilities in a hybrid quantum-classical setup.

Applications are diverse, but one extremely promising area is quantum simulation. Because they follow the same rules as atoms and molecules, quantum computers can operate as controllable demonstrators of what is possible within physical materials. This is why they will be so useful for tasks such as innovation in battery technology[6] and drug design for medical intervention.[7] Another much-publicised task is decryption. Quantum computers pose a threat to many of today's cryptographic protocols, whose security relies on mathematical routines that are inaccessible only to classical computation.[8] Because the mathematical routines followed by quantum computers are fundamentally different, this security is compromised by the existence of suitably powerful quantum processors that can run a computation known as Shor's algorithm. This is why a number of governments around the world are now investing heavily in "post-quantum" cryptography.[9]

KEY TAKEAWAYS

After more than 40 years in development, quantum computing is coming of age, and looks likely to become a multi-billion-dollar industry over the next couple of decades. Though progress has been faster than expected, **Quantum hardware development** remains a challenge, and there is still no consensus over which of the many hardware approaches will eventually achieve scaleable fault-tolerant quantum computation. Similarly, **Quantum algorithms design** is still in its early stages, and the number and range of applications that are uniquely suited to quantum computing remain small. Because noise-inducing disturbances of any kind are a fundamental obstacle to quantum computing, a significant effort is being made in the field of **Quantum error correction and noise mitigation**. Here too, there is reason for optimism, as implementations are growing in complexity. Implementations of **Near-term applications of quantum computing** are achieving not only proofs of principle, but also rudimentary — and promising — advances in areas such as battery development and cancer treatment.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Impactful breakthroughs in Quantum Computing are expected to happen with a high level of confidence in five to 10 years. Developments in hardware and algorithm design are the sub-topics with highest transformative effects. These are the areas that also require more internationally coordinated action to realise future opportunities, driving the high Anticipation Potential score of this field.

MORE INFORMATION:

**go.gesda.global/1-2**

# 1.2.1 Quantum hardware development

**Because quantum computing is most useful at scale, it is important that the qubits are available in large numbers, connected to each other in low-noise (and thus low-error) configurations. A range of hardware approaches exist: superconducting qubits; neutral atoms; trapped ions; photonics implementations; spins-in-silicon; diamond nitrogen-vacancy centres and several more. There is also a range of architectures: some are based on digital logic gates, others are analogue implementations. All of them have advantages and disadvantages, depending on the envisaged application. As yet, there is no consensus on which approach, or approaches, will ultimately achieve quantum computing that goes beyond what is classically possible. The era of useful quantum computing will probably see a wide-ranging set of options used, with each one suited to different kinds of tasks, running algorithms designed to take advantage of the hardware's specific features and capabilities.**

There is currently no metric by which the various hardware approaches can be compared, but many of them are now sufficiently advanced to allow on-site or remote access (via the cloud) to interested parties. This has created a positive feedback regime, where users are contributing to design and performance improvements. However, the machines and design principles that currently exist are likely to be only a bridge to better future approaches, so there are good scientific and economic reasons for holding off on scaling up many of the current systems.

## 5-YEAR HORIZON

**Access to quantum processors improves**

More hardware originators offer access to end users, creating co-design opportunities and further accelerating innovation. Europe's integration of quantum computing into high-performance classical-computing centres leads to new application ideas. The drive to improve quantum computing hardware creates secondary benefits by further stimulating innovation and demand in classical control electronics, laser systems and other technologies.

## 10-YEAR HORIZON

**Quantum advantage is widely accepted**

Qubit counts on superconducting processors reach many hundreds of thousands, allowing the useful implementation of quantum algorithms able to solve complex problems and generate business value. The performance of quantum computing hardware drives the development of better high-performance classical computing.

## 25-YEAR HORIZON

**The million logical qubit era arrives**

Processors that incorporate millions of logical qubits are routinely available, accessible via cloud services. Hardware development focuses on a relatively small number of the most successful technologies, with "losers" dropping out of the running.

## 1.2.2 Quantum algorithms design

**Software for quantum computing is evolving along with the hardware. At present, there are relatively few algorithms that will make the quantum computing era truly revolutionary. But as hardware becomes more accessible, co-design between hardware and algorithm designers is likely to change that.**

Already of interest is the use of quantum computers to perform quantum simulation. Because they follow the same rules as physical entities on the atomic and subatomic scales, quantum computers can enable discovery and mimicry of the characteristics and dynamical processes of these materials, aiding pure science discovery as well as technological innovation. The most useful calculations of this type are intractable on classical computers. One example is calculating the quantum states of molecules involved in chemical energy storage, which will improve battery technology. Similarly, the details of various chemical reactions involved in the efficacy of pharmaceutical drugs are beyond the capabilities of classical computing, but may be achievable on quantum computers with relatively few (perhaps around 100) physical qubits. Other healthcare and life-science applications are also envisaged.[10] Many quantum algorithms for quantum simulations use both quantum computers and classical ones in an integrated manner. This is because only part of a very complex molecular simulation benefits from quantum algorithms; the rest of it can be performed by conventional simulation methods, including machine learning techniques. This framework is known as hybrid quantum computing and it is considered nowadays the only path to scalability.

There is also increasing interest in using quantum computers to assist machine learning algorithms[11] and financial modelling.[12] Similarly, logistics applications, such as routing and scheduling, may benefit from the advantages offered by quantum search algorithms. As well as mathematically rigorous algorithm design, there is scope for heuristics, where quantum computing advantages can be achieved through trial-and-error approaches.

### 5-YEAR HORIZON

**Niche algorithms provide proof of principle**

The small scale of available quantum computers is reflected in the limited ambitions of algorithm designers. However, a drive for implementable algorithms, combined with increasingly powerful error mitigation methods, creates a wave of niche useful applications whose success encourages further search for areas where quantum computing provides a useful resource.

### 10-YEAR HORIZON

**Quantum chemistry comes of age**

Implementations of chemistry algorithms on large-scale processors are changing materials science and enabling previously incalculable tasks. Breakthroughs in high-energy physics, stimulated by quantum algorithms that simulate subatomic particles, are achieved.

### 25-YEAR HORIZON

**Medical quantum computing algorithms proliferate**

Medical, pharmaceutical and machine learning applications proliferate, with algorithm design benefitting from the ever-growing capabilities of the processors. Significant numbers of financial institutions boast quantum computing divisions that seek to leverage quantum advantage in their sector.

## 1.2.3 Quantum error correction and noise mitigation

**The single most difficult challenge facing quantum computing is the problem of noise. External input of any kind, whether it comes from heat, mechanical vibrations, electrical or magnetic interference from surrounding circuits, or any other source, has the potential to cause "decoherence", which alters the quantum state held in the qubits, instigating errors or even unrecoverable halts in the computation.**

Researchers have long planned to integrate quantum error correction (QEC) resources into their quantum processors.[13] Theoretical research indicates that holding the quantum information in a network of qubits designed to detect and correct errors as they arise can significantly reduce the chances of a computation going awry. Examples include the surface code[14] and the low-density parity code (LDPC).[15] Though this approach increases the required number of qubits, research in this area has uncovered ways in which this overhead can be reduced.[16]

To avoid the overhead of error correction, some other techniques have been effective for "noisy intermediate-scale quantum" (NISQ) devices. These include the implementations of "error suppression", which decreases the errors created in hardware operations, and "error mitigation" routines that inspect circuit operation and inject "inverted" noise to clean up qubit states while a computation is ongoing.[17,18] Other recent error mitigation methods deal with noise fully in post-processing, that is after the readout of quantum computers, and have been proven to be optimal.[19,20] Noise reduction techniques applied to the classical electronics used to control the circuit have also proved to be useful. These can reconfigure the electronics' settings and the signals applied so that the information held in qubits is better protected.

### 5-YEAR HORIZON

**QEC becomes significantly more efficient**

The number of qubits required for implementing effective error correction routines continues to shrink. Qubits themselves are developed to be less noisy. Noise control techniques reduce the estimates of when a useful large-scale quantum computer will become available. Hardware and algorithm designers work alongside error correction specialists to improve co-design outcomes.

### 10-YEAR HORIZON

**Error correction is routine**

The number of provably effective quantum error-correction routines grows, and research makes their implementation ever more efficient. Error mitigation techniques are integrated with error correction in commercial quantum computing.

### 25-YEAR HORIZON

**Qubit availability makes QEC easy**

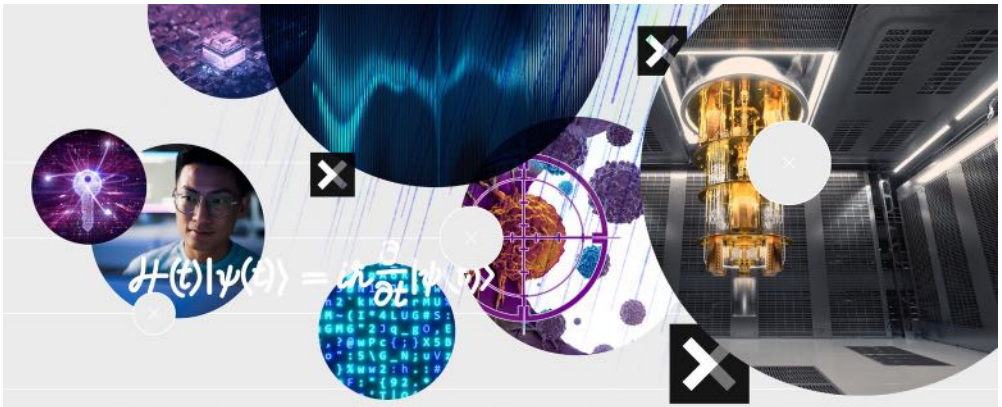
Qubits are available at scale and at low cost, enabling full-scale quantum computers to use quantum error correction routines as standard. Hybrid classical-quantum computing is the standard approach, and noise mitigation and reduction techniques developed for classical circuits remain an important component of the hybrid processor.

## 1.2.4 Near-term applications of quantum computing

**For a number of years now, quantum computing researchers have spoken of computing with noisy, intermediate-scale quantum (NISQ) processors.[21] These processors are not able to perform applications such as those using Shor's algorithm, which requires large-scale, fault-tolerant, error-corrected quantum computers. However, there may be near-term applications where small, noise-affected machines can still perform useful tasks, especially given the growing number of noise mitigation solutions.**

One area of imminent application is in light-activated cancer drugs.[22] Quantum computation allows researchers to design drugs with molecular energy states that allow them to be activated with particular wavelengths of light, which makes the process of generating cancer-killing reactive oxygen species less harmful to the patient than can be achieved using classical means.

Near-term quantum computers could also speed up readouts from quantum sensors and machine learning-based tasks,[23] and simulate realistic models of materials, thanks to recent understanding of measures that can reduce the resources required by several orders of magnitude.[24] XPRIZE Quantum Applications, a competition designed to generate algorithms that can help solve current real-world challenges, may also stimulate progress.[25] (GESDA is the presenting sponsor of this initiative.)



### 5-YEAR HORIZON

**Niche applications make small-scale quantum computing useful**

Bespoke algorithms running on small, noisy quantum processors radically improve resolution of sensing, and are also used for materials and chemistry applications. NISQ processors running in academic labs provide useful insights into noise and other fundamental issues in quantum computing. International trade and collaboration restrictions, imposed due to unfounded fears about decryption capabilities, stifle progress in this era.

### 10-YEAR HORIZON

**New application ideas flood the market**

Algorithms designed for NISQ processors are adapted to improve the performance of larger-scale quantum computers. Interest stimulated by initiatives such as the XPRIZE creates a flood of new application ideas, many of which have positive impacts in niche areas.
.

### 25-YEAR HORIZON

**NISQ machines become learning tools**

NISQ processors are largely superseded for computing purposes, but remain useful for workforce training and algorithm development.

1.3

# Unconventional Computing

CO-CHAIRS:

**Johannes Schemmel**
Head of the ASIC Laboratory and the Electronic Vision(s) Group, Heidelberg University

**Lena Smirnova**
Assistant Professor, Johns Hopkins University, President International MPS Society

**Ángel Goñi Moreno**
Head of Biocomputation Lab, Technical University Madrid

**Charles Roques-Carmes**
Visiting Scientist, Research Laboratory of Electronics at the Massachusetts Institute of Technology

CONTRIBUTORS:
**Chiara Bartoluzzi, Thomas Gorochowski, Yiota Poirazi, Steve Furber, Thomas Hartung, Katarina Vulic**

**The silicon transistor is one of the most far-reaching inventions in human history. However, the exponential improvements in computing performance predicted by Moore's Law have begun to falter as the technology hits fundamental physical limits. This has sparked renewed interest in alternative computing technologies that could provide workarounds to these constraints.**

In part, the interest in Unconventional Computing has been driven by a growing appreciation that information processing is a fundamental part of many natural processes, and that clever engineering can help harness these processes for our own use. Efforts to exploit the unique behaviour of quantum systems — covered elsewhere in the Radar — have achieved the most attention and investment. But a host of other unconventional approaches to computing show promise.

The unique capabilities of the human brain have drawn considerable attention, for example. Today's AI software is already loosely inspired by the way neurons work, but neuromorphic engineers are attempting to go a step further and reproduce the brain's physical architecture in hardware. Others are investigating whether small conglomerations of brain cells known as organoids can be coaxed into solving computational tasks.

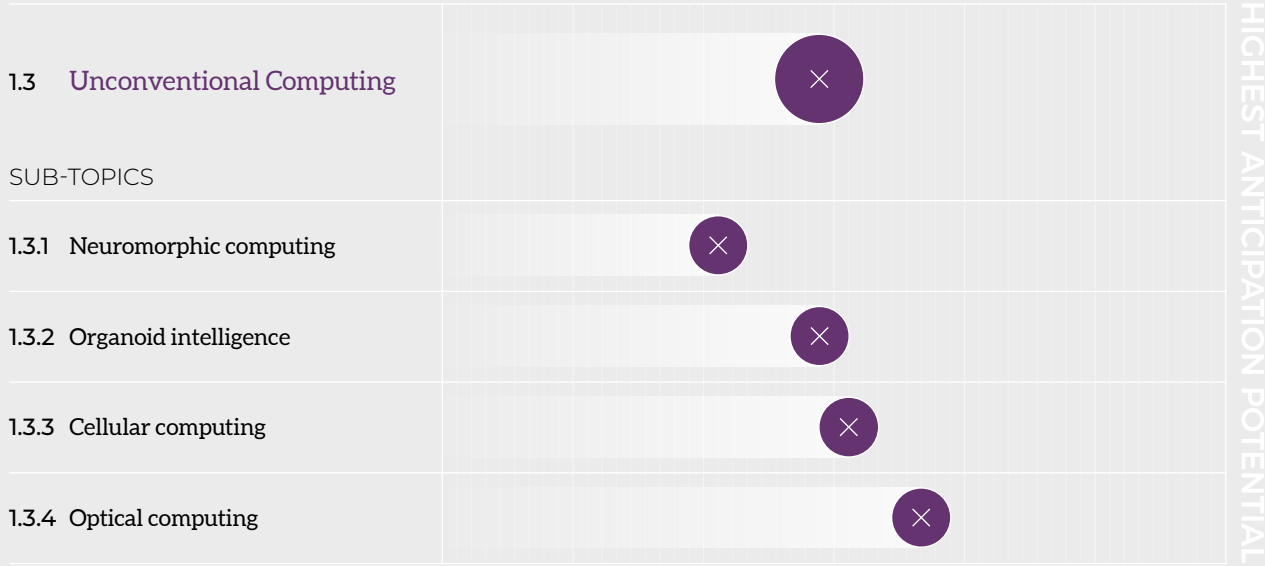
Even simpler biological processes may hold enormous computing potential. DNA's ability to encode, transform and replicate information holds clear parallels to the binary code at the heart of classical computers, and raises the possibility of controlling more complex cellular and intercellular processes that could enable us to go beyond conventional circuit-based computing paradigms.

The prospect of encoding computations in light rather than electricity is also showing significant promise. The approach could offer substantial speed-ups on a variety of problems, including AI, and commercialisation is already well under way.

KEY TAKEAWAYS

Although the standard pathways of computing technology have created a revolution in the human experience, there are other ways of processing information that might offer radically different possibilities. One is **Neuromorphic computing**, where technology aims to mimic the architectures and processes, where they are understood, of the biological brain. Given evolution's role in developing biological brains, this has the potential to be fast and energy-efficient. Also in progress is an exploration of **Organoid intelligence**, where biological brain tissue is grown at very small scale and its signal- and information-processing capabilities explored in in-vitro experiments. In **Cellular computing**, the biological machinery inside networks of cells is being harnessed to solve challenges in areas as varied as environmental remediation and drug discovery. This involves computing with whole molecules as the input and output, and has the potential to perform a variety of tasks that are beyond the capabilities of conventional computing. On a different tack, researchers are experimenting with replacing the electrons of traditional computing with the photons of **Optical computing**. This has several potential advantages, including high data throughput and improved energy efficiency.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

The field of Optical computing is young enough that major breakthroughs are expected to happen further away in time, with a high degree of uncertainty. However, when the breakthroughs do come, they are likely to have highly transformative effects on science. In contrast, Cellular computing is a field that is expected to mature in five years, with a primary impact on society and the economy. There is less uncertainty around future developments in Neuromorphic computing, which has a clearer roadmap to development, reducing the Anticipation Potential score for this sub-topic.

MORE INFORMATION:

**go.gesda.global/1-3**

# 1.3.1 Neuromorphic computing

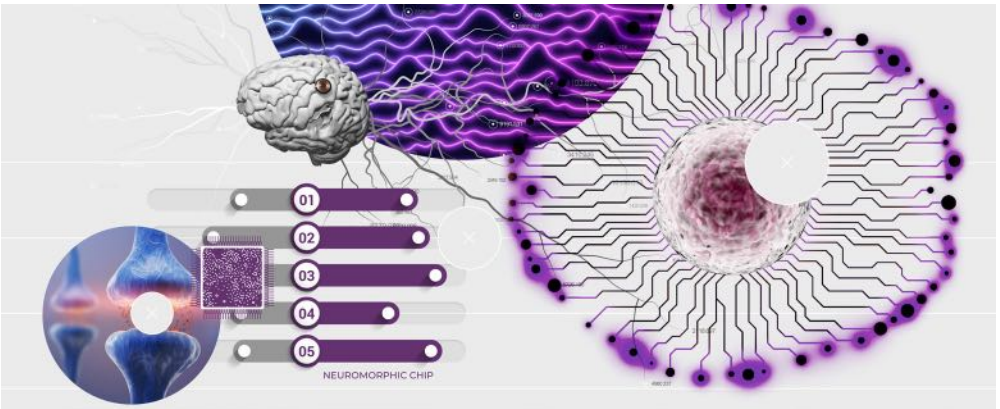
**Neuromorphic computing seeks to replicate aspects of the structure and function of biological neural networks in electronics. The aim is to develop machines that will ultimately display the same capabilities as the human brain, including its incredible energy efficiency.[1]**

This requires the development of new kinds of computer chips that more faithfully mimic the way neurons work and are arranged.[2,3] One particular challenge is to replicate how brain cells communicate via spikes of electrical activity, which is very different from how conventional processors operate. Current models of biological neurons and learning rules are also too simplistic, brushing over physiological details known to play an important role in the brain.

Nonetheless, large-scale neuromorphic systems are coming online. Intel's new Hala Point system combines 1152 of its Loihi 2 neuromorphic processors to emulate up to 1.15 billion neurons.[4] And SpiNNcloud Systems is selling neuromorphic supercomputers based on chip designs pioneered by the SpiNNAker project at the University of Manchester, UK.[5,6]

There have also been breakthroughs in chips that carry out computation directly in memory.[7] These are well-suited to implementing neuromorphic computing, but also holds promise for reducing deep learning AI's energy consumption. That could lead to growing convergence between the two fields.

However, biological realism is still limited. Breakthroughs in mapping neural connections in real brains and more biologically plausible learning approaches are helping close the gap.[8,9] But faithfully replicating the brain's function and structure in silicon remains a distant goal.




## 5-YEAR HORIZON

**Useful neuronal architectures emerge**

New memory-based hardware better suited to implementing spiking neural networks reaches commercial scale thanks largely to demand for more energy-efficient chips for deep learning. Algorithms for navigation, trajectory generation and motor control create building blocks that can be deployed in small robots, but only in research settings as they still underperform deep learning. Neuromorphic technologies that mimic how the brain processes vision and smell show promise.

## 10-YEAR HORIZON

**Neuromorphic computing is developed for embodied AI**

More sophisticated models of neurons and a deeper understanding of plasticity rules boost the capabilities of neuromorphic architectures. Deep learning AI models are increasingly adapted to work on neuromorphic hardware to take advantage of energy savings. Neuro-emulators carry out brain-scale simulations of bio-inspired architectures, advancing fundamental understanding of brain dynamics. Neuromorphic engineers understand how to combine algorithmic building blocks to accomplish complex tasks. Low-power neuromorphic edge devices are used to pre-process all kinds of sensor data.

## 25-YEAR HORIZON

**Experiments demonstrate brain-like memory and logic**

A better understanding of the processes and causal relationships between different levels of the brain develops. Research maps the connectivity and structure, as well as the genetic programs and rules of plasticity by which the structure is formed. Various experimental realisations of neuromorphic computing demonstrate memory and logic that work in recognisably mammalian ways. Robots powered by neuromorphic computing are widely deployed in the defence and care sectors, with AI a pervasive and an integral part of our environment.

## 1.3.2 Organoid intelligence

**Rather than trying to create software and hardware that mimics the way the brain works, an emerging field of research seeks to coax nature's most powerful computing technology — biological neural networks — into carrying out computations.**

This possibility has only just become tractable thanks to recent advances in organoids: simplified and miniaturised versions of organs created using stem-cell technology. Small conglomerations of human neurons have replicated some of the form and function of our brains.[10] Now, researchers are investigating whether these organoids could be used to create new hybrid computing technologies that combine biological and electronic components.[11]

Early experiments have shown that neural cultures can be taught to play video games or show features of reservoir computing.[12,13] If the technology can be scaled up it could have applications in AI and robotics and brain-machine interfaces and could even help us discover the algorithms that power the brain.

Significant advances will be needed first, however, including an ability to engineer larger and more complex organoids, interface with them reliably, and understand how they learn and compute.[14] Combining organoids to create more sophisticated "assembloids" that model several brain regions will be crucial, as will boosting the diversity of cell types.[15,16] Reproducibility and standardisation are major issues currently, as small changes in the environment can significantly impact activity. There are also ethical concerns around when, and whether, more sophisticated organoids could be thought of as conscious entities in their own right.[17,18]

### 5-YEAR HORIZON

**Organoids become more complex and addressable**

Our ability to build complex brain organoids with multiple cell types and extensive vascularisation improves significantly, as does our ability to combine them to create more advanced assembloids. The development of reliable, high-density 3D microelectrode arrays makes it possible to accurately record organoids' neural activity on the surface and in the core of the organoid and transmit data to them for processing. This provides rudimentary models of plasticity and cognition with immediate applications in drug development.

### 10-YEAR HORIZON

**Fundamental science breakthroughs give organoids useful function**

Vast amounts of data collected from experiments with brain organoids helps tease out the specifics of the algorithms that underpin learning and memory in humans. This provides important insights for research into neurological diseases and exciting new avenues for AI. Brain organoids connected to retinal, olfactory and other sensory organoids show promise as energy-efficient environmental sensors. The difficulty of packaging and sustaining organoids remains a barrier to practical applications.

### 25-YEAR HORIZON

**Organoids are integrated with conventional electronics**

Improvements in the technology required to sustain and interface with organoids mean that they can now be easily integrated with conventional electronics in an ethical manner. They are routinely used for sensory functions in robotics and interconnected networks of organoids are now able to carry out highly complex computations. Unconstrained by the body, brain organoids can be built at scales beyond anything possible in nature, allowing them to tackle novel computational problems. The rapidly improving capabilities of organoids provoke ethical frameworks.

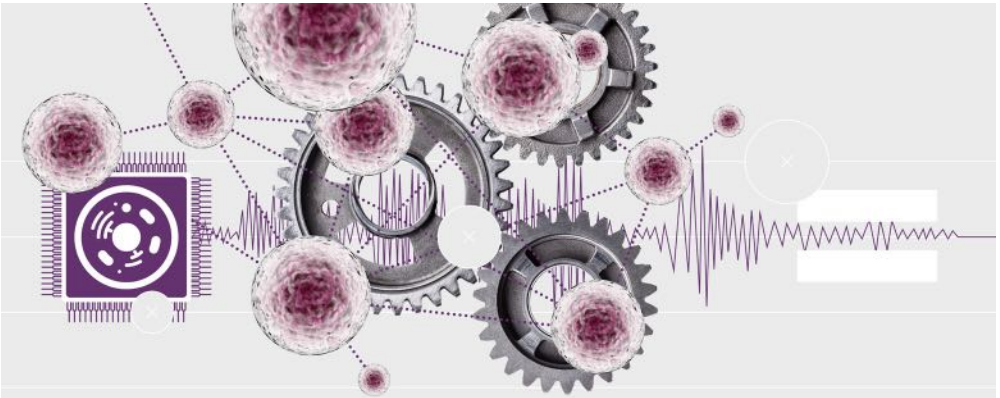
# 1.3.3 Cellular computing

**Many biological processes take a molecular input, carry out some process using molecular or cellular "machinery", and output a different set of molecules. This observation has seeded a field in which researchers attempt to modify these processes to perform useful computing-like routines. So far, most work uses synthetic biology to build "genetic circuits" equivalent to logic circuits in conventional computers.[19]**

Cellular computing can go beyond mimicking standard computing, though.[20] A cell's components can be reconfigured in response to external stimuli, and evolution allows populations of cells to adapt to changing environmental circumstances. They also function well in the presence of noise. There are multiple signal pathways within each cell, enabling concurrent, massively parallel information processing.[21] And communication pathways between cells allow for new forms of distributed computation.[22,23]

This opens up the prospect of performing "whole-cell biocomputations" or even using networks of cells to solve challenges as varied as environmental remediation, drug discovery and medical diagnosis.[24] Neuromorphic computing is proving a useful framework for guiding adaptive cellular processes.[25] And newly engineered plant-microbe communication channels open up the prospect of programming entire ecosystems.[26]

That said, significant improvements in our ability to manipulate and interface with biological processes, and to understand and measure the state of a cell, are needed to make this a reality. The field also needs deeper engagement with theoretical computer science to give it a firmer conceptual footing.



## 5-YEAR HORIZON

**Parts and processes are standardised**

Lab automation makes it possible to conduct experiments at greater scale and AI helps to crunch through the resulting data to provide new insights. Standardisation of biological parts and processes is established, opening the door to commercialisation. This leads to a flowering of computer-aided design tools to help programmers build cellular computers. Biological computing becomes the focus of an increasing number of venture capital-supported companies exploring the commercial potential of the field using proprietary biological hardware solutions.

## 10-YEAR HORIZON

**New biocomputing pathways are designed and developed**

Growing engagement with theoretical computer science results in novel computing paradigms able to harness cells' unique capabilities. Researchers establish ways to harness a cell's metabolism to perform computations, with applications in pollution remediation, disease diagnosis and atmospheric sensing. Hybrid models that combine cellular computing with other technologies show promise. Monitoring the mechanisms of bacterial evolution provides inspiration for the design of new biocomputing pathways.

## 25-YEAR HORIZON

**Biocomputing goes beyond Boolean logic**

Research catalogues an array of natural biocomputing pathways and creates a new, post-Boolean set of logic operations and design tools for information processing. The full computational power of the cells is formalised. Biological computation combines with quantum biology research to create interesting and potentially fruitful new approaches to information processing.

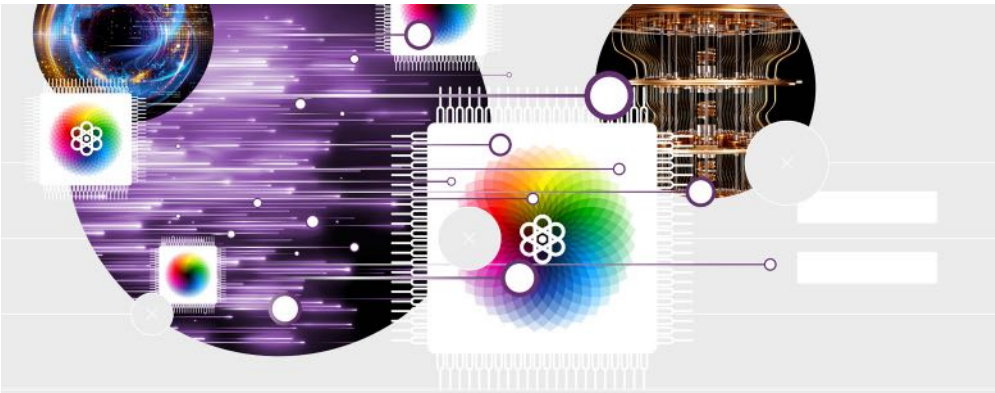
## 1.3.4 Optical computing

**Almost all of the modern world's information-processing tasks are powered by electrons. But scientists have long considered whether the photon — the quantum particle of light — could be a more promising candidate. Optical systems are not subject to electrical resistance and they can transmit data across multiple frequencies in parallel, massively boosting energy efficiency and data flows.[27]**

These advantages have been known about for decades, but recent innovations, driven by investments from the telecoms industry, have started to make optical computing devices practical. Breakthroughs in silicon photonics are making it possible to build sophisticated optical processors using the same technology as the existing chip industry.[28]

The most promising near-term application appears to be in AI. That is because optical processors are very efficient at carrying out operations known as matrix multiplications; these are fundamental to all deep learning algorithms.[29] But photonic technology appears to be a fundamental building block that could also be used to build quantum computers, neuromorphic processors, memristors and even analogue computing devices.[30,31,32,33] The inherent noisiness of optical systems, in particular, is a novel feature that can be harnessed for tasks like probabilistic machine learning and optimisation.[34,35]

There are reasons for caution: catching up with and displacing decades of progress in silicon transistor technology remains an enormous engineering and financial challenge. In addition, photonic chips rely on wavelengths of light measured in micrometres, making it unlikely they could achieve the kind of miniaturisation found in silicon chips that already boast nanoscale features.



### 5-YEAR HORIZON

**Photonic hardware matures and is put to work**

Advances in chip manufacturing make it possible to combine photonic and electronic components on the same chip. These hybrid processors become a popular approach for running computer vision models in applications where speed and energy efficiency are important. Noisy optical chips also become the go-to for implementing probabilistic neural networks. Photonics becomes a popular approach for processing inherently optical signals such as LIDAR and camera data.

### 10-YEAR HORIZON

**Quantum computing embraces photonic hardware**

Photonic approaches to quantum computing gain traction, thanks to the simplicity of the hardware compared with superconducting approaches and their compatibility with light-based quantum and classical communication technology. The technology also enables new analogue computing paradigms that significantly boost scientists' ability to model some complex phenomena.

### 25-YEAR HORIZON

**Fabrication progress creates high-performance photonic computing**

The success of optical devices in certain specialised applications drives progress in fabrication and integration technology, helping photonics to close the gap with silicon-based chips. It becomes a general-purpose computing technology and, thanks to faster processing speeds and much lower energy requirement, replaces conventional computing hardware in several important tasks and applications.

1.4

# Robotics and Embodied Intelligence

CONTRIBUTORS:
**Rachid Alami, Minoru Asada, Aude Billard, Gordon Cheng, Peter Corke, Hiroshi Ishiguro, Danica Kragic, Christophe Leroux, Sergey Levine, Shogo Tanaka, Astrid Rosenthal von der Pütten,**

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**Technologists have long dreamed of automating dull, dirty and dangerous jobs, freeing up humans for higher-value work. Advances in AI are at last opening up the prospect of smart, dextrous robots working alongside humans.**[1]

Robots have played a crucial role in industry for decades, with close to 4 million in operation today.[2] However, getting them off factory floors and into the real world has proven challenging. Despite our ability to build machines that easily surpass humans in terms of power and precision, imbuing them with the intelligence and perceptual capabilities to carry out even the simplest human jobs has proven tougher than expected.

Much of that is to do with the challenges of the physical environment. Traditionally, programming robots has involved creating detailed mathematical models of the robot and its environment, which are then used to deterministically control its actions. The approach is effective for well-defined tasks in predictable environments, such as assembling vehicles in an automotive factory. But this hand-engineered approach struggles with open-ended problems and the complexity encountered in environments that were not designed with robots in mind.

AI, and in particular machine learning, promises a solution to this challenge. These techniques learn how to behave by training on data, which means they are not constrained by the designer's preconceptions. This makes them more flexible and adaptable. There has already been significant success in using these approaches to improve robots' visual perception and navigational capabilities. But recent advances are now making it possible to apply AI to more complex functions like sensorimotor control, planning and human interaction.

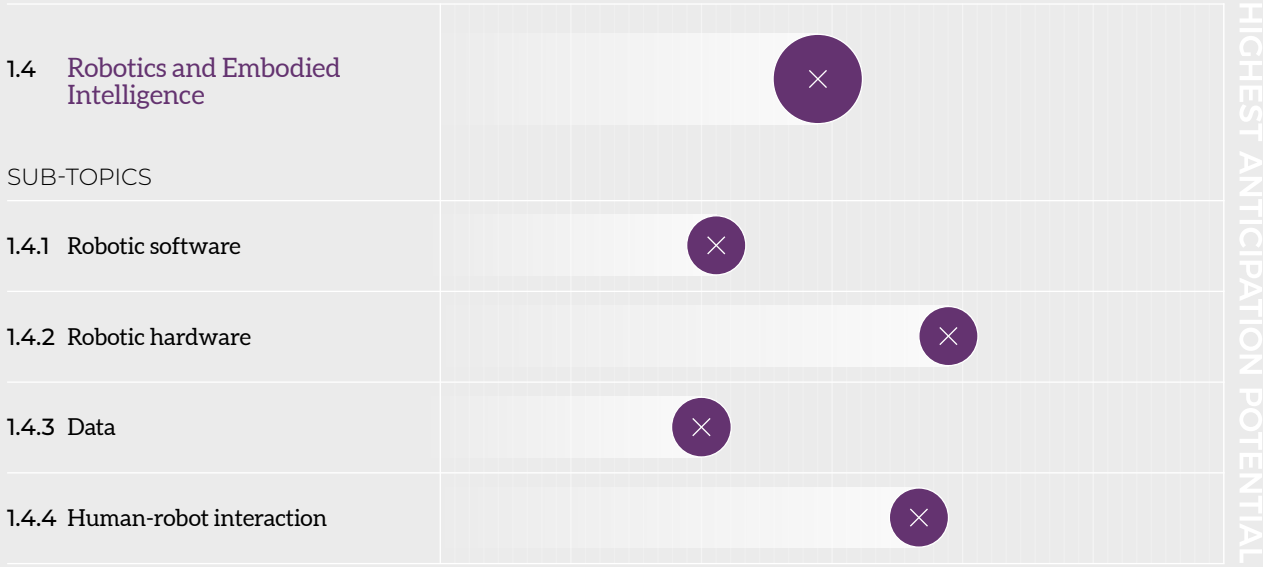
This gives the potential for a new generation of mobile robots to have the physical, and even social, intelligence to work seamlessly alongside us. Some of the most promising use cases are in areas such as logistics, manufacturing, agriculture, food preparation and care work. Thanks to investor exuberance following recent AI advances, funding for these possible futures has been growing significantly.[3]

That said, robots still struggle with tasks that humans find effortless, such as folding clothes or navigating crowded spaces. Solving these challenges with AI will require vast amounts of real-world robotics data that is both difficult and costly to obtain. In the face of shrinking workforces and ageing populations around the world, proponents say the investment will be worth it. However, it is also important to anticipate the potential disruption to employment that could ensue if a significant number of robots start entering the workforce.[4]

KEY TAKEAWAYS

Rapid advances in AI are transforming **Robotic software**, replacing hand-engineered, modular systems with massive models that can simultaneously solve perception, control and planning. Caution is warranted, however, as these models are data- and power-hungry, and their decision-making is hard to decipher. To take full advantage of these new capabilities will also require breakthroughs in **Robotic hardware**. Better tactile sensing could allow robots to take on dextrous tasks currently out of reach for robots, for example. Advances in both battery technology and energy-efficient chips will be necessary to boost mobile robot run times. Open **Data** repositories are helping broaden access and training models in simulations could provide a potential workaround to the problem of AI's insatiable thirst for data. Ensuring seamless **Human-robot interaction** will be more of a challenge. Large language models have opened up a promising new way to interface with robots, but imbuing them with social intelligence and the ability to predict human behaviours remains a distant goal.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

All sub-topics of Robotics and Embodied Intelligence have a high Anticipation Potential score. The main challenge in the field remains the expected major breakthroughs in Robotic hardware technology, which are believed to require another 15 years of research and development before they are realised. Human-robot interaction is a topic that will mature twice as fast and be highly transformative for society. Robotic software is the area that is believed to require the most international coordinated action.

MORE INFORMATION:

**go.gesda.global/1-4**

## 1.4.1 Robotic software

**Robotic control software is typically modular, featuring various subsystems that solve specific problems, including perception, navigation or motor control.[5] Historically, these modules have been hand-coded, incorporating physical models of the robot's hardware and environment, and decision trees telling it what to do in different situations.**

This can achieve impressive results. Boston Dynamic's agile humanoid robots use this approach,[6] for instance — but typically only for highly constrained tasks. Advances in AI mean these modules are increasingly being replaced by more flexible, learned models. Deep learning already powers simultaneous localisation and mapping (SLAM) in autonomous vehicles and drones,[7] and helps sorting robots pick out and manipulate objects.[8] Progress is being made in applying AI to locomotion and planning too.[9]

Transformers — the algorithms behind large language models (LLMs) — promise to greatly expand AI's use in robotics.[10] LLMs themselves provide a more natural way to interface with robots via language.[11] But transformers also power new multimodal models that can work with multiple data types.[12]

At the cutting edge, this is driving a shift from modular architectures to "end-to-end" models that simultaneously solve perception, control, and planning.[13] The ability to draw correlations between different data sources, including language, vision and motion, could allow robots to develop a deeper understanding of the physical world and their place in it — something referred to as embodied intelligence.[14,15,16] Through interactions with the real world, robots also have the potential to overcome AI's "symbol grounding problem",[17] able to link the learned word or "symbol" of an object, such as "cup", to the object's real-world context. In turn, embodiment may allow AI to develop a sense of "self",[18,19] although a comprehensive theoretical understanding of consciousness and its emergence from physical and social interactions remains a challenge.

Moreover, current models are data- and power-hungry and incapable of learning on the fly. Their decision-making is also inscrutable, raising safety concerns. The seamless integration of sensory, motor and cognitive functions will be required to enable real-time learning and adaptation, and breakthroughs in lifelong learning and interpretability will be crucial in the long run.[20]

### 5-YEAR HORIZON

**Mobile robots conscious of their own intent become commonplace**

Mobile robots designed to operate in real-world environments become almost entirely AI-powered. Locomotion in diverse environments becomes a solved problem, greatly expanding application areas. LLMs make it possible for non-experts to direct robots through simple natural-language commands.

### 10-YEAR HORIZON

**End-to-end AI replaces modular systems**

End-to-end approaches to robotic control replace modular architectures for the vast majority of applications. The most advanced robots start to exhibit sophisticated embodied intelligence, allowing them to undertake increasingly complex tasks and rapidly adapt to new challenges. Breakthroughs in interpretable AI as well as social acceptance of the technology allay some of the safety concerns around widespread robotic deployment.

### 25-YEAR HORIZON

**Self-conscious robots become life-long learners**

As the deployment of robotic systems accelerates, autonomous embodied AI systems are capable of complex social interactions, empathy and moral reasoning. Breakthroughs in lifelong learning make it possible for robots to learn directly from their own experience rather than rely on generic pre-trained models.

## 1.4.2 Robotic hardware

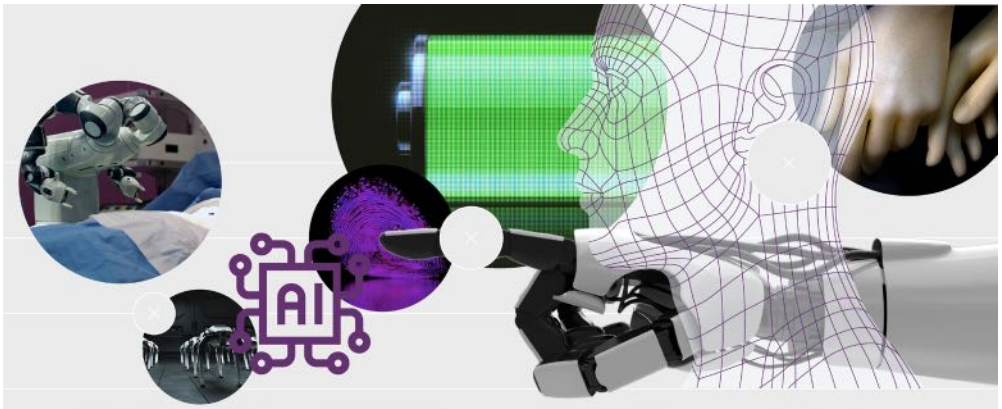
**Software has long been the biggest bottleneck to robotics advances, but for the technology to reach its full potential, breakthroughs in hardware are also crucial.**

Novel manipulator designs are allowing robots to carry out more delicate tasks than were previously possible.[21] But they are still a long way from replicating the dexterity of the human hand. In particular, tactile sensing is still unable to provide the precise feedback crucial for handling soft and delicate objects or operating safely and socially alongside humans.[22,23]

The field of soft robotics could provide solutions, in the form of active materials that can sense and actuate simultaneously.[24] Artificial muscle technology is a promising option,[25,26,27] and the ability to rapidly transition between soft and rigid states could make it safer to deploy around humans than conventional hardware.

There are more prosaic concerns, though. Both the computer hardware required to run AI and the mechatronics that enable robots to move are power-hungry, severely limiting run times for mobile robots. Better battery technology and more efficient chips will be crucial before robots can be more widely deployed. Robotic hardware is also expensive, though prices are falling.[28]

More broadly, there is often a lack of imagination when it comes robotic body plans. Most research is focussed on robotic arms, quadrupeds or humanoid robots, but the technology doesn't need to be constrained to form factors already found in nature. Evolutionary robotics, which adapts robot designs to specific challenges,[29] and robots that can dynamically alter their configuration hold considerable promise.[30]




### 5-YEAR HORIZON

**Robots become master manipulators**

More advanced manipulators and advances in tactile sensing allow robots to take on tasks requiring greater dexterity, becoming commonplace in industries like retail, logistics, recycling and manufacturing. Economies of scale see the cost of robotic hardware fall significantly, further spurring adoption.

### 10-YEAR HORIZON

**Humanoid robots take over**

Breakthroughs in battery technology significantly increase run times of mobile robots. Humanoid robots become the dominant form factor due to the ease of integrating them into environments already adapted for humans. While still largely mechanical, robots feature an increasing number of soft components, particularly those deployed in safety-conscious areas like medicine and care work.

### 25-YEAR HORIZON

**Robot bodies evolve**

Advances in hardware capabilities make it possible to realise the exotic designs dreamed up by evolutionary robotics algorithms, leading to a rapid diversification in robot body shapes. Robots look increasingly "organic" as they are now primarily composed of soft, active materials and powered by artificial muscles.

# 1.4.3 Data

**Today's state-of-the-art AI is incredibly data-hungry, which presents significant challenges for robotics applications. Most recent advances have come in domains like computer vision and natural-language processing, which can take advantage of the reams of image and text data on the internet. But real-world robotics data is much harder to come by, constraining the ability to train sophisticated models.**

Transformer-based AI presents both opportunities and fresh problems. Transfer learning — the ability to take a model trained on one kind of robot and deploy it on another — has been a long-standing challenge.[31] Even small changes in environment or robot configuration can throw models off, meaning robots have to be individually trained. Transformers are able to train on data from multiple robots to create more general policies that work across varied embodiments and environments.[32] However, training one of these models requires colossal amounts of data.

One potential workaround involves training models in simulations before porting them over to real-world robots.[33] But many of the tasks planned for robots, such as handling soft and delicate objects, are incredibly hard to simulate.[34] Designing virtual worlds is also complicated and expensive, requiring sustained effort from multidisciplinary teams.[35]

Pooling data-collection efforts will be crucial going forward, and there are promising efforts to create massive open robotics datasets.[36] There will also be a growing focus on more data-efficient training approaches.[37] Data shortages are likely to ease as more robots are deployed, though this will benefit the private companies that build them more than academic researchers.

### 5-YEAR HORIZON

**Data remains a bottleneck**

Data remains the biggest bottleneck on robotic advances, despite the increasing availability of open robotics data. This spurs the development of more data-efficient training approaches. Ambitious governments start to set up national robotics centres with large numbers of robots that can carry out more ambitious experiments and collect more data.

### 10-YEAR HORIZON

**A virtuous circle eases data woes**

Widespread deployment of robots leads to a steadily increasing deluge of robotics data. This helps accelerate advances, providing a further boost to deployment and creating a virtuous circle of progress. The robotics companies that build the devices are the greatest beneficiaries.

### 25-YEAR HORIZON

**The data crunch is over**

Data access ceases to be a significant problem due to the vast amounts being produced by widely deployed robots and more data-efficient training approaches. Data is no longer a differentiator, encouraging private companies to open up their datasets, providing a boost to academic research.

## 1.4.4 Human-robot interaction

**Most industrial robots today are deliberately isolated from workers due to safety concerns. But ideally, we would like robots to work seamlessly alongside, or even in coordination with, humans.**

At the most basic level, there has been progress on "human-aware" navigation algorithms that allow robots to safely occupy the same space as people.[38] Collaborative robots, or "cobots", are also capable of simple interactions like object handovers.[39] But more sophisticated forms of human interaction are facilitated by deep reservoirs of implicit knowledge about social etiquette, and efforts to imbue this understanding and corresponding behaviour in machines remain rudimentary.

LLMs present a promising opportunity to chip away at these challenges by allowing humans to interface with robots through natural language.[40] There is even tentative evidence that they have some ability to model the mental states of humans.[41] The outputs of these models can be inconsistent and unreliable though, which makes them unsafe to deploy in many real-world situations.

Understanding how humans interact with robots, both physically and psychologically, and what their expectations of the technology are, is also crucial.[42] Better understanding of how integrating robots into groups of humans impacts social dynamics is also needed.[43] Given the prevalence of bias in AI training data, there is a risk that robots could replicate existing patterns of discrimination.[44] Developing socially adept robots which feel empathy, exhibit moral reasoning and act accordingly may also require them to be able to feel pain, raising many ethical questions.[45] Establishing legal guidelines and frameworks to address the rights and responsibilities of autonomous robots will be required.

### 5-YEAR HORIZON

**Cobots enter the workplace**

Human-aware navigation is solved, making it possible for robots to be physically integrated into everyday life. LLMs allow people to have more complex and intuitive interactions with robots. Initial prototypes of robots with basic pain and empathy systems are developed. Collaborative robots become more common in the workplace, though only in the most routine jobs. Avatars, remote representations of real people, enable wider distribution of highly skilled services such as healthcare.

### 10-YEAR HORIZON

**Robots start to read human intention**

Autonomous robots now have a rudimentary ability to understand human intentions and adapt to them. They also grasp basic social etiquette, such as turn-taking in conversations. Collaborative robots are able to take on more complex jobs when paired with a human expert who can guide the machine. There is increased adoption of empathetic robots in caregiving, education and companionship roles.

### 25-YEAR HORIZON

**Humans and robots adapt to each other**

Humans and robots are able to interact seamlessly and work side-by-side in most environments. Robots have developed sophisticated social intelligence and self-awareness, able to understand and respond to human emotions, while humans have adapted to the ways in which robotic "cognition" is different from the way humans think.

1.5

# Augmented Reality

CHAIR:
**Alex Ilic**
Executive Director and co-founder of the ETH AI Center

CONTRIBUTORS:
**Doug Bowman, Doron Friedman, Belinda Lang, Marc Pollefeys, Mel Slater**

**People's digital experiences have become a central part of their daily lives thanks to the advent of personal computers, smartphones and social media. Now real and virtual worlds are poised to become even more tightly enmeshed as augmented reality (AR) technology advances.**

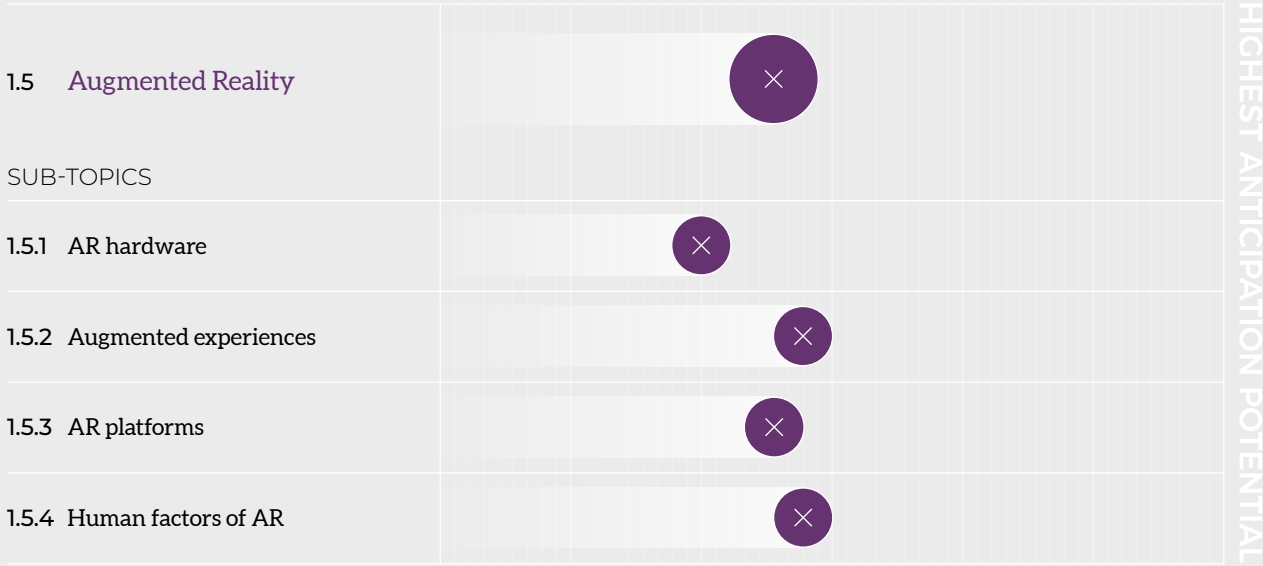
AR refers to the use of display technologies, usually embedded in smart glasses, to overlay digital information and virtual objects onto a user's view of the real world. AR is part of a broader extended reality (XR) ecosystem[1], but its blending of real and virtual makes it qualitatively different from and more impactful from other XR technologies like virtual reality and telepresence. Consumer-grade headsets from Apple and Meta are already bringing a limited vision of AR to the masses. And the technology is finding applications in education[2,3], workplace training[4,5] and industry.[6,7] In combination with data streams from the expanding "internet of things",[8] AR will create an intuitive new layer of information for workers — allowing them to easily and continuously check the status of industrial processes, for example, or providing navigation tools when operating in unfamiliar surroundings.

The ultimate promise of AR is a fundamental transition in the way people interact with computers. Everything people currently use their smartphones for may eventually be beamed directly onto AR glasses that augment their field of view. This shift is being accelerated by the search for devices that can take full advantage of recent breakthroughs in AI language and visual skills. AR headsets could open the door to AI "co-pilots" that see the world from your perspective, providing an always-on, highly personalised overlay of digital information. As hardware improves it could also become possible to seamlessly switch between augmented and virtual reality, opening a door to the "metaverse", which — despite the hype — should be taken seriously as a likely future phenomenon.[9] The blurring of the boundaries between the physical and digital worlds that this entails holds unknown and potentially enormous implications for society.

KEY TAKEAWAYS

As technology progresses, humans' everyday experience of reality is likely to become an integrated mix of inputs from real-world and digital sources. Interfacing with the digital world will become ever more intuitive, and the separation between real and digital existence ever less significant. This will only be possible, however, with progress in the creation of **AR hardware**, especially cheaper, lighter, more power-efficient displays. Once this is achieved, **Augmented experiences** will improve professional performance in medical and engineering spheres, among others. It will also usher in the era of spatial computing, where devices can understand and interact with their surroundings, and present useful data to human senses in intuitive, user-friendly ways. A global rollout of AR will require **AR platforms:** large-scale computing resources dedicated to maintaining both shared and private AR experiences. This infrastructure will involve developing new algorithms, computing and networking technologies, allowing time to consider the **Human factors of AR**. There is significant potential for augmented reality to create means of manipulating individuals and groups, for instance, since real-world and digital information will become ever harder to tell apart. There are also potential upsides: AR will provide a new means of understanding and experimenting on human cognition, and of disease diagnosis and treatment.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Augmented Reality is a rapidly developing field, with major breakthroughs expected over all areas surveyed in only five years. Conversely, research into the cognitive and societal effects of advanced Augmented Reality systems is still far from maturity and remains highly uncertain. This drives the higher Anticipation Potential score for this sub-topic.

MORE INFORMATION:

**go.gesda.global/1-5**

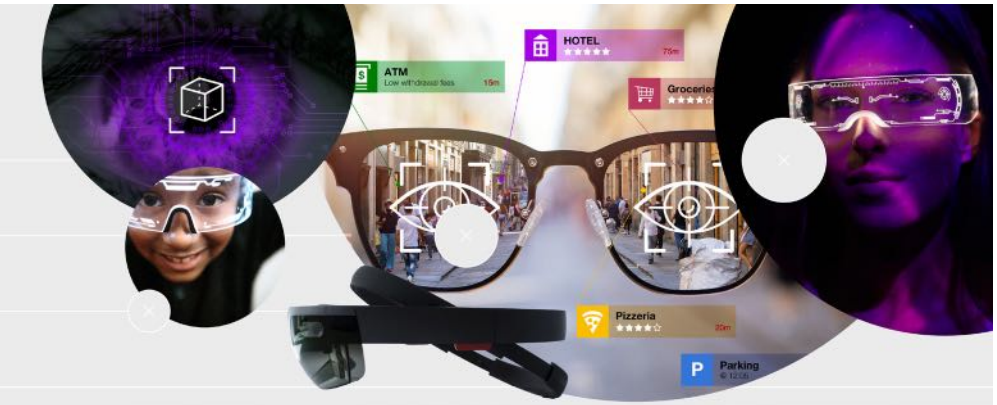
# 1.5.1 Augmented reality hardware

**AR glasses with see-through optical displays like the Microsoft HoloLens 2, Google Glass Enterprise Edition 2 and Magic Leap 2 are already being used commercially. But low display resolution, small field of view, short battery life, bulky form factors and high costs have restricted them to a limited range of tasks. Apple's Vision Pro headset and Meta's Quest 3 also provide AR experiences by streaming a live video feed of the wearer's surroundings to the device's display, interleaved with digital content.**

All of these devices are ungainly and power-hungry. For the technology to achieve widespread use, it needs to be indistinguishable from a normal pair of glasses. This will require breakthroughs in optics,[10] energy-efficient computing and wireless communication, but the biggest challenge is safely dissipating heat from on-board electronics.[11] Balancing the competing pressures will require careful co-design of hardware and software.[12]

Tricks like "foveated rendering",[13] where the eyes are tracked and only the area of focus is rendered in high definition, could help sidestep hardware limitations. A companion device, such as a smartphone that does the bulk of the processing, or sensors with built-in processing capabilities, could also reduce computational loads.[14]

Creating truly immersive augmented reality will also require breakthroughs in generalised haptics that can mimic a wide variety of sensations. Spatial audio could work in concert with visual cues to deepen immersion or guide attention,[15] and physiological monitoring through EEG and skin conductance could help understand the user's intention to optimise the information displayed. Augmented reality may eventually be mediated by brain-machine interfaces connected directly to the nervous system.




## 5-YEAR HORIZON

### Hardware begins to mature

The first generation of AR glasses reaches maturity, with widespread industrial and commercial use for those working in field operations. Optical breakthroughs improve field of view, but most processing is still done on a companion device and beamed to glasses over 5G. A breakout product from a leading device company could start to make consumer applications attractive to a wider audience.

## 10-YEAR HORIZON

### AR displays can be worn all day

The heat dissipation problem is solved, making it possible to build AR devices indistinguishable from normal glasses. This allows people to wear them all day, replacing the smartphone as the primary digital interface. Improvements in display resolution make the devices useful for knowledge work like information processing and 3D collaboration. Devices become capable of switching seamlessly between AR and VR, opening the gates to the metaverse.

## 25-YEAR HORIZON

### AR and VR begin to feel like reality

Generalised haptic interfaces that can replicate a broad range of tactile sensations are realised, making both AR and VR experiences almost indistinguishable from reality. Advances in brain-machine interfaces start to make it possible to transmit visual and haptic information directly to the brain.

## 1.5.2 Augmented experiences

**AR's initial offerings are services such as overlaying instructions or translations on the real world, or participating in virtual meetings.[16] Near real-time interaction is already possible , and AR is now useable in engineering and medical applications. Eventually, AR glasses will be able to integrate complex virtual objects into real-world scenes. However, this will require significant breakthroughs in 3D scene reconstruction[17] and low-latency graphics to improve realism.**

More ambitiously, AR could unlock an entirely new technological paradigm. "Spatial computing" envisages devices that can understand and interact with their surroundings.[18] Sensor-laden smart glasses that project digital content onto the user's environment could bring the idea to life. This transition will be tightly coupled to advances in AI. Increasingly powerful computer vision will allow devices to understand their spatial context, while language and voice capabilities will provide a natural, hands-free way to interface with them.[19]

A crucial aspect will be innovations in user experience:[20] how to present virtual content to people in ways that are both intuitive and powerful. This will require some standardisation in interfaces so that people can seamlessly switch between AR apps. Always-on AR will require careful design to ensure that users aren't overwhelmed with information or notifications.

To achieve this, AR devices will have to become adaptive, using AI to analyse data from physiological sensors and cameras to understand the user. This will require breakthroughs in continual learning[21] — so that AI can update models of the user on the fly — and activity recognition,[22] so that AR devices can understand the user's context and anticipate their needs.

5-YEAR HORIZON

**AR overlays for simple information**

AR is primarily used as a display replacement, overlaying simple information like navigation instructions, translations or diagnostics, or allowing people to make video calls. User interfaces become standardised, making it easier to switch between AR apps. Breakthroughs in continual-learning AI begin to make it possible for AR software to adapt to users, and to enable collaboration and shared experiences.

10-YEAR HORIZON

**Consumer-grade glasses and adaptive user interfaces**

AI-powered adaptive user interfaces that can understand the environment and personalise themselves to a user's preferences will have been perfected in time for the release of consumer-grade AR glasses. Smart glasses become the primary way for people to interact with AI, providing users with always-on AI support in their everyday lives. The boundary between AR and VR becomes blurred as breakthroughs in graphics enable complex virtual content.

25-YEAR HORIZON

**Individually tailored reality becomes the norm**

Virtual content becomes indistinguishable from reality thanks to dramatic improvements in graphics and associated technology. Each AR user now has a personalised AI assistant that continually tailors their experience of reality to optimise all aspects of their life.

## 1.5.3 AR platforms

**Connecting the virtual and the physical worlds will require a new global computing infrastructure. Responsive 3D content tied to spatial information requires far more data and processing than the text, images and videos that make up today's internet. AR hardware will not be capable of providing this alone and so a massive expansion in cloud services will be necessary to render high-fidelity graphics at scale and support the required AI models.[23] Faster wireless technology, including 5G, and edge stations that can bring processing closer to the user, will be crucial for ensuring AR content is delivered with low latency.[24]**

There are likely to be multiple competing platforms providing access to AR, analogous to different operating systems for PCs and smartphones. For the full potential of AR to be realised these platforms will need to be interoperable, which will require the development of common standards for things like 3D graphics, spatial data and the physics governing virtual content.[25] Whether these ecosystems will be open or closed remains unclear, but could have significant implications for the development of the technology.[26]

Platforms will also have to address tricky questions around what elements of AR should be shared experiences and what should be controlled by users. The diversity of content that AR enables will also require innovations in moderation algorithms and technologies.[27]

### 5-YEAR HORIZON

**Early commercial AR applications emerge**

A global roll-out of 5G technology provides the backbone for early commercial applications of AR. Work commences on creating new standards for AR content that will enable interoperability across different platforms and services.

### 10-YEAR HORIZON

**High-fidelity AR experiences transmitted wirelessly**

5G is established and used as low-latency access for off-device computation and streamed applications. The first ideas for using the speed and data capacity of 6G technology begin to emerge, and engineers plan for delivery of high-fidelity AR experiences to headsets via wireless, significantly boosting realism and immersion. Companies dramatically expand their cloud infrastructure to support the huge amounts of data required to support millions of AR users. Moderating AR content becomes a major concern for AR platforms.

### 25-YEAR HORIZON

**Era of the open metaverse begins**

Breakthroughs in the processing power of AR devices means content no longer has to be served from the cloud, reducing infrastructure requirements again. Platforms have settled on common standards that allow seamless interoperability, creating an open metaverse where users can easily transition between different AR services and experiences.

## 1.5.4 Human factors of AR

**AR will lead to a blurring of the boundaries between the physical and digital worlds, which could have profound impacts on human psychology and social relations. The reality-distorting effects of social media are a harbinger of what could come, and phenomena like disinformation, echo chambers[28] and body dysmorphia caused by image filters[29] could all be turbocharged by AR technology. The ability to tweak users' perceptions of the world around them could also manipulate them in novel ways.[30] The personalisation of AR experiences could ultimately lead to a breakdown in the shared reality that is essential for the smooth functioning of societies. Extensive psychology, neuroscience and social science research will be required to understand how AR will impact humanity and pre-empt potential pitfalls. VR simulations of future AR scenarios could provide crucial insights.**

At the same time, AR will provide a powerful new tool to understand human perception and cognition.[31] The ability to simultaneously control sensory stimuli and record physiological responses such as eye movement and skin conductance in real-world environments could provide unprecedented insights for physicians, psychologists and neuroscientists.[32] Such advances could, for example, enable early disease diagnoses, accelerate rehabilitation of cognitive and neurological disorders, and even help optimise everyday behaviours such as eating or sleep patterns.[33]

### 5-YEAR HORIZON

**Research maps out social implications of AR**

Simple consumer AR devices that implement basic features like image filters prompt a major push to study their impact on human behaviour. More advanced commercial glasses become a crucial tool in studying perception and cognition. Immersive simulations of AR in VR help researchers to begin to map out the social implications of the technology.

### 10-YEAR HORIZON

**Government regulation begins**

As AR becomes a consumer technology, concerns around its potential impact on society become more salient, forcing governments to start regulating the industry. AR glasses become a powerful medical tool that provide early warning of disease and help optimise healthy behaviours.

### 25-YEAR HORIZON

**Pervasive AR threatens shared reality**

AR is so pervasive that it becomes necessary to find ways to preserve a shared experience of reality in order to avoid compromising societal cohesion. The ability to create virtual experiences that are indistinguishable from reality makes it increasingly easy to manipulate people for commercial or political purposes, forcing governments to impose strict controls on AR platforms.

1.6

# Collective Intelligence

CHAIR:
**Geoff Mulgan**
Professor of Collective Intelligence, Public Policy and Social Innovation, UCL, London

CONTRIBUTORS:
**Seth Bullock, Mirta Galesic, Martin Kornberger, Thomas Malone, Lex Paulson, Mark Steyvers, Anita Woolley**

**The field of Collective Intelligence (CI) is founded on the principle that when people come together to solve problems, the sum can be greater than its parts. It aims to improve understanding of the dynamics underpinning human collaboration and to enhance and guide these processes to tackle the world's biggest challenges.**

CI is an emerging field, drawing from a broad range of disciplines including biology, psychology, economics and computer science.[1] That said, CI methods are already widely used in various fields, such as citizen science, experiments in democracy, mobilising consumers for product design, predictions in finance, and solving urgent global problems.

The methods of CI make it possible to look more systematically at how teams, organisations and even entire communities think, observe, analyse, plan and create. Better understanding of these processes can then be used to help groups think more successfully.

Principles from CI are being applied in areas as varied as organisational design, citizen science and open democracy, and can help to improve everything from social-media moderation to predicting and responding to natural disasters. Harnessing CI could provide a new, more inclusive and more effective model for global governance,[2] and play a vital role in tackling climate change,[3] the UN's Sustainable Development Goals[4] and a host of other thorny societal problems.[5]

In the last decade, there has been significant growth in the use of technology to enhance the CI of groups, both large and small.[6] This ranges from web platforms designed to coordinate large-scale collaboration to the use of artificial intelligence to facilitate group discussions. The advent of AI chatbots has created a powerful new way for humans to interface with machines, making it increasingly important to consider how AI-human teams will operate in the future.

However, efforts to apply ideas from CI in the real world are piecemeal. The vast majority of organisations are failing to employ simple principles that could significantly enhance their effectiveness, suggesting a need for more translational research. And where there are attempts to harness CI, the practice is often well ahead of the theory. Significant research is required to improve our understanding of the fundamentals underpinning CI and how to design and apply new tools to enhance it. Current models of collective action have delivered innovation, but they themselves have remained remarkably unchanged over centuries; the field of collective intelligence seeks to challenge and alter these paradigms.[7]

KEY TAKEAWAYS

Solving the world's biggest challenges will require input from large numbers of people with diverse experience and expertise, all of whom must be able to work collaboratively. The field of Collective Intelligence (CI) seeks to understand the theory and practice of human cooperation to make this a reality. Thanks to digital technology **Large-scale collaboration** can now be used to solve scientific challenges, innovate new ideas and even revitalise democracy. But organisations and institutions need to be redesigned to help put these ideas into action. Insights into group dynamics and new tools are helping create **Smarter teams** in a time when working practices are in flux. Increasingly powerful AI agents could soon play a vital supporting role and may eventually become team members themselves. But continuing progress is reliant on better models of **Collective cognition** — how groups "think" as a unit. The theoretical underpinnings of CI are fragmented, which is holding back efforts to understand and enhance these processes. Attempts to use technology to boost CI also require advances in **Human-computer interaction** research. Our understanding of how people perceive and use decision-making tools remains piecemeal and AI is a long way from exhibiting the kind of social intelligence required to operate seamlessly alongside human teammates.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

There is little consensus on how to advance towards Collective cognition, increasing the uncertainty associated with this sub-topic and pushing up its Anticipation Potential score. Large-scale collaboration is another area of Collective Intelligence which scores highly, mainly due to the expected transformative effects of future advances on science and technology, and the requirement for more coordinated international action to drive breakthroughs.

MORE INFORMATION:

**go.gesda.global/1-6**

# 1.6.1 Large-scale collaboration

**Digital technology allows collaboration on scales unimaginable in the past. This has led to a reimagining of how humans can organise themselves to solve problems.**

Crowdsourcing information or small chunks of work from large numbers of people can tackle challenges as varied as training AI to predicting floods.[8] Citizen-science projects engage the general public to help scientists collect and analyse data. Open innovation platforms like Kaggle and InnoCentive let companies outsource engineering challenges to independent experts. Deliberative democracy is involving everyday citizens in political decision-making in countries.[9]

New tools for gathering and visualising data, and open-source repositories of information and tools, are helping enhance the CI of large groups. AI is also playing a growing role in facilitating CI by filtering and summarising complex data, organising human knowledge, helping to connect experts and optimising deliberative processes.[10] Powerful large language models (LLMs) are opening up the prospect of AI acting as a facilitator to coordinate group discussions at massive scale.[11] The advent of AI agents that can operate autonomously is driving efforts to understand and exploit the CI of human-AI groups.[12]

While CI has shown promise for generating novel solutions, existing decision-making processes are often too slow and inflexible to take full advantage. This is leading to a growing focus on designing organisations and institutions that promote and harness CI to help with multiple aspects of, and approaches to, thought at scale — including observation, interpretation, memory, prediction and creativity.[13] AI could help here too, suggesting the best organisational set-up for specific problems.[14] Decentralisation technologies like blockchain and quadratic voting also open up avenues for enhancing CI by helping run organisations in a distributed and non-hierarchical fashion.[15]

### 5-YEAR HORIZON

**CI approaches gain traction**

CI-based thinking becomes more ingrained in everyday life, with many tools that originated in CI emerging to help people deal with a range of issues, such as getting support for specific medical conditions, DIY home repairs and business or personal mentoring. Increasingly powerful language and vision AI gradually displaces humans in many crowd-sourcing and citizen-science applications.

### 10-YEAR HORIZON

**CI applications grow**

Tools from CI start to be applied in mainstream applications, as well as helping large-scale approaches to tackling big global challenges such as climate change, access to water and pandemic response. Organisations embrace new tools that combine AI and CI to better organise scientific knowledge and bring in perspectives from more diverse groups. The complicated process of redesigning institutions to better harness CI begins, although organisational inertia and resistance from vested interests holds up progress.

### 25-YEAR HORIZON

**Deliberative democracy becomes widespread**

Democratic assemblies around the world embrace the CI tools of deliberative democracy as standard practice, helping to involve people far beyond the elected representatives in political decision-making. Companies' use of open innovation to solve problems becomes mainstream. Advanced AI agents become ubiquitous, requiring a shift in focus to enhancing the CI of human-AI groups.

## 1.6.2 Smarter teams

**Most human collaboration happens in small groups and this is where the core of CI research is focused. Building on previous work in organisational psychology, behavioural economics and group dynamics, researchers are now trying to understand and enhance the CI of teams.**

This involves solving several challenges, including goal alignment, task prioritisation, progress tracking, maintaining attention, distribution of responsibilities and ensuring that deliberative processes are efficient and equitable. This is becoming increasingly complicated, as more fluid organisational structures mean team composition and structure is often dynamic.[16] Globalisation and the rise of hybrid work also means teams frequently work remotely and asynchronously, raising new challenges for group cohesion.[17]

Nonetheless, research into group dynamics is providing simple yet powerful insights into how to improve the CI of small groups. These include intermittent breaks in collaboration,[18] boosting the variety of solutions explored[19] and ensuring the right balance of cognitive diversity and gender.[20,21] It is also laying the foundations for new tools to enhance team performance. These include real-time visualisations of how much effort members are putting in,[22] information dashboards that summarise people's skills[23] and chatbots that help teams allocate work based on members' expertise.[24] AI is an increasingly important tool, particularly to orchestrate the thought of large groups, to synthesise evidence in particular fields or for the organisation of meetings.

Recent breakthroughs in LLMs also enable sophisticated analysis of conversational dynamics[25] and are opening up the prospect of AI agents working alongside humans in hybrid teams.[26] These agents could be a crucial tool for asynchronous collaboration, acting as a "shared brain" for the group and keeping team dialogue flowing even when members can't speak directly. They could ultimately act as moderators, steering group deliberations to boost CI.

### 5-YEAR HORIZON

**Understanding of team structure and behaviour aids CI**

Researchers develop a better understanding of the team structures and behaviours that negatively impact CI, making it possible to develop strategies to neutralise them. Simple AI-powered facilitators designed to lubricate group deliberations become commonplace.

### 10-YEAR HORIZON

**AI moderates discussions**

Decisions in crucial areas like medicine and criminal justice are made by systems that combine individual human knowledge, orchestrated collective intelligence and AI supervision. More advanced AI systems are now able to moderate discussions between groups of humans in ways designed to enhance CI.

### 25-YEAR HORIZON

**Brain interfaces augment human deliberation**

A combination of AI and crowd intelligence provides the populace with a form of "cognitive autocomplete" via brain interfaces that help them quickly access important information and augment their ability to deliberate.

# 1.6.3 Collective cognition

**A better understanding of Collective cognition — how groups of humans "think" as a unit — will be critical for moving the field forward. Just as in individuals, a group's cognitive processes can be subdivided into various components such as memory, attention and reasoning. But these operate in very different ways at a group level, necessitating novel theories to explain them.[27,28]**

Research has shown that collective cognition is not uniform and is shaped by the social structures in which the groups operate.[29] Groups in the real world also have to navigate numerous, disparate and ever-changing challenges, which means they are in a constant process of adaption.[30] One particularly under-studied aspect of collective cognition is the role of narrative. Stories are central to the way groups coalesce around particular goals or shared visions of reality, which is an essential precursor to any form of collective reasoning.[31]

Increasing use of technology to enhance CI also necessitates the development of new metrics of collective cognition that can be used by digital platforms or AI to improve group collaboration. While there has been progress on defining and even measuring CI itself,[32] decisions about what characterises "intelligent" group behaviour often remain subjective. Taking a multidisciplinary approach that pulls insights from biology, computer science and the social sciences will be crucial for developing a holistic view of CI,[33] and establishing what we mean by "intelligence" may be a precursor to being able to explain and improve CI.[34,35]

## 5-YEAR HORIZON

### Coherent theory of CI emerges

Academic research delineates the various national, cultural and social influences on collective cognition, paving the way for a coherent theory of human CI. Attempts to harness CI for practical applications are increasingly informed by CI theory. A more integrated evolutionary theory of collective intelligence, combining archaeology, primatology, psychology and computer science, among other disciplines, begins to emerge.

## 10-YEAR HORIZON

### Metrics quantify CI

Data-gathering from online collective activities allows researchers to develop metrics for different aspects of CI, producing better models of collective cognition and acting as input for CI-enhancing tools. Large-scale collection of stories from different communities is used to train LLMs, which can then help analyse the narratives driving the collective cognition of society at large.

## 25-YEAR HORIZON

### CI theory incorporates machines

Comprehensive models of collective cognition make it possible to boost the effectiveness of both small and large groups of humans. CI theory is broadened to incorporate increasingly intelligent machines in theories of collective cognition.

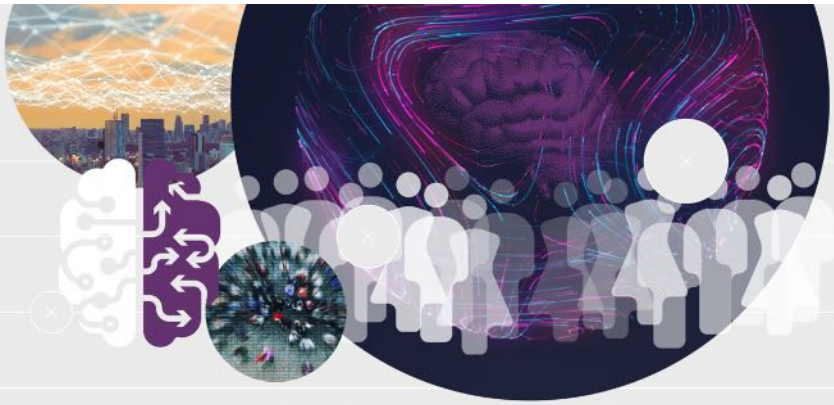
## 1.6.4 Human-computer interaction

**Using technology to enhance CI will require breakthroughs in the theory and practice of human-computer interaction. Computer systems designed to facilitate decision-making have a long history, but have often foundered due to a failure to understand how humans use and perceive such technology. To avoid the mistakes of the past, it is crucial to base the design of interactive systems on fundamental theories of human behaviour.[36]**

There is considerable excitement around LLMs, which have opened up an intuitive new way for humans to interface with computers through natural language. But AI struggles with certain challenging aspects of human interaction. Human decision-making is highly context-dependent, for instance, and that context is not static. Group interactions are also governed by subtle cues and complex social conventions.

AI researchers have made some progress in understanding context[37] and gesture recognition,[38] and there is tentative evidence that LLMs have a rudimentary ability to model human mental states (known as theory of mind).[39] But imbuing machines with true social intelligence remains a distant goal, and will require a multidisciplinary effort spanning the social, behavioural and natural sciences.[40] A concerted effort is also needed to improve our understanding of how humans perceive and interact with conversational AI.[41]

In addition, AI chatbots raise significant privacy and security concerns.[42] And their propensity to confidently assert incorrect information, or “hallucinate”, makes it essential to ensure people understand the technology’s limits so they don’t become overly trusting of it.[43] As technology increasingly mediates group interactions it will also be important to measure whether it is enhancing human capabilities or causing them to atrophy.



### 5-YEAR HORIZON

**Improved interaction boosts effectiveness**

Renewed focus on improving how humans interact with CI tools significantly improves the tools' effectiveness. The increasing use of technology to boost human collaboration prompts efforts to begin monitoring its impact on human behaviour and relations.

### 10-YEAR HORIZON

**AI breakthroughs bring more effective collaboration**

Breakthroughs in key AI capabilities like context-awareness and continual learning make it possible for CI tools to adapt to users and more effectively guide human collaboration. Evidence that some efforts to harness CI are actually causing humans' skills to atrophy prompts a refocusing of efforts on tools that enhance human capabilities rather than replacing them.

### 25-YEAR HORIZON

**Artificial agents join collaborative teams**

Advances in AI make it possible to imbue AI with a true theory of mind, allowing artificial agents to become equal members in AI-human teams. CI-literate AI is used to represent the interests of nature — forests or ocean ecosystems, say — or to represent the interests of future generations. Organisations such as the IPCC and UN use human-AI teams to aid cross-cultural negotiations.

INVITED CONTRIBUTION

# Artificial Cognition

**Chris Eliasmith**

Professor, Founding Director, Centre for Theoretical Neuroscience, Canada Research Chair in Theoretical Neuroscience, University of Waterloo, Canada

MORE INFORMATION:

**go.gesda.global/1-IC-1**

**Recent years have seen repeated remarkable advances in the creation of deep learning systems, most recently large language models (LLMs). These systems have demonstrated the ability to respond to complex natural-language prompts with informative answers and perform a wide variety of cognitive tasks on par with humans.[1] Oftentimes their abilities have surprised many of us and even significantly exceeded the expectations of their creators.**

As a result, there is a growing debate about whether or not these models represent a significant step towards *artificial cognition* — that is, towards building machines that can perceive, remember, reason and solve problems across many domains at human levels of performance. I believe they do represent such a step, and that we stand on the cusp of a technological revolution akin to those that have defined human progress throughout history, such as the printing press, electric light, powered flight and the internet.

Large language models are trained on very large datasets of natural language, usually scraped from online sources, and have impressed many people with their ability to carry on naturalistic conversations. Despite this, it is often claimed that they are not "cognitive" in an interesting way because they only respond to inputs and are restricted to language. That is to say, they do not "think for themselves" and have no conception of the world beyond its representation in text. As a result, they struggle with many forms of reasoning, do not understand causality and are prone to generating erroneous outputs (or “hallucinations”). However, the current AI landscape is rich with sophisticated techniques for improving these models, and enhancements are arriving monthly. We should expect these shortcomings to be mitigated by such advances, particularly when informed by studies of biological cognition.

Despite the apparent differences between artificial and real neural networks — including very different “neurons”, very different connection patterns and very different learning methods — there have also been shown to be strong correlations between artificial networks and how human brains function. For example, in the realm of visual processing, Chengxu Zhuang and colleagues trained a neural network with data gathered from children's head-mounted cameras and found that the representations it learned resembled those found in the primate ventral visual stream — a pathway critical for object recognition and visual identification.[2] More recently, LLMs have also been shown to have some alignment with brain activity in language-processing areas in humans.[3]

Nevertheless, there are many aspects of biological cognition that have not been addressed by the work in deep learning. The dynamic, continuous and interactive nature of biological systems can be particularly challenging for current deep learning methods to capture. As a result, large-scale brain models are also crucial for understanding how various elements of the human brain coordinate to produce the general, dynamic and adaptive intelligence exhibited by humans. Such models — like Spaun, built in my lab,[4] or some of the work done under the aegis of the Human Brain Project[5] — consist of large numbers of simulated neurons, organised in ways similar to neurons found in the brain.

A particular strength of our Spaun model is that it captures high-level behaviour by modelling many components of the brain and organising them in a manner that allows us to investigate how the brain coordinates its parts to solve cognitive tasks dynamically. The latest version of our model, from 2018, has about 6 million neurons and 20 billion connections, and is able to perform tasks including object recognition, copying visual inputs using a muscle-controlled arm, following instructions and solving key elements of a test of fluid intelligence. Building this large, dynamic model has taught us how the brain might exploit the chaotic dynamics of neural activity to solve cognitive problems and provides insights into the neural implementation of cognitive functions ranging from working memory and learning to decision-making and linguistic representation.

What does the future of artificial cognition research hold in this context of LLMs and large-scale functional brain models? Over the next five years, I fully expect LLMs and their extensions to easily pass the Turing Test, which some take to be a requirement for achieving artificial cognition. The key to transcending the current limitations of LLMs probably lies in an integrated approach, extending the modalities to which LLMs can be applied and combining them with techniques used to build large brain models to better capture the dynamics of reasoning and online adaptability. However, others believe that true artificial cognition will only be achieved when we move beyond the limited text interface of the Turing Test.

Beyond this five-year time frame, I expect the integration of these approaches to continue to deepen, resulting in more powerful models that interact on their own with the physical world. Consider how the role of coordinating structures in Spaun could be used to integrate deep neural networks that are function-specific into a larger model. In the brain, this role is played by the basal ganglia — a subcortical structure that is implicated in selecting which actions to perform. Structures like these may be instrumental in harmonising disparate cognitive functions such as vision, motor control, reasoning and language. For instance, imagine that I see a restaurant, determine if I'm hungry and have a method of payment, walk over to the restaurant, navigate my way inside and read the menu. To perform such cognitive tasks, information flow between various brain functions must be controlled and results evaluated to determine the best course of action — exactly the role played by Spaun's "basal ganglia". These capabilities also depend on a self-evaluating and self-correcting system, akin to the human capacity for introspection and error correction. Such a system could potentially eclipse current models in detecting and correcting cognitive errors and do so while being embedded in the physical world.

The evolution of artificial cognition is likely to be driven by the need for systems like this — systems that can handle increasingly complex tasks and make difficult decisions under uncertainty. These would be expected to learn and adapt continuously, refining their algorithms through experiences much as humans do through learning and memory consolidation. The incorporation of social intelligence and an understanding of human values would also become crucial as artificial cognitive systems become more intertwined with societal structures and daily life. The foundations of such behaviour lie in our biology and identifying them may require a deep understanding of emotional processing and related environmental interactions. Continuing to integrate technical and biological approaches to cognition will be essential to expanding the capabilities of artificial agents. This progression could lead to models that not only replicate human thought processes but also develop novel ways of solving problems and interacting with others, potentially outpacing the human intellect in their ability to do so.

As we steer toward this new epoch, the ethical implications of creating entities with cognitive capabilities comparable with or exceeding those of humans will have to be addressed. Questions surrounding the autonomy of artificial cognitive systems, their rights and the legal frameworks governing their interactions with humans and the environment will become paramount. Furthermore, the societal impacts of such advancements could be vast, influencing every sector from healthcare to education, and from defence to policy-making. The economic landscape would also undergo a transformation, as certain jobs performed by humans become redundant, necessitating a reimagining of work, purpose and economic distribution.

As we venture into the next 25 years, AI is poised to evolve in ways that will profoundly affect every aspect of human life. The development of artificial cognition, once no more than science fiction, is fast becoming a tangible reality. The convergence of computational power, rich datasets, an improved understanding of the mechanisms of biological cognition and sophisticated optimisation methods has set the stage for systems with cognitive capacities that challenge our traditional understanding of intelligence.

The pursuit of artificial cognition represents a pinnacle of human technological aspiration, encapsulating our relentless quest for knowledge and mastery over our environment. It is a journey that will undoubtedly reshape our society, our relationships with machines and, ultimately, the very essence of what it means to be intelligent — not only a testament to human ingenuity but a portal to a future replete with both profound challenges and unimagined opportunities.

INVITED CONTRIBUTION

# Superconductivity

**Carmine Senatore**
Head of the Applied Superconductivity Group
at the University of Geneva

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**If you cool certain materials down to a very low temperature, they begin to conduct electricity with zero resistance, meaning that no energy is lost in transmission. This phenomenon — superconductivity — is rooted in quantum mechanics and has far-reaching implications for science, technology and society in sectors such as healthcare, clean energy and transportation. Superconductive materials include alloys and simple intermetallic compounds: those most commonly used are based on niobium, as well as an entire class of ceramic compounds known as high-temperature superconductors, such as yttrium barium copper oxide (YBCO). A third group, iron-based superconductors, was discovered more recently.**

Many will have heard of this field in the context of repeated excitement over potential "room-temperature" superconductors. However, the existence of such materials, much less their discovery, remains extremely uncertain. The greater opportunity lies in making the most of the materials we currently have. Superconductors are integral to the construction of extremely powerful magnets, which play a crucial role in medical diagnostics and research. These magnets permit high-resolution magnetic-resonance imaging (MRI), which has revolutionised medical diagnostics by enabling biological tissues and processes to be visualised and characterised non-invasively with unprecedented clarity and detail.

Further advances in superconductor technology, such as the development of high-temperature superconductors that can generate higher magnetic fields and enable new magnet configurations with smaller-footprint designs, will bring about significant improvements. These advancements will not only lead to a wider diffusion of MRI as a diagnostic tool due to more accessible and compact systems but also enhance imaging capabilities with higher fields. That in turn will facilitate better understanding, diagnosis and treatments: for example, being able to explore brain function at the cellular level will advance neurological medicine. High-resolution nuclear magnetic resonance (NMR) spectroscopy also uses superconducting magnets, in this case for understanding the structure, dynamics and function of complex proteins; this is essential to the development of vaccines and other medical treatments.

Similarly, in oncology, progress in superconductor technology could expand access to advanced cancer-treatment modalities. For example, conventional radiotherapy relies on X-rays or gamma rays to destroy tumours, but these are difficult to direct precisely. Hadron therapy, by contrast, uses beams of charged particles such as protons or light ions. These can be more easily directed to precisely deliver radiation to cancerous tissues while sparing adjacent healthy tissues, offering patients a more effective and tolerable treatment option. However, making such charged particles currently requires large and unwieldy particle accelerators, which has limited the adoption of hadron therapy despite its proven effectiveness. Ongoing research and development effort aims to leverage advances in superconducting magnet technologies to design more compact, efficient and cost-effective systems, paving the way to hadron therapy becoming a mainstream treatment modality.

Superconductivity also holds immense potential for sustainable energy solutions in the pursuit of the transition towards a low-carbon future. The fusion of atomic nuclei could produce vast amounts of clean and abundant energy with minimal environmental impact. However, achieving this in a controlled way is a formidable and long-standing scientific and engineering challenge. The industrial maturity of high-temperature superconductors, capable of generating exceptionally strong magnetic fields, has reinvigorated interest and investment in fusion-energy research, with more than $4 billion invested in private companies since 2021. According to the 2023 report of the Fusion Industry Association, compact reactors could begin to deliver commercial fusion power as early as the 2030s.

Superconducting technologies could also transform the efficiency and sustainability of power transmission and distribution systems. Superconducting cables, capable of carrying up to 10 times more power than conventional conductors of the same size, provide a cost-effective and space-efficient means of upgrading existing grid infrastructure to accommodate higher power loads and mitigate the risks of grid congestion and power outages. This capability is particularly relevant in the context of renewable-energy integration, where the intermittent nature of sources such as wind and solar power necessitates robust, efficient and flexible grid systems. In the context of urbanisation and smart-city development, superconductivity has the potential to enhance power-distribution capacity and meet the growing demands of electric mobility and sustainable urban infrastructure.

By enabling the generation of clean energy, enhancing the efficiency of power transmission and distribution, and supporting advanced smart-grid technologies, superconductors can contribute to the realisation of resilient, efficient and sustainable energy ecosystems that support economic growth, environmental stewardship and social equity. However, superconductor technologies, despite their remarkable promise, present a significant challenge: they only operate only at temperatures between -269°C and -196°C, depending on the specific application at hand. This has long been an obstacle to their widespread, large-scale adoption — but now the potential adoption of hydrogen as a clean and sustainable energy carrier holds promise for facilitating the use of superconductors. Liquid hydrogen also demands cryogenic storage at exceptionally low temperatures (-253°C) to maintain its liquid state. Consequently, the adoption of liquid hydrogen as an energy carrier will drive the widespread development of cryogenic infrastructures that can also be utilised to cool down superconductors.

For example, in energy transmission networks, hydrogen and electricity could be transported together using liquid-hydrogen-cooled superconducting cables, maximising efficiency and reducing costs. Additionally, as part of initiatives aimed at reducing the environmental impact of the aviation sector, leading aerospace manufacturers are actively exploring the feasibility of integrating superconducting motors into future aircraft designs powered by hydrogen fuel cells. Leveraging the cold source provided by liquid hydrogen fuel, these systems would offer the added benefit of cooling the superconductors at no extra cost.

Superconductivity could also enable the development of more powerful and lightweight electric motors, with the potential to revolutionise the design and performance of electric aircraft, trains and ships. For example, the conventional permanent magnets used in electric propulsion systems could be substituted with superconducting coils. This would significantly enhance power output while reducing weight and energy consumption, not only improving the efficiency of electric transportation systems but also reducing our dependence on the rare-earth elements currently used. Such elements are sourced from a limited number of countries, posing a substantial risk to the global supply chain.

In conclusion, the mainstreaming of superconductivity holds immense potential for generating socio-economic benefits and addressing global challenges across diverse domains aligned with the UN Sustainable Development Goals (SDGs), thus for the realisation of a more equitable, prosperous and sustainable future for all.

However, realising this potential requires sustained investments in research and development, supportive policies and strategic collaborations across academia, industry and government to overcome technical, economic and regulatory barriers and unlock the full promise of this remarkable technology. Specifically, investments should be directed towards both basic research and scale-up industrialisation. Basic research is crucial for understanding the fundamental mechanisms and discovering new superconductors, with the dream of reaching room-temperature superconductivity. Concurrently, investments should foster the scaling up and industrialisation of technologies that have been demonstrated. This ensures that the current and potential achievements of superconductors extend well beyond the anticipation of a room-temperature breakthrough, offering tangible solutions to pressing global challenges.

GESDA GEOPOLITICAL LENS

# Anticipating the Geopolitical Impact of Advanced AI

**Emmanuel R. Goffi**
Head of the Ethics, Management, Personal and Professional Project Department, and professor-researcher in ethics applied to AI at ISEP — Paris Institute of Digital Technology, France

**Fabien Toux**
Project manager, Human Technology Foundation

An expanded version of this essay can be found at:

**go.gesda.global/1-Lens-2**

**Artificial intelligence (AI) systems are being deployed on a massive scale throughout the world. While the technology is still developing, it is clear that it will have equally massive potential consequences for a wide variety of sectors — and diplomacy and international relations are no exception. AI systems can act as force multipliers for both war and peace, and in the service of individuals, states, non-state actors — such as major technological players — and the international system.**

In an unpredictable world, forecasting the risks and rewards of these technologies is a demanding exercise. With the rise of AI integrated into complex systems, and more recently the emergence of generative AI systems, the challenge of anticipation has become even more complex. There are two options for analysis: try to imagine the evolution of trends that are already apparent; or try to "think the unthinkable", attempting to foresee developments for which there is as yet no evidence. Over the 10-year horizon, the first approach is the more reasonable — without altogether excluding the second.

Some trends are clear. The development and democratisation of AI systems, their evolution towards increasingly general and autonomous systems, combined with the massive use of social networks and the consequent networking of billions of people around the world, can only be a major cause of concern. In the realms of the "unthinkable", we could imagine that, in a not-so-distant future, AI might become autonomous or even "conscious" (see topic 2.4: Future of Consciousness). In that event, we might, like numerous AI specialists, wonder about the potential existential threat these technologies represent for humanity.

But let us stick for the moment to the foreseeable. AI systems could be influential through their direct application towards conflict, or through their unintended or undesirable effects as they converge and cross over with other technologies and infrastructures. Conversely, they could play a role in maintaining peace and international equilibrium. Analysing massive quantities of data on theatres of tension or conflict could be critical in developing solutions for controlling or resolving them. Such intelligent surveillance systems could be used for early warning of conflict scenarios before they are evident (see topics 4.1: Science-based Diplomacy, and 4.5: Behavioural Science of Groups).

One of the major impacts of AI will undeniably be on communication. In political science, perceptions are a powerful vector of world understanding and therefore a key element which determines peaceful or belligerent behaviour. The actual capabilities of AI systems will be important, but so will the dialogues deployed to argue for the ways in which they are used. AI will represent a fundamental challenge to the status quo in two ways. First, they have a multiplier effect — enabling content to be produced and disseminated with greatly increased speed and scale. Second, they can be used to generate fake or misleading content which is impossible to distinguish from real information.

As AI is exploited by ever more experienced actors with diverse intentions, the combined effect will be to foster the emergence of competing claims to "reality" in which attackers become victims, self-defence becomes aggression and critical events can be presented in any number of ways to different audiences, massively relayed by social networks and the mass media. Thousands of AI-generated images and videos will flood digital space, with no filters to assess their veracity or provenance. The media, overwhelmed by data perceived as information and constrained by the ever-diminishing temporality of news, will relay oriented narratives without having been able to control their source or relevance (see topic 4.5: Behavioural Science of Groups).

As long as these systems are not perfectly autonomous, this capacity for influence will be exploited, sometimes by friendly actors wishing to support peace and international collaboration, and sometimes to inflame hate and generate conflict. The manipulation of opinions and the control of individuals, already historically practised, will be amplified and used to destabilise states or geopolitical areas and discredit individuals or public and private organisations. These narratives — whether peaceful or bellicose — will affect perceptions. Normative debates will become biased, and biased perceptions will lead to distorted analyses and inappropriate positions.

That will, in turn, influence behaviour: false information or synthetic data shapes perceptions and makes diplomatic work and political communication ever more complicated. Geopolitical players will have to come to terms with these competing narratives, with a significant impact on international stability. Diplomacy, largely driven by communication, will become distributed on a large scale among an ever-increasing number of players, whose influence will be broadened and amplified by information technologies and artificial intelligence.

As ideologised and arbitrary positions become established in law and policy, biased perspectives and new conflicts may arise. Today's digital world takes Western perspectives on acceptable positions as pre-eminent, giving them a relative weight disproportionate to their real-world importance. The issue of bias — involving, say, questions of discrimination on the basis of gender or skin colour — is presented as a universal problem to be regulated, whereas it is not universally perceived as a problem. This itself introduces a bias into the treatment of the subject that could find its way into legal norms that would infringe the conceptions or cultural positions of many global actors.

The imposition of these standards through diplomacy, largely led by the West, would therefore be arbitrary, based on a geographically and culturally circumscribed ideology. The greater the complexity of this discourse, the more diplomatic management of international relations becomes a high-risk challenge.

Generations who grow up in a world full of AI-generated and mediated content will develop new relationships with technology and information. Some will elevate AI systems to the status of technical demiurges, with transhumanist movements reinforcing the weight of AI systems by encouraging the augmentation of humans through these technologies. Civilians and soldiers alike will be increasingly connected via exogenous equipment such as augmented-reality goggles or exoskeletons and devices implanted directly in or on bodies (see topics 1.5: Augmented Reality, and 2.1: Cognitive Enhancement).

Ultimately — to return to "thinking the unthinkable" — humans may end up in direct connection with what Vladimir Vernadsky and Pierre Teilhard de Chardin termed a "noosphere": a harmonised collective of consciousnesses similar to a super-consciousness, both natural and artificial. This will allow access to an effectively infinite mass of data that individuals will be unable to process efficiently: humans will be dependent on automated actors who will exploit this data for them and make it readable. The narratives they convey and promote will be revered as truths, regardless of any factual considerations. The human being will no longer be in, on or out of the loop: they will be no more than an element in a network, a cog in a complex system over which their control will have been reduced to a minimum.

## Impacts on warfare

Artificial intelligence will profoundly transform the experience of war, affecting both military personnel and civilians, and raising major ethical and operational challenges. One obvious progression from today's increasing reliance on remote warfare, using drones and heavily computerised weaponry, is to delegate decisions on targeting and deploying force to quasi-autonomous weapons systems controlled by AI. This will optimise and accelerate decision-making but raise new ethical and legal questions, such as calling into question the nature of human responsibility on the battlefield. Just as commercial and custom-made drones have become a weapon of war, so we can expect AI-controlled weapons systems to become widely used outside conventional military procurement, training and deployment. The resulting "civilianisation" of war will raise substantial ethical concerns, inducing a warlike bias within the population itself.

The military, for their part, will have to adapt quickly to these new technologies, even if the integration of AI systems leads to a reduction in manpower and a potential loss of skills inside the armed forces. Augmenting human soldiers through neuroscience and AI may provide new capabilities that compensate for this down-skilling, but will also raise concerns about privacy, individual autonomy and, more broadly, the ability of human action to influence its future and its environment. The race for technological supremacy in military AI will intensify between states and non-state actors, each seeking to gain economic and geopolitical advantage, including access to the scarce resources that enable the development of these systems.

The emergence of these technologies will thus reinvigorate power dynamics, defence strategies and military tactics. This will be amplified by stories of AI systems' success circulating on social networks, while raising questions of sovereignty and technological dependence. A battle for normative influence will be waged in cyberspace, with the emergence of divergent narratives on how to respond to cyberattacks. The qualitative and quantitative explosion of AIs will challenge the established order and weaken international organisations and their credibility, favouring the rise of non-state actors with diverse agendas.

Indeed, the generation of diverse content that does not represent reality and is widely disseminated will help to discredit international organisations that are already struggling to establish their legitimacy. Fake pictures of massacres or atrocities will raise doubts in people's minds about the ability of major international organisations such as the UN or NATO to manage conflicts. We have already seen campaigns to discredit the United Nations, and in particular "blue helmets", but also national contingents, seriously undermining the credibility of peacekeeping forces. The use of AIs to create totally artificial situations and disseminate them on a massive scale will weaken international organisations, foster instability and contribute to international destabilisation.

International law will be ill-suited to the realities of cyberspace and AI, deeply challenging the principles of humanitarian law. Technological developments in the field of AI and cyberspace require a degree of normative flexibility that international law is unable to offer. Moreover, if competing realities emerge, the law will not be able to deal with them all. The applicability of existing laws in the metaverse, for example, remains problematic, because the reality of this space is different from traditional reality. The rules applicable in the tangible world will not be adapted to worlds built around competing realities. The law will therefore not be able to adapt to worlds that are very different from one another, where a multitude of players with various agendas will try to impose their rules.

Faced with these complex issues, a new, solid ethical and legal framework will be essential to guide the development and responsible use of these technologies, while preserving fundamental human values. Multilateral efforts will be needed to establish international standards, involving all relevant stakeholders. But the regulation of AI systems, whether civilian or military, will come up against numerous obstacles, not least the risk of arbitrariness or cultural bias in the new normative frameworks. A "standards war" between major powers will make it impossible to reach a consensus, with the resultant threat to international stability. Influence campaigns will proliferate, themselves amplified by AI systems and their democratisation; these will shape the perceptions of the public and the international community when it comes to the social acceptability of military AI.

## Impacts on peace

AI can also be used to promote peace on a global scale. Visionary individuals, operating as moral entrepreneurs, will be able to leverage their notoriety and influence and capitalise on the democratisation of access to AIs. Using the multiplier power of social platforms and cutting-edge technological tools, these actors will be able to convey a discourse of concord and considerably amplify their advocacy of peace. Their efforts could directly target state and international institutions, with the aim of influencing policies and changing mentalities. This innovative approach, combining the strategic use of AI and the mobilisation of social networks, has the potential to redefine peacebuilding methods, enabling individual voices or committed groups to have a significant impact on political decisions and international peace dynamics. It will also have a direct impact on people's perceptions and individual behaviour.

Soft power will thus incorporate AI technology as an essential component of its action, enabling states to strengthen their strategic autonomy. However, this technological breakthrough will amplify asymmetries between powers, particularly in terms of their ability to develop adequate infrastructures, access the necessary resources and upgrade the skills of their populations. The technological gap will widen, particularly in the military field, where AI-equipped weapons systems will offer a significant advantage to their owners, who will be able to put them to use in the service of international peacekeeping and maintaining security. But this situation of asymmetry will threaten the sovereignty of low-income countries, with implications for the management of peace processes and humanitarian actions.

Nevertheless, AI systems will offer opportunities for peace-building, through their use by state and non-state actors to disseminate peaceful messages, moderate belligerent content and develop non-lethal means of conflict resolution. By processing massive amounts of data, they will also be able to provide decision-makers with accurate analyses, taking into account all aspects of the conflict, and thus fostering the implementation of processes aimed at establishing or restoring positive peace. AI can also revolutionise early-warning systems, improve the effectiveness of peacekeeping operations and facilitate ceasefire monitoring. AI systems can also provide forward-looking scenarios for anticipating and resolving potential conflict situations (see topics 4.1: Science-based Diplomacy, and 4.3: Prediction, Foresight and Futures Literacy).

On top of this, AIs can help define inclusive norms conducive to peace, develop effective communication strategies and identify solutions to information asymmetry, enabling large-scale digital dialogues (see topic 1.6: Collective Intelligence). Finally, they will provide valuable information on the views of populations in conflict zones, as we are already seeing with drone warfare. Remoteness from the consequences of conflict reduces resistance to war, because the price to be paid is lower. Within this framework of positive peacemaking actions, AIs will facilitate dialogue between conflicting parties, and improve decision-making by analysing feelings and narratives.

On an international scale, major international and inter-state bodies will continue to take significant steps to frame and promote the responsible and beneficial use of AI. As part of a proactive approach aimed at harnessing the potential of AI to achieve the UN Sustainable Development Goals (SDGs), its application will make it possible to prevent conflicts, supervise and control peace processes, reduce hunger through better management of food supplies and reduce tensions around strategic resources by optimising their exploitation.

Whether it is a question of soft or hard power, AI systems are force multipliers with undeniable potential. Whether from the point of view of individuals, states and non-state actors, or the international system, the impact of AI systems on peace and war will be multi-faceted and difficult to control. In the absence of real, definitive control, power will belong to whoever has mastered the narrative and can exploit it to their advantage.

GESDA GEOPOLITICAL LENS

# AI Futures, Peace and War

**Peter Kingsley**
Chairman, The Oracle Partnership

**Wendy Hall**
Regius Professor of Computer Science, Associate Vice President (International Engagement) and Director of the Web Science Institute, University of Southampton, UK

An expanded version of this essay can be found at:

**go.gesda.global/1-Lens-1**

**Geostrategic security is in crisis at a time when urgent action on humanity's intertwined environmental, technological and infrastructure systems is critical to long-term sustainability. The natural world, energy, food, water, raw materials, health systems and digital information networks are in volatile transition. Scientific discovery and invention bring revolutionary progress, yet often generate unanticipated systemic risks.**

Artificial intelligence (AI) and other technologies amplify the challenges of the next decade and beyond, threatening to undermine prospects for peace. Yet specialist applications promise to bring solutions, not just to address the root causes of conflict, but to transform governance.

AI systems will act both as force multipliers in conflict and war and yet form part of a set of methods and tools that will revolutionise early warning and, in turn, create the system conditions and pathways to peace.

We believe that novel ways of thinking about possible futures — together with a new generation of knowledge engineering and AI-based simulation methodologies — have the potential to bridge gaps in understanding that are both systemic and strategic, spanning governance and diplomacy.

Indeed, AI-based predictive models and early warning on emerging core-infrastructure crises have the potential to transform the way we govern at national and international levels.

The more ambitious target is to frame governance and policy as system-level interventions set in long-term, scenario-based strategic frameworks. In our view, policy navigational models should focus on early anticipation and prevention of events, ultimately in real time — beyond the conventional, static scenario models and linear forecasts that have constrained governance for decades.

Only by simulating emerging events, possible shocks, surprises and "unknown unknowns" can leadership teams develop shared understanding and recognise the risks of future inter-systemic crises long before they begin to develop momentum.

The grand challenge is to reinvent governance to match the demands of a potentially chaotic world dominated by the cascading impacts of poorly understood, fast-moving events that threaten fragmentation and breakdowns in trust. Nowhere is the challenge as acute or urgent as in the deeply interconnected worlds of AI, peace and war.

There are many theories of how peace turns to conflict and war and how war ends and brings peace. Historians often talk about failures of understanding and failures of imagination. In his book *The Earth Transformed* (Bloomsbury, 2023), Peter Frankopan makes the case that "Much of human history has been about the failure to understand or adapt to changing circumstances in the physical and natural world around us."

The expression "failure of imagination" dominates the narrative in reviews of catastrophic events over the last few decades, surrounding everything from 9/11 to Hurricane Katrina and the 2007-8 financial crisis.

In *The Sleepwalkers: How Europe Went to War in 1914* (Penguin, 2013), Christopher Clark examines leadership behaviour in the lead-up to World War One and concludes that the protagonists were "sleepwalking":

> They were not sleepwalking unconsciously, but all constantly scheming and calculating, plotting virtual futures and measuring them against each other…I was struck by the narrowness of their vision.

The paradox is that humanity's defining talent at the individual level is that consciousness is characterised by constant simulations of possible futures, as the latest models of neuroscience tell us.

In this context, imagined futures are cultural realities — mental simulations that shape decisions in the here and now. They are also contested and so a defining feature of uncertainty, driving everything from rivalry over "industries of the future" and risks of misjudgment and misunderstanding in crises, to competing visions about the future of AI.

These perspectives have growing relevance. Never before have world leaders faced multiple highly interconnected, fast-moving and accelerating threats. As interconnections in a system increase, so do complexity and uncertainty. Creating a shared social sense of reality — critical to political authority, trust and social stability — becomes increasingly difficult. Growing uncertainty feeds public feelings of disorder and threatens traditional leadership norms and institutional authority.

With the acceleration of AI, digital technologies, robotics and open media, the number of interconnections between people, places and things will continue to grow exponentially.

This brings us to some of the critical system-level variables and uncertainties, each with multiple outcomes that will shape the landscape of AI, peace and war over the next decade. To take a simple example, action on climate change may turn out to be "too little, too late". Alternatively, exponential, system-level innovation in green technologies may create drastic cuts in emissions and herald the emergence of a secure, sustainable world.

Looking ahead, geostrategic disorder and chaos may become the new norm, with pervasive conflicts in cyberspace and over supply chains and natural resources. Integrated AI, quantum, neurocomputing and cyberwar technologies may become the defining source of tension and driver of conflict between major powers.

The pivotal uncertainty is the extent to which complexity, uncertainty and speed will overwhelm global leaders and governance institutions at national and international levels. In the absence of a widely shared sense of vision and purpose, a world of unintended consequences may perpetuate tensions between political, public, humanitarian and security interests and well-financed technology companies. Relationships between state and non-state actors may remain locked in conflicts over power and money.

As the digitisation of core infrastructure systems gathers pace, the unresolved threats to security and social stability may grow. Core infrastructures may become part of the volatile and widening digital "theatre of conflict" that extends from media and communications networks to command and control, all enveloped in a web of semi-autonomous AI systems that threaten to create their own realities, transcend boundaries and elude security and governance systems.

This is important because distinctions between machine intelligence and human intelligence are easily blurred. Machines can deliver human-like output, yet cannot be explained in human terms, even by their designers. We are vulnerable to treating AIs as if they were human, with human ethics, emotions, motives and intentions.

Another critical uncertainty is the extent to which AI will amplify the risks of misinterpretation, miscalculation and misjudgement, particularly in the world of military decision-making, peacekeeping and intelligence. At multiple levels, current AIs are opaque. Accuracy, novelty and "edge cases" are problematic. Transparency, explainability, provenance, authenticity and trust in mass-market AI products and services are elusive. They may remain so.

Alternatively, or in parallel, specialist high-trust AI systems and data networks may dominate "mission-critical" areas such as finance, insurance, infrastructure, aviation, shipping, health and security communications. Internationally agreed "guard rails" may embody rules about AI, cross-border cyberwar and disinformation. Much depends on the intentions of major technology companies that may, over time, focus on sustainable development.

Might we see the development of distributed digital worlds, regulated within global norms but controlled at state level, with "sovereign" data and AI systems managed within boundaries?

There are thousands of possible scenarios that may emerge over the next decade. In the scenarios we explore in the full web version of this essay, we draw on our library of simulation models that map multiple "high impact" variables, each with potentially extreme outcomes that will develop and interact in novel and often surprising ways over time. We illustrate just three: Dark Ages, Walled Gardens and Renaissance. These are deliberately extreme possible outcomes designed to inspire dialogue about what sort of world we want.

Any viable organisation must be able to cope with the dynamic complexity and uncertainty of its future environment. The same applies to states, cities, corporations and humanitarian agencies most concerned with creating the system conditions for peace.

The starting point is a shared understanding of possible futures. We define resilience as adaptive policies that work in even the most extreme possible scenarios. In practice, "adaptive" does not mean rapid responses to events but collective action on simulations and foresight in anticipation of crises. The alternatives lead inevitably to "too little, too late".

As the scenarios illustrate, humanity has many choices between multiple alternative futures.

Renaissance describes one of many possible pathways to a more sustainable world. In this positive vision, AI systems have the potential, deployed with human expertise, imagination, inventiveness and a shared sense of purpose, to transform governance, policy-making and diplomacy at national and international levels and, in turn, prospects for peace.

CONFERENCE PROCEEDINGS

# Shaping the Future of Artificial Intelligence

## 1.1 Advanced AI

Although artificial intelligence has been in existence since the 1950s, the astonishingly rapid acceleration in its recent development means that new tools such as generative AI are already being widely adopted across industries and societies in record time. As the impact of AI transcends national boundaries, what opportunities and challenges remain in achieving international cooperation to ensure that AI is used for the common good and in ways that benefit all of humanity?

PARTICIPANTS
Moderated by:

**Alexander Ilic**
Executive Director, ETH AI Center, Swiss Federal Institute of Technology Zürich (ETHZ)

With:

**Alessandro Curioni**
Vice President, IBM Europe and Africa, Director, IBM Research Lab, Switzerland

**Sylvie Delacroix**
Professor in Law and Ethics, University of Birmingham, UK

**Pascale Fung**
Director, Centre for Artificial Intelligence Research, Chair Professor, Department of Electronic & Computer Engineering and Department of Computer Science & Engineering, Hong Kong University of Science and Technology

**Amandeep Singh Gill**
UN Secretary-General's Envoy on Technology

MORE INFORMATION:

go.gesda.global/1-1-Diplomacy

TAKEAWAY MESSAGES

*"From its development in the 1950s to the recent surge in generative AI, artificial intelligence has transcended national and cultural boundaries. Taking ChatGPT as an example, its fast adoption exemplifies the need for proactive consideration and discussion of profound questions about emerging technologies before it's too late to act."*

*"United Nations Secretary-General António Guterres recognises AI's potential to accelerate the UN's Sustainable Development Goals (SDGs) but emphasises the importance of governance to prevent malicious use. There are calls for the creation of a UN entity to govern AI, modelled after UN agencies like the International Atomic Energy Agency, International Civil Aviation Organization or the Intergovernmental Panel on Climate Change."*

*"While the speed in scientific advancement is clear, more innovation in governance is needed. Reinforcing international collaboration means that countries and regions must come together to treat this as a global challenge for humanity, while being optimistic about governance."*

*"As AI models become more multi-modal, learning from images, video and audio, they become more powerful, because machines, like humans, learn from multiple signals from the physical world. Some people refer to this trend as artificial general intelligence and researchers have yet to discover its full capabilities."*

CONFERENCE PROCEEDINGS

# Quantum Solutions for all: The Incubation of the Open Quantum Institute

1.2 Quantum Computing

From drug discovery to global agriculture, quantum computing has the potential to transform industries and societies as evidenced by the awarding of Nobel prizes and billions of dollars of investment over recent years. Join this session to learn how the Open Quantum Institute will ensure that quantum solutions are accessible and available to all for the benefit of humanity.

MORE INFORMATION:

go.gesda.global/1-2-Diplomacy

PARTICIPANTS

Opening remarks by:

**Peter Brabeck-Letmathe**
Chairman, Board of Directors, GESDA

**Ignazio Cassis**
Federal Councillor and Minister of Foreign Affairs, Switzerland

Moderated by:

**Barry Sanders**
Scientific Director, Quantum City, Calgary, Canada

With:

**Matthias Christandl**
Professor, Department of Mathematical Sciences, University of Copenhagen, Denmark

**Sana Odeh**
Clinical Professor of Computer Science, New York University

**Prince Osei**
Director, Quantum Leap Africa

**Laura Piddock**
Scientific Director, Global Antibiotic R&D Partnership (GARDP)

**Matthias Troyer**
Technical Fellow and Corporate Vice-President Microsoft Quantum, Team Smart Current (Allen Baranov of Massachusetts Institute of Technology and Yafa Hassan Jaradat of Palestine Polytechnic University), first prize winners of the 2023 NYUAD Hackathon for Social Good in the Arab World

Closing remarks by:

**Urbasi Sinha**
Professor, Quantum Information and Quantum Computing Lab, Raman Research Institute, Bengaluru, India

TAKEAWAY MESSAGES

*"The official launch of the Open Quantum Institute (OQI) at the 2023 GESDA Summit capped a two-year journey from design phase to incubation phase, ushering in the next start-up phase: a three-year pilot programme hosted by the European Organization for Nuclear Research (CERN). Designed and incubated by GESDA with 130 partners worldwide, the OQI was slated to open its doors at CERN on March 1, 2024."*

*"Scientists and engineers are working on quantum devices for a range of uses such as secure communications, precisely measuring magnetic fields, energy-efficient ways of producing fertilisers and creating materials for batteries with higher energy density."*

*"The potential for new drug discovery, particularly research that could impact the growing problem of antimicrobial resistance around the world, is a promising use case because a drug's molecules are made of atoms that behave quantum mechanically."*

*"GESDA initiated the creation of the OQI to ensure that quantum computing is primarily used to advance the UN's 17 Sustainable Development Goals for 2030. It will work according to three priorities: ensuring access to a pool of private and public quantum computers; promoting education and training in quantum computing; and activating diplomacy to shape multilateral governance rules for quantum computing."*

CONFERENCE PROCEEDINGS

# Quantum Solutions for all: High-Level Political Segment

## 1.3 Advanced AI

Ministers and decision-makers discuss the opportunities and challenges offered by quantum technology.

MORE INFORMATION:

go.gesda.global/1-3-Diplomacy

PARTICIPANTS

Moderated by:

**Alexandre Fasel**
State Secretary for Foreign Affairs, Switzerland

With:

**Sarah Bint Yousef Al Amiri**
Minister of State for Public Education and Advanced Technology, United Arab Emirates

**Viscount Camrose**
Minister for AI and Intellectual Property, UK

**Ignazio Cassis**
Federal Councillor and Minister of Foreign Affairs, Switzerland

**Patricia Gruber**
Science and Technology Advisor to the Secretary of State, US

**Joel Hernández Garcia**
Under-Secretary of Foreign Affairs, Mexico (video message)

**Yoichiro Matsumoto**
Science and Technology Advisor to the Minister of Foreign Affairs, Japan (message)

**Emilija Stojmenova Duh**
Minister of Digital Transformation, Slovenia (video message)

**Péter Sztáray**
State Secretary for Security Policy and Energy Security, Hungary

**Tatiana Valovaya**
Director-General, United Nations Office at Geneva

*"High-ranking government officials from countries in Asia, Europe, the Middle East and North America strongly endorsed an initiative to scale up the Open Quantum Institute (OQI) in Geneva as a hub for ensuring the technology is accessible and is used in service of the UN's 17 Sustainable Development Goals for 2030."*

*"Ministers and top-level advisers participated from Hungary, Japan, Mexico, Slovenia, Switzerland, the United Arab Emirates, the UK and the US, along with Tatiana Valovaya, Director-General of the UN Office at Geneva."*

*"Countries, notably those from the Global South, not only want access to quantum computing resources but also the opportunity to co-develop them."*

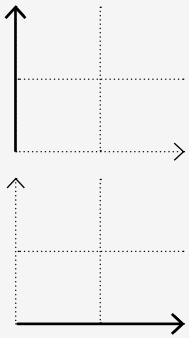
*"The latest UN assessment of the SDGs, a roadmap to shared peace and prosperity endorsed by the 193-nation UN General Assembly in 2015, shows 85 per cent of the associated 168 targets are off track and unlikely to be accomplished."*

*"Switzerland wants the OQI to serve as an umbrella for quantum national strategies by exploring use cases for quantum technologies to maximise the chances while minimising the risks."*

# Media-Innovation Analysis

Collective Intelligence and Advanced AI are driving innovation and public discourse whereas the scientific advancements in Robotics and Embodied Intelligence and Augmented Reality are not receiving corresponding coverage.

LEGEND:

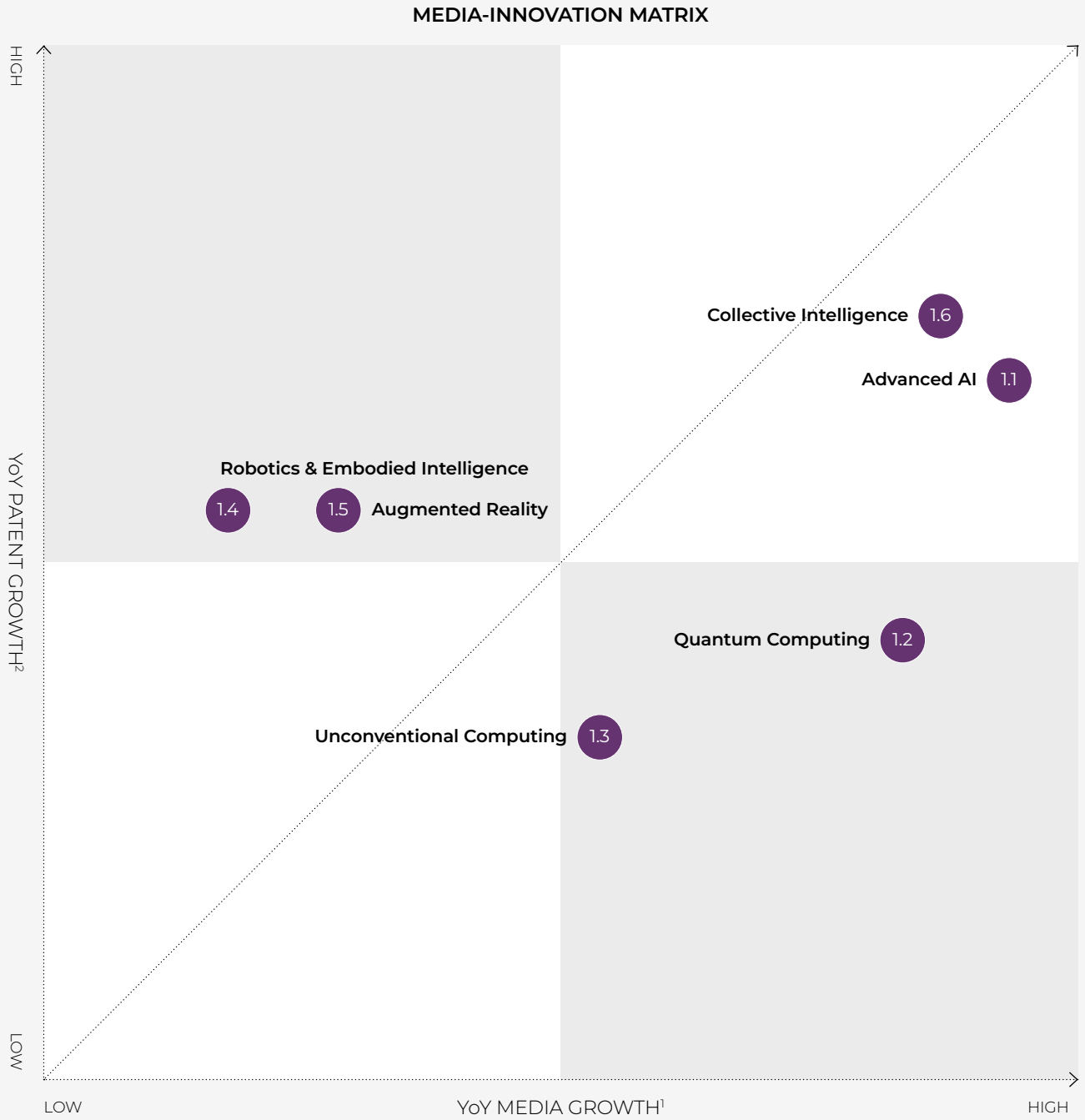


**YoY PATENT GROWTH**
YoY (year-on-year) growth of granted topic patents[1] from May 2022/April 2023 to May 2023/April 2024

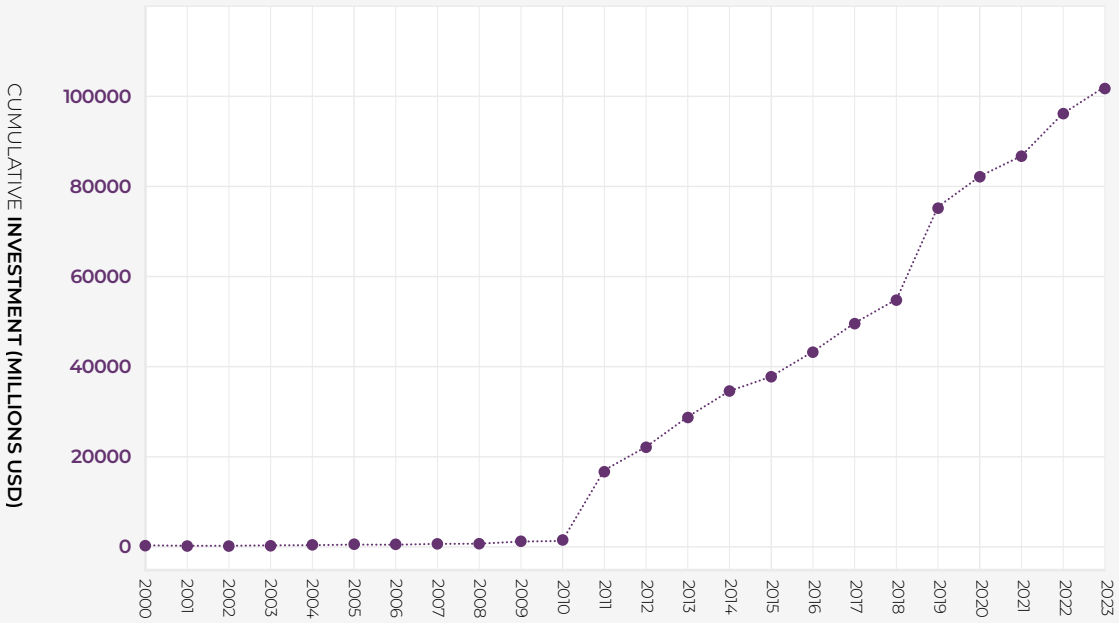
**YoY MEDIA GROWTH**
YoY (year-on-year) growth of topic mentions in news and blogs from May 2022/April 2023 to May 2023/April 2024

MORE INFORMATION:

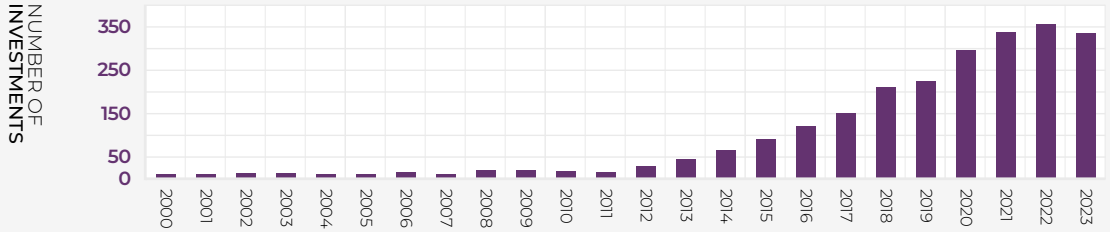
go.gesda.global/Impact



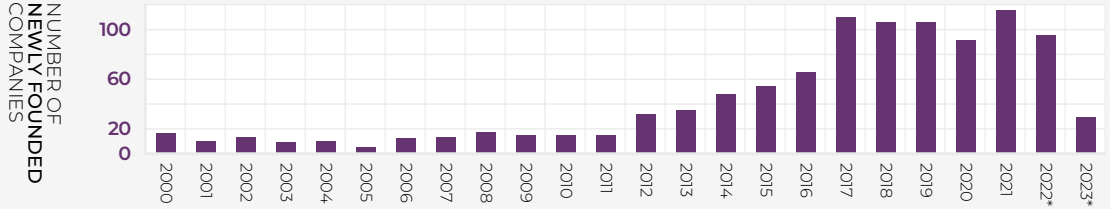
## CUMULATIVE INVESTMENT IN QUANTUM COMPUTING COMPANIES




## NUMBER OF NEW INVESTMENTS IN QUANTUM COMPUTING COMPANIES




## NUMBER OF NEWLY-FOUNDED QUANTUM COMPUTING COMPANIES




IMPACT FOCUS:

# 1.2 Investment and Company Creation in Quantum Computing

Investments in quantum computing companies took off in 2011, one year after the publication in the scientific journal *Nature* of a first "quantum machine" capable of using quantum physics to control a mechanical object. This achievement — awarded "breakthrough of the year" by the American Association for the Advancement of Science — initiated a series of fundamental developments which have demonstrated the practical usability of quantum computing. After a surge of new companies created in 2017, the rate of company creation has remained steady since. The value of investments in these companies has kept growing, with no sign of the 2020 pandemic- and economic-related slowdown in investment observed in other sectors.

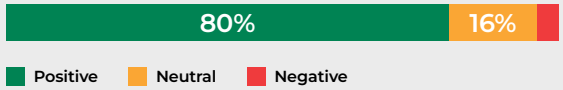
Source, facing page: Deep View analysis from 1 May 2022 to 20 April 2024; (1) YoY media growth = YoY growth of topic mentions from May 2022/Apr 2023 to May 2023/Apr 2024; (2) YoY patent growth = YoY growth of granted topic patents from May 2022/Apr 2023 to May 2023/Apr 2024.

Source, this page: Pitchbook
*Data on newly-founded companies in 2023 is incomplete and will be updated once first funding is raised. Projections indicate similar levels of company creation to 2021.

## What do people say?

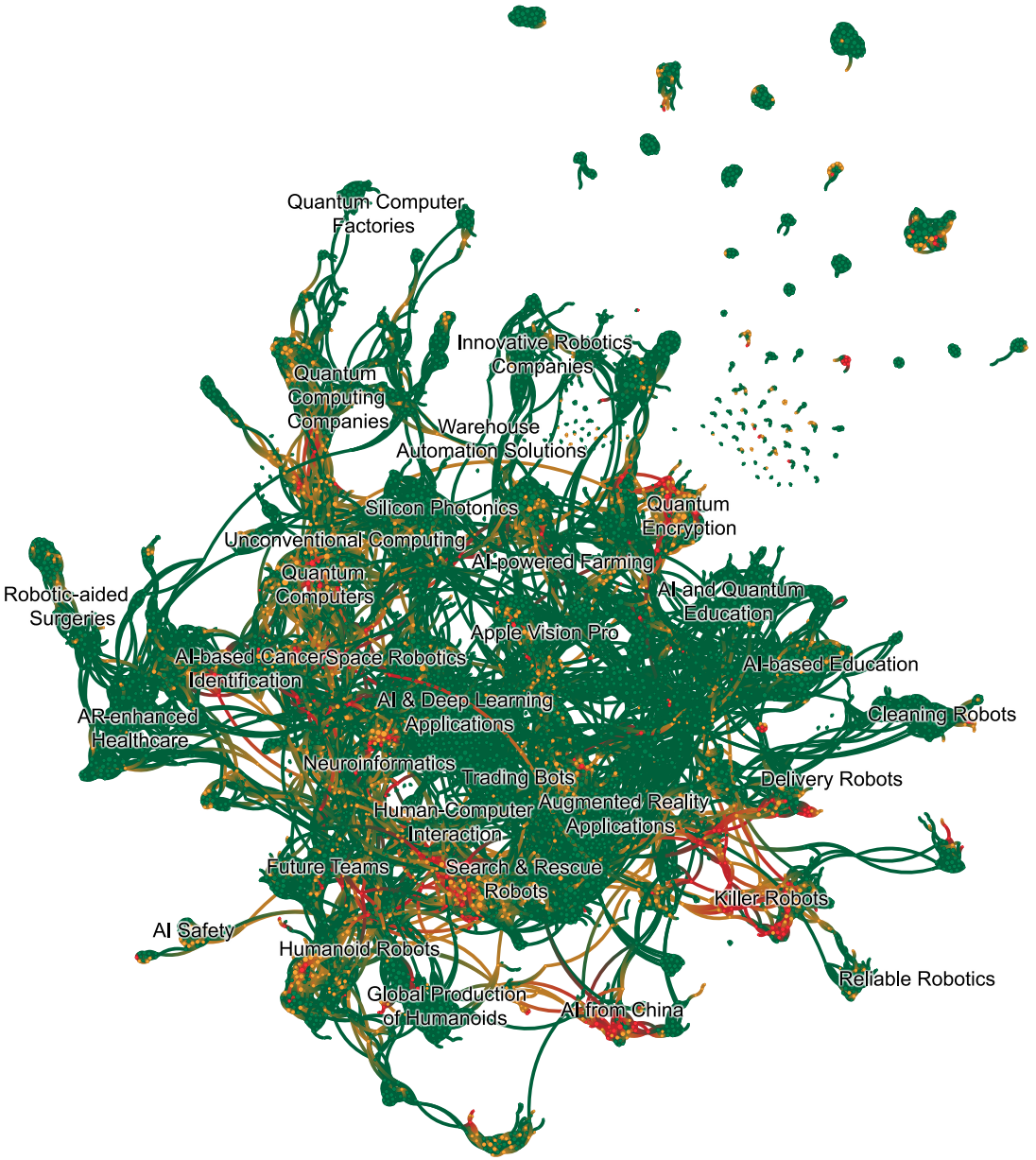
Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months shows that recent breakthroughs in Artificial Intelligence are fuelling many discussions in the domain of the Quantum Revolution & Advanced AI. Despite the commonly-quoted fears around the potential threats associated with these disruptive technologies, relating to security issues and human agency, the conversation about these topics is overwhelmingly positive, with an overall positive sentiment of 90 per cent, as assessed in mainstream media outlets.

MAINSTREAM MEDIA SENTIMENT

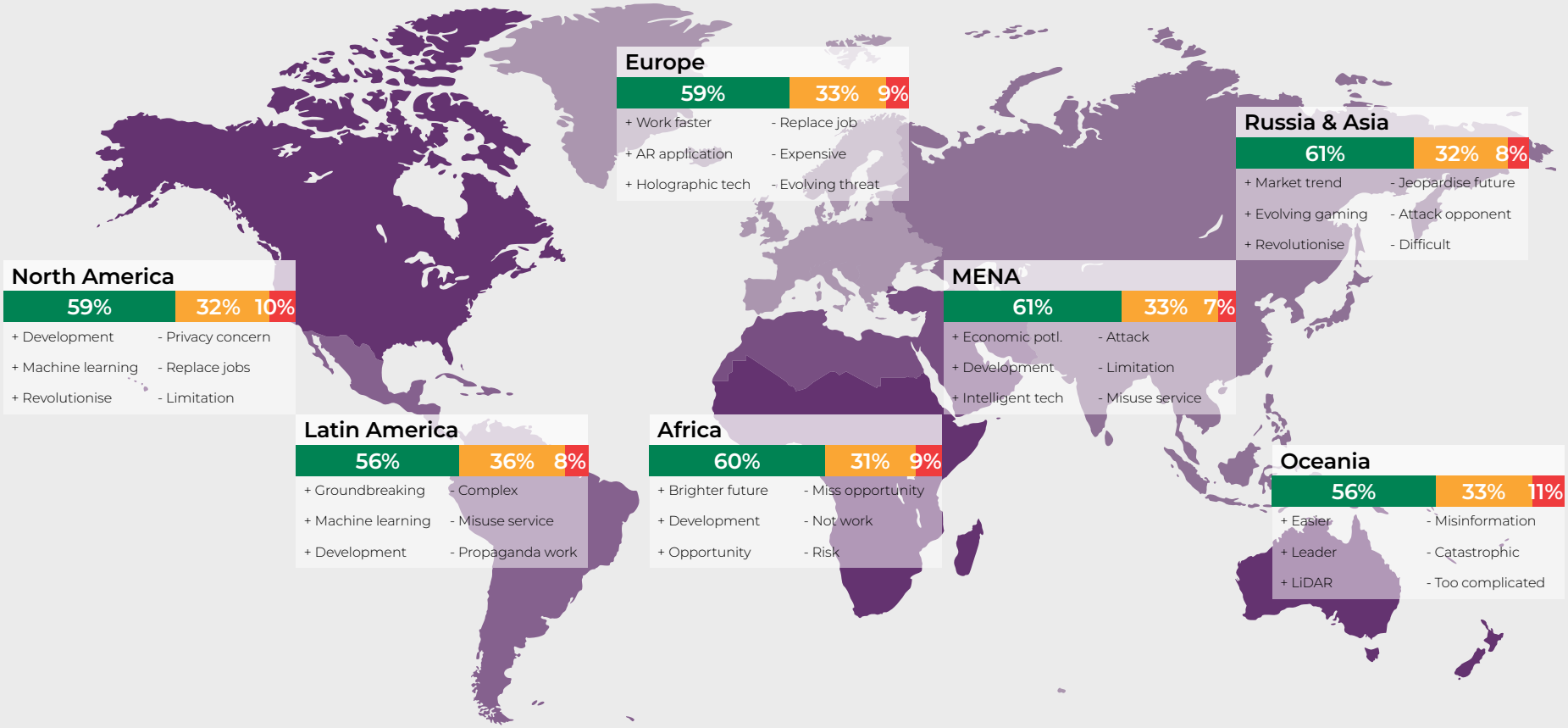



| MAINSTREAM MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| UNIQUE ARTICLES | **510**k |
| VISUALISED ARTICLES | **6**k |
| NET SENTIMENT | **90**% |
| ARTICLE UNIQUENESS | **13**% |

| SOCIAL MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| NUMBER OF POSTS | **3754**k |
| VISUALISED POSTS | **10**k |
| NET SENTIMENT | **73**% |
| UNIQUE IMPRESSIONS | **333**b |



## DEMOGRAPHICS & SENTIMENT PER REGION




## GLOBAL SENTIMENT

- Across the globe, sentiments towards Quantum Revolution & Advanced AI are **generally positive,** with these technologies widely recognised as **catalysts for economic growth**.

- Major concerns include the **potential for job displacement**, a sentiment that is particularly strong in North America and Europe. In **emerging regions like Africa, Asia and Latin America**, there is apprehension regarding the local workforce's ability to **harness these complex technologies** for economic benefit due to perceived gaps in necessary competencies.

- The distribution of discourse varies by region: **in North America, 95% of posts originate from the United States** with the remainder from Canada. **Latin America shows diverse contributions, with 26% originating from Brazil**, 17% from Mexico and 24% from Colombia. In the **MENA region, 37% of posts come from Turkey** and 21% from Saudi Arabia.

- In **Russia & Asia, 52% of the discourse is led by India**, with other countries contributing relatively equally. Meanwhile, in **Oceania, Australia dominates the conversation**, accounting for 79% of posts, with other contributions being minimal.

Source: Quid Social, containing the past 24 months of English language data from 10+ social media sources in 200+ countries.

# Media Analysis

GROWTH

Advanced AI, the fastest-growing emerging topic, and Robotics & Embodied Intelligence dominate public discussions related to the Quantum Revolution & Advanced AI, accounting for nearly two-thirds of all news and blog mentions.

DOMINANCE

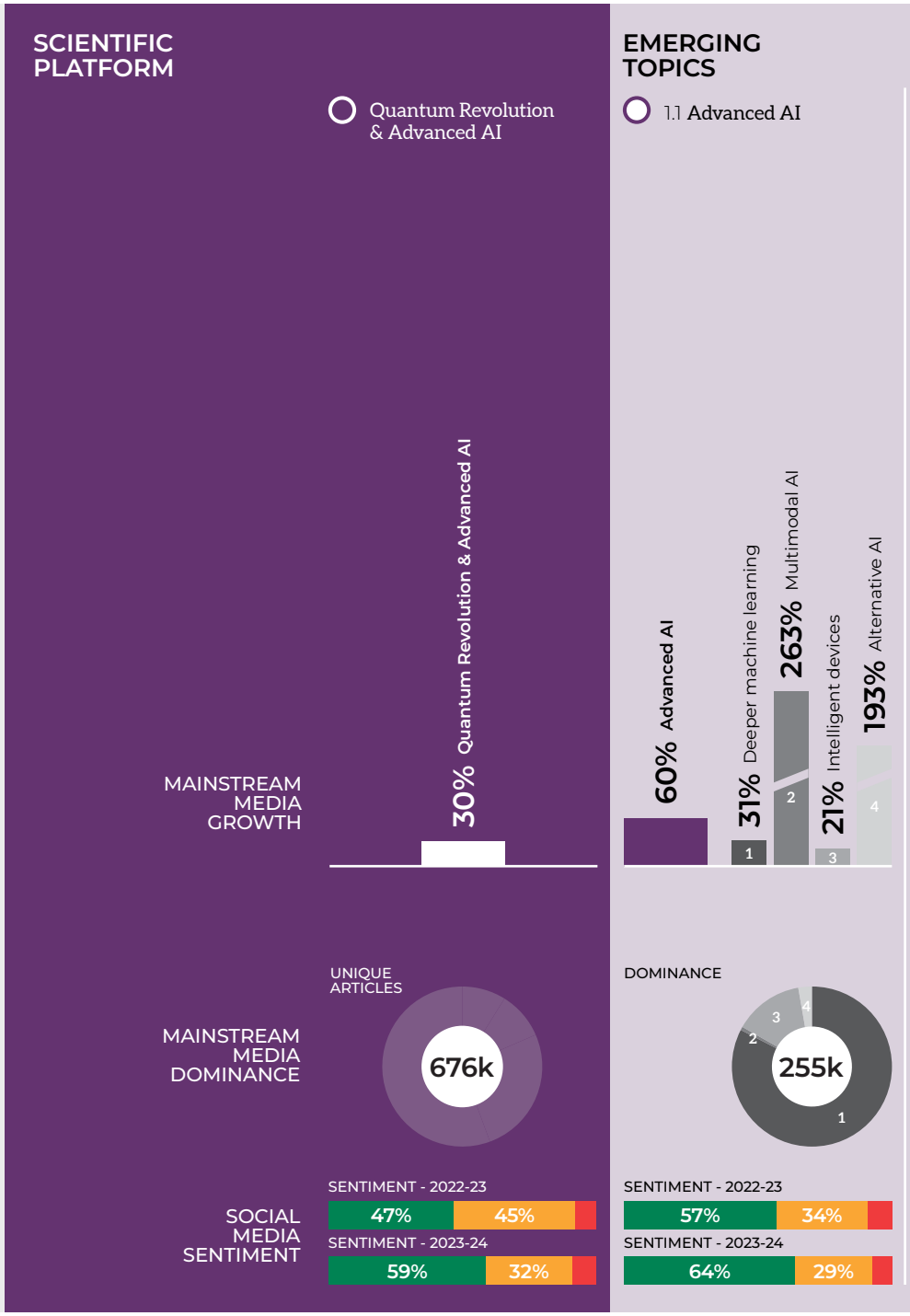
Individual sub-fields within the context of Artificial Intelligence are rapidly gaining traction, especially discussions around AI for robots and Multimodal AI, which have increased significantly, by 312 per cent and 263 per cent, respectively. While the public discourse around Augmented Reality is stagnating compared with other emerging topics, the public interest in Collective Intelligence has increased by 37 per cent, highlighting the growing importance of tech-enabled collaboration.

SOCIAL SENTIMENT

Social media sentiment towards Quantum Revolution & Advanced AI is very positive, indicating an increasing tech optimism.

MORE INFORMATION:

**go.gesda.global/Society**



## 1.2 Quantum Computing




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 1.3 Unconventional Computing




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 1.4 Robotics & Embodied Intelligence




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 1.5 Augmented Reality




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 1.6 Collective Intelligence




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24

SCIENTIFIC PLATFORM

2

# Human Augmentation

Our understanding of human biology is now advancing to the point where researchers are beginning to find ways to enhance cognitive abilities, engineer the genome, extend healthspan and create novel solutions for fighting disease. If any of these innovations are to achieve their full potential for improving human well-being and establishing more inclusive societies, questions of how, why and for whom they are deployed must be addressed. Here, we examine the research on human augmentation now under way, and anticipate how opportunities may be realised for future breakthroughs to be truly transformational.

PULSE OF **SCIENCE** (pages 90-133)

Containing deep insights into anticipated advances associated with Human Augmentation over the next 5, 10 and 25 years, the GESDA Pulse of Science reports the opinions of leading researchers working in the fields of cognitive enhancement, genetic engineering, healthspan extension, consciousness research, organoids and advanced therapeutics.

PULSE OF **DIPLOMACY** (pages 134-135)

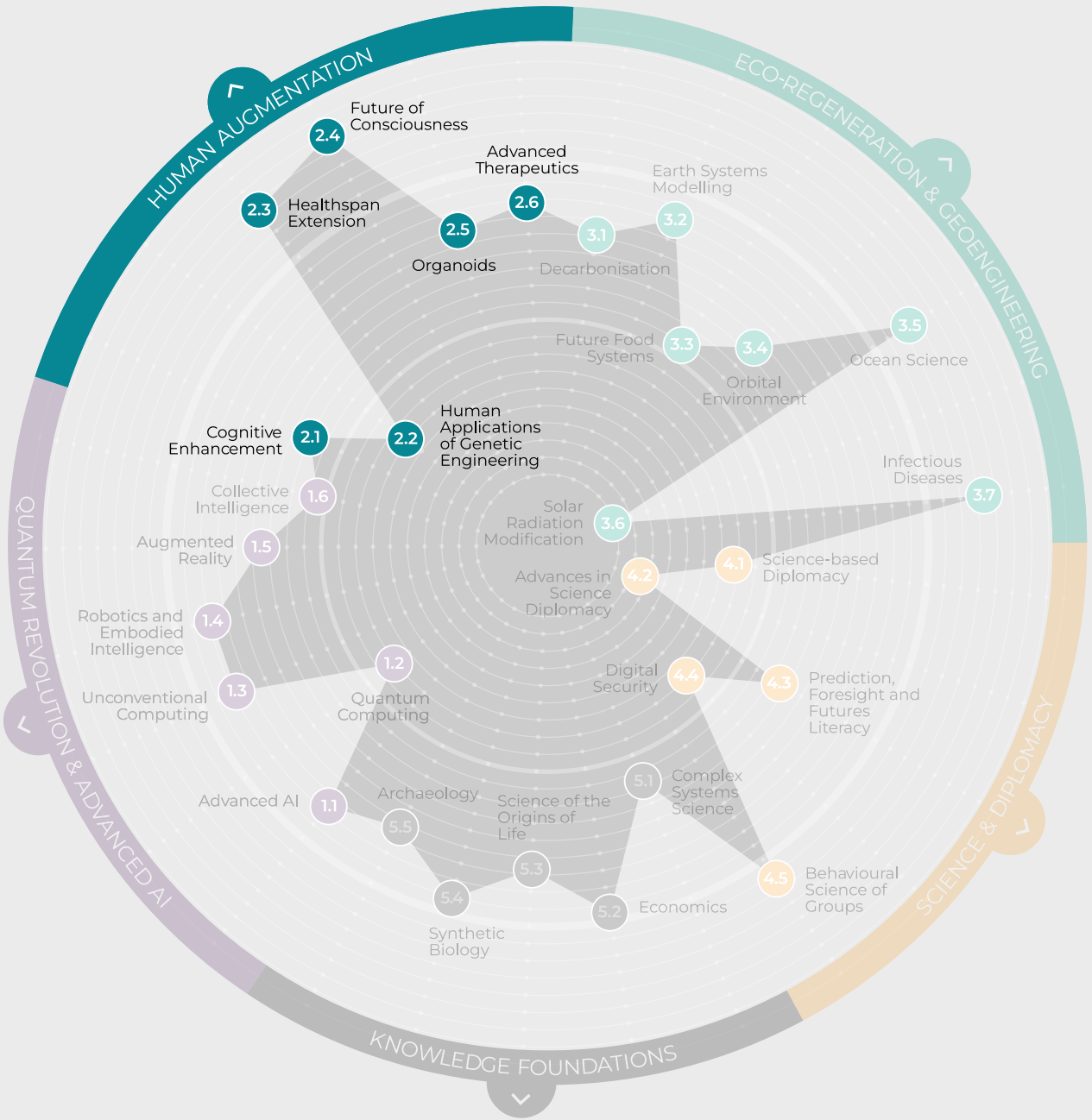
The GESDA Pulse of Diplomacy captures the latest discussions between diplomats and scientists at the 2023 GESDA Science and Anticipation Summit, covering topics such as disease prevention, brain implants, the development of organs for transplant and prospects for mitigating the effects of ageing.

PULSE OF **IMPACT** (pages 136-137)

Current investment trends and dynamics of company creation highlight cognitive enhancement as an increasingly significant topic. The GESDA Pulse of Impact provides data detailing private-sector investment, intellectual-property activity and company creation in this area since 2000.

PULSE OF **SOCIETY** (pages 138-141)

Powered by AI, the GESDA Pulse of Society's network and dynamic sentiment analysis of both mainstream and social media reveals macro and micro trends in public opinion around the world on topics relating to human augmentation.



2.1

# Cognitive Enhancement

CHAIR:
**Jaimie Henderson**
Director, Stereotactic and Functional Neurosurgery, Stanford University School of Medicine; Co-Director, Stanford Neural Prosthetics Translational Laboratory (NPTL), Stanford University

CONTRIBUTORS:
**Olaf Blanke, Andrew Hessel, Itzhak Fried, Bryan Johnson, Michael Kahana, Johannes Gräff, Baptiste Gauthier**

**The 21st century has seen an acceleration in our ability to decode cognitive states from both invasive brain implants and, increasingly, non-invasive techniques. It has also become possible to manipulate those brain states in increasingly targeted ways using a wide spectrum of methods, from electrical to chemical.**

Thanks to these recent insights from neuroscience and the development of tools able to restore impaired brain function, demands for upgrades to healthy cognitive functioning have steadily grown.[1] The field is making very rapid progress and by the end of the decade commercial systems for restoring communication are likely to emerge, as are further advances in understanding how the brain turns thoughts into words.

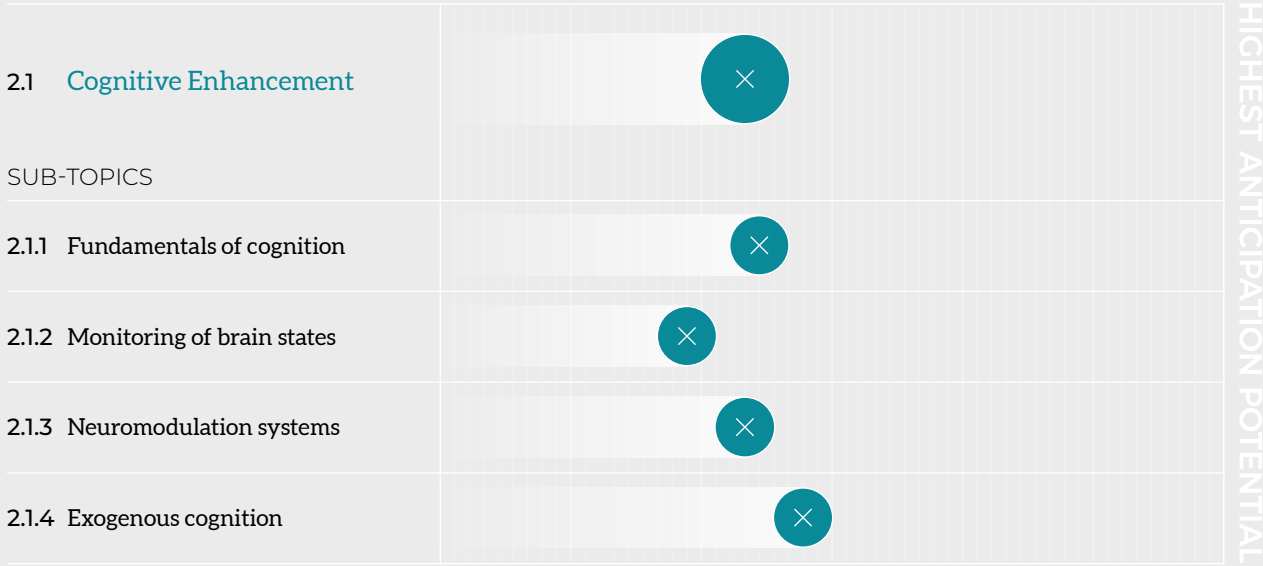
Most existing investigations into cognitive enhancement have sought to restore it when deemed disordered or impaired, for example to aid people with incapacitating disorders of memory such as Alzheimer's disease. More recently, new stakeholders have emerged in the race to monitor and boost cognitive states in healthy people. Imminent brain-monitoring technologies, aided by ever more capable AI, provide the ability to decode and alter cognitive and emotional states and make them increasingly transparent. Several employers already use monitoring, for example to ensure employees do not lose focus or concentration while driving or operating machinery.[2] Systems to enhance, rather than just monitor, cognition vary in their efficacy. Truly successful enhancement of healthy cognition will need to build on more specific, mechanistic theories.

The ability to monitor and change cognitive capacity is something many people want. This suggests that it will be widely adopted once the technology gets to a particular inflection point, and will yield unexpected applications across society. New privacy schemes must be developed and ethical guidance formalised ahead of these technologies, to ensure that this kind of data is protected, including "neurorights" and cognitive liberty. Even more urgent is governance around emerging ways to alter and improve cognition. Unanticipated societal outcomes are guaranteed, and society must be ready.

KEY TAKEAWAYS

Progress is being made in understanding the **Fundamentals of cognition**, such as the baseline of "normal" function for tasks such as working memory or executive function. This allows researchers to explore the potential for enhancements, as well as monitor their effects when implemented. **Monitoring of brain states** using a variety of technologies is enabling greater understanding of how best to decode cognitive and emotional states, and to elucidate fundamental principles behind restoring functions such as speech and movement. There have been significant steps forward in the development of **Neuromodulation systems** that can change brain states through energy-delivering interventions such as electrical stimulation and drugs such as modafinil. The cognitive assistance we get from using computers and suitably developed and interfaced machine-learning algorithms offer the potential for **Exogenous cognition**, augmenting the natural abilities of the human brain. This might eventually include altered, enhanced or added body parts that stimulate new forms of cognition through the brain's natural plasticity.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Major breakthroughs in understanding the Fundamentals of cognition appear to be a decade away still, but could significantly impact developments in other areas of science and technology — and society more broadly. Neuromodulation systems and brain monitoring technologies are much more mature and are already being deployed, reducing their Anticipation Potential scores. In contrast, Exogenous cognition is an area where developments are more uncertain, with major breakthroughs expected by the contributing community in 20 years.

MORE INFORMATION:

**go.gesda.global/2-1**

## 2.1.1 Fundamentals of cognition

**Cognition comprises elements including executive function, focus, cognitive flexibility and working memory. While these can be impaired by a variety of disorders, the most common pathway of deterioration is through ageing. For older individuals, cognitive enhancement can delay or compensate for the cognitive decline, prolonging autonomy.[3]**

Successful enhancement of healthy cognition will require a foundation of more specific, mechanistic theories, and may require consensus around hallmarks of "normal" cognition, and how and under what circumstances it could or should be enhanced. An early study is underway in China to benchmark average markers of brain health against age, which could underpin future early-warning systems of an abnormal rate of decline and illuminate interventions that work to halt such decline.[4] Other trials now underway promise to yield biomarkers of good cognitive function.

There is still much to learn about why different enhancing techniques seem to have a differential impact on enhancing cognition in healthy humans across the lifespan. Physical exercise seems to be particularly effective in children[5]; non-invasive brain stimulation is a good candidate to compensate for cognitive decline in ageing;[6] playing action video games may provide a route to improved cognition in healthy adults,[7] which might provide advantage in dynamic, information-driven work environments. Open research questions include whether boosting some aspects of cognition could have hidden downsides.[8]

### 5-YEAR HORIZON

**Biomarkers of cognitive decline are understood**

Results from several ongoing trials yield biomarkers of age-related cognitive decline; new studies give robust evidence of which methods can slow the cognitive decline that comes with age.

### 10-YEAR HORIZON

**Research provides effective brain-boosting techniques**

A Chinese study yields experimental results on what empirically can prevent premature cognitive decline. New insights from biomarkers show which types of cognition respond best to what kind of boosting.

### 25-YEAR HORIZON

**Digital modelling improves intervention outcomes**

Digital models of brains will help us to predict outcomes of interventions and perform experiments in-silico, rather than in people and animals. A combination of genetic engineering and implants will allow widespread enhancement of intelligence in healthy individuals.

## 2.1.2 Monitoring of brain states

**Rapid advances in a wide range of technologies make it possible to measure brain state markers from electrical potentials to blood oxygenation: newer penetrating brain implants are in trials, and tools like functional Near-Infrared Spectroscopy (fNIRS) devices are being miniaturised.[9] Some are only used in research and clinical settings while others — EEG wearables, for example — are emerging onto the unregulated market for use by the general population.**

Big data approaches to increasing amounts of raw brain data will enable researchers to decode cognitive and emotional states and to elucidate fundamental principles of cognition and memory.[10] Machine learning has implications for neural decoding, including determination of the neural correlates of memory encoding, retention and retrieval.[11] Speech decoding is now possible at near-normal speeds, with some systems boasting vocabularies of 125,000 words and with extremely low error rates, allowing near-naturalistic communication.[12,13]

The rise of predictive large language models means semantic decoding becomes possible even without brain implants; one has decoded continuous language from fMRI.[14] Brain monitoring for interfacing with external technology is seeing rapid progress. Neuralink, for instance, has implanted its "Telepathy" chip in a human brain, enabling wireless, thought-enabled operation of a computer cursor. Many other companies are operating in this space, hoping to respond to brain signals to restore a person's movement or speech. Synchron, for example, has implanted stentrodes in ten people's brains, and is making preparations to conduct a much larger trial of its technology.[15,16]

### 5-YEAR HORIZON

**Digital models improve understanding of brain signals**

Digital models generate a reference brain simulation to allow testing of interventions on cognition in silico. AI continues to improve the process of parsing meaning from the brain's electrical signals. Technology for monitoring brain states achieves higher resolution, allowing more accurate and interpretable readout and better fMRI.

### 10-YEAR HORIZON

**Open brain data stimulates research**

Digital brain models provide sandbox systems that show which interventions alter cognition. Miniaturisation makes brain-state monitoring more commonplace.

### 25-YEAR HORIZON

**High-resolution devices facilitate access to some brain states**

Cheap, portable non-invasive imaging technologies are used in a greater variety of real-world situations. Standalone systems enable accurate reporting on brain states that open access to memory, mood and cognition.

## 2.1.3 Neuromodulation systems

**A wide variety of interventions can change cognitive function. Some are behavioural, including exercise, meditation, sleep hygiene or cognitive training. More targeted approaches include drugs and nutritional supplements, such as the attention-boosting drugs methylphenidate and modafinil, initially developed to treat cognition-limiting disorders. At present, however, the most widely discussed strategies involve brain stimulation via electromagnetic fields: transcranial magnetic stimulation (TMS), transcranial direct-current stimulation (tDCS) and deep brain stimulation (DBS).**

tDCS and TMS have been shown to enhance certain cognitive functions, such as episodic memory in older adults.[17,18] DBS, which has been successful for Parkinson's and obsessive-compulsive disorder, has also alleviated some symptoms of Alzheimer's disease in some participants in a small clinical trial.[19] Other penetrating electrical brain implants are mooted to provide prosthetic memories for people with traumatic brain injuries.[20]

Further progress will come with "adaptive closed-loop systems". These can read and decode brain signals, and respond by making decisions — often aided by AI — to engage stimulation in order to override, dampen or amplify a particular signal.[21] Better materials[22] and implantation devices and methods are under development.

### 5-YEAR HORIZON

**Brain-stimulation devices proliferate**

Next-generation implants from a variety of companies are in human trials, allowing for simultaneous recording and stimulation in multiple regions across the brain. More electrode designs are approved for use in humans, including Stentrodes[23] and Neuropixels.[24] A DBS trial for Alzheimer's sheds light on which brain areas are best for implantation. Edge computing aids processing on closed-loop devices, hastening the acquisition of clinical neurological data. Wearable EEG devices enhance the depth and quality of sleep.

### 10-YEAR HORIZON

**Miniaturisation drives wider adoption of cognitive modulation**

Aided by AI, miniaturisation and brain-based chip design, safer closed-loop implanted devices treat an increasing variety of disorders, including depression. It becomes possible to identify areas of the brain where electrical stimulation gives healthy people a boost in memory capacity.

### 25-YEAR HORIZON

**AI improves recovery from trauma**

AI-enabled closed-loop systems are used to modulate brain signals that arise as a result of injury or disease, helping to reduce problematic symptoms. In some cases, patients are able to work with an AI system to retrain their brain so that it returns to its previous functionality.

## 2.1.4 Exogenous cognition

**Among the most important drivers of cognitive enhancement in the coming decade will be advances in artificial intelligence that allow us to integrate external cognitive systems with our biology. Machine-learning algorithms, applied to data gathered from proliferating brain-surveillance techniques, will enable a better understanding of the principles of cognition and memory, and thus lead to develop better closed-loop devices. A feedback loop will thus emerge: advances in AI will be based on new insights in neuroscience; and better AI will improve human cognitive abilities.**[25]

It is likely that AI will eventually be integrated into human cognition, embedded in devices worn by consumers to augment their cognitive abilities. People may eventually invest in brain implants that seamlessly provide information and tune their brain activity as needed. The scope of future applications is wide and includes downregulating undesirable brain states and tuning the brain for optimal task-specific performance.

Technologically mediated changes to the body plan could also alter embodied cognition, exploiting the brain's plasticity to find new ways to act on its environment. For example, experiments with a "third thumb" — a second, robotically articulated thumb attached to one hand — have revealed that the brain quickly adapts to controlling the new digit and integrates it into its body plan, rewiring circuits to accommodate the addition.[26]

### 5-YEAR HORIZON

**Novel brain circuits are put to work**

Artificial cognition informs new kinds of circuits and architectures; those brain circuits start emerging in the world and into devices. Companies adopt the third thumb for efficiency gain in the workforce.

### 10-YEAR HORIZON

**Brain implants enhance cognition through exogenous AI**

Advances in human neuroscience and new machine-learning models and algorithms begin to unravel the fundamentals of cognition. Non-essential "cosmetic" augmentation of healthy brains becomes a growing trend. Pattern-detecting AIs working in conjunction with brain implants provide drug target prediction for combatting age-related declines in cognition and numerous neurological disorders.

### 25-YEAR HORIZON

**AI-informed gene editing changes biological memory and cognition**

Thanks to insights from AI, researchers begin to understand how human brains build internal models of the world, and use these insights to enhance the performance and usefulness of these models. Medium-scale "digital twins" of human brains are developed for personalised medicine that can test neurological interventions in advance of real-world action.

2.2

# Human Applications of Genetic Engineering

CHAIR:
**Robin Lovell-Badge**
Principal Group Leader, Stem Cell Biology and Developmental Genetics Laboratory, Francis Crick Institute

CONTRIBUTORS:
**Samira Kiani, Isabelle Mansuy, Kelly Ormond, Alex Chavez, Philip Kim**

**Gene editing has achieved significant successes in a range of areas, and has gained regulatory approval for targeting cancer,[1,2,3] eye diseases[4] and blood diseases.[5] Its next act will be to move from rare and difficult diseases into more common disorders and cancers, and from there into cracking the fundaments of ageing.**

The ultimate goal for gene editing is a one-shot wonder drug — a one-time injection that cures heritable or acquired disease for the rest of the patient's life. However, it is becoming increasingly clear that the gene-editing tool that has underpinned most clinical and research breakthroughs will not be the main way forward. CRISPR, an editor that can snip DNA to alter its sequence, also creates dangerous and irreversible breaks in DNA.[6] The future of gene editing will rely on new, more efficient, more accurate techniques now under investigation and in early trials, along with novel ideas about how to manipulate the genome indirectly, transiently and even perhaps reversibly.

They will also rely on improved delivery methods. Today, most gene editing is not applied to living embryos or directly done on patients, but is ex vivo: as, for example, in treatments for sickle-cell anaemia.[7] But this limits the number of diseases that can be targeted. More targeted payload delivery is being developed to be more precise and less toxic, thereby creating fewer side effects and immune reactions. This could deliver the editor into tissues that are traditionally hard to reach. Better diagnostics, better editors and delivery methods could be a result of advances in machine learning. AI could make it easier to diagnose and even predict heritable disorders.

It is generally agreed that future research needs to move forward with an eye to lowering the staggering costs of gene therapy. Currently, the biggest barriers to making gene editing a medical reality are not only technological: they also include public health messaging, infrastructure and cost. Recently approved haemophilia and sickle cell disease therapies cost $2-$3 million.[8] The expense is multifactorial but new initiatives are under way to make them cheaper and more accessible.[9] Crucial to the future of scientific success will be public acceptance, and understanding that this is not always led by the West.[10] As this therapeutic modality moves into more medical interventions, more infrastructure needs to be developed to address the interpretability of the science (for example, genetic counsellors are needed to interpret genetic test results but are in short supply).

KEY TAKEAWAYS

Editing human genetics is a promising route towards disease prevention and reduction. Work to improve **Diagnostics** tools for reading and interpreting the genome has achieved fast identification of pathogens and promises to enable insight into the most suitable gene therapies for an individual. This will be complemented by developments in **Next generation editors and delivery**, which will manipulate the genome in ways that avoid unwanted immune system responses. A number of processes will benefit from **Engineered organism and AI-based** tools, such as testing of proposed therapies on synthetic organisms and accelerated reading of whole genomes through the use of AI. Researchers are exploring **Alternatives to direct gene editing**, including epigenome editing, which might facilitate the fine-grained control of gene expression.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

The relatively low Anticipation Potential scores for the sub-topics covered in the Human Applications of Genetic Engineering topic are linked to lower transformative effects scores and the high awareness they benefit from. The ability to use AI to engineer new organisms is still in its early phase and will require more than 10 years of further research before transformative effects on society and the economy start to be seen. Combined with the high uncertainty, this explains the higher Anticipation Potential score for this field.

MORE INFORMATION:

go.gesda.global/2-2

## 2.2.1 Diagnostics

**Reading and interpreting the genome — whole-genome sequencing of patient DNA — is increasingly common in medical practice for developing and adequately deploying therapeutics. Better reading technologies have already helped to diagnose disease, genetic predispositions to disease and even infections.[11] For example, the CRISPR-Cas system is enabling the fast detection of pathogens; Cas12a has detected hepatitis B in less than 30 minutes.[12] More typically, sequencing is now possible in hours to days.[13] Costs are also falling.[14]**

Faster, better and cheaper diagnostics coming into the mainstream will act as a fact-checker on the new generations of genome editors, detecting and preventing DNA editing errors. These technologies need to be further refined to ensure every laboratory can easily adopt them when in vivo editing becomes mainstream.

Much progress will be thanks to the new ability to do long-read sequencing, more accurate than the previously more common usage of short-read sequencing. This could identify more clinically relevant gene variants, and it could also provide epigenetic information that can bring epigenome editing to the clinic.[15] Diagnostics will be able to tell patients what kind of gene therapy they are suited for, or even which interventions and lifestyle changes will most affect their chances of expressing a genetic disease. However, analysis and interpretation are a major bottleneck: a shortage of genetic counsellors is an increasing problem.[16]

### 5-YEAR HORIZON

**Faster, cheaper, better diagnostics become available**

CRISPR-based diagnostic methods are developed for a variety of targets, including cancer, viruses and other pathogens. Rapid, reliable, widespread whole genome sequencing shortens rare-disease diagnosis and cancer diagnosis, prognosis and management. Cost drops to $100-$200 a genome.[17] Therapeutic investment explodes. Genome targeting for pathogen diagnosis comes to point-of-care settings, including pharmacogenomics when drugs are prescribed. AI interprets sequencing.

### 10-YEAR HORIZON

**Genome-reading finds a broad range of applications**

The time for whole-human-genome sequencing drops to an hour. Same-day diagnosis of cancers and rare diseases shortens time to treatment. Genome sequencing influences retirement plans and insurance. AI helps fill unmet need for genetic counsellors.

### 25-YEAR HORIZON

**Gene-reading goes mainstream**

Rapid diagnostics enable to-go or home-based devices for pathogen detection and better prediction of complex diseases. Editing technology, combined with AI, obviates most genetic concerns over partner choice. Heritability and environmental conditions are included in assessments of polygenic risk scores for everything from cancer to obesity.

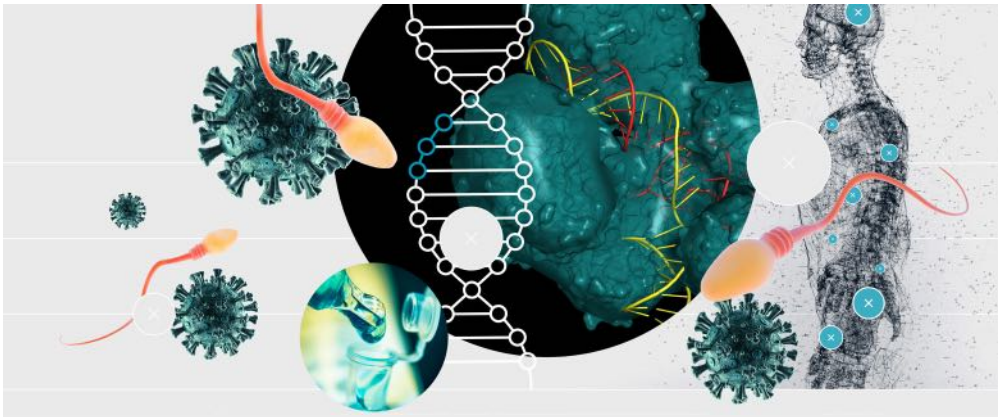
## 2.2.2 Next-generation editors and delivery

**CRISPR-Cas9 is now the most widely used gene-editing technology in the world, successfully treating blood diseases, cancers and eye diseases.[18] Several therapies have been approved for clinical use and many more are in trials. However, CRISPR's ability to correct gene defects depends on making double-strand breaks that are repaired by cellular processes. It is increasingly accepted that such double strand breaks are dangerous,[19] resulting in potential chromosomal rearrangements or loss.[20] Drugs in the pipeline will not be abandoned, but future therapies will rely on more efficient and accurate techniques.**

The two likeliest candidates are base and prime editing. Base editing is powerful against point mutations, which account for 80 per cent of human genetic diseases.[21] It also enables mitochondrial gene editing, which is harder to achieve with CRISPR.[22] Prime editing is also more specific and accurate, and new research continues to enhance its efficiency.[23] Research is under way to replicate CRISPR successes in sickle-cell disease and beyond with base and prime editing.[24,25,26] Prime editing can target multiple genes at the same time.[27,28]

Modified adeno-associated viruses (AAVs) can deliver gene editors, although the large quantities required can trigger dangerous immune responses. Efforts are under way to re-engineer AAV to be bigger and evade immune response. One alternative is more efficient lentiviral vectors or viruses engineered to make them preferentially infect specific cell types, for example neural cells or airway cells.[29]

Non-viral delivery has become an increasingly viable alternative, thanks to rapid progress in the use of lipid nanoparticles and inorganic nanoparticle-based delivery systems.[30,31]



### 5-YEAR HORIZON

**Ex vivo and in vivo therapies advance**

More large-scale stage III clinical trials for ex vivo therapies take place, with more therapeutics approved and commercially licensed.[32] Patient data shows mid stage results of crispr-based haemophilia and retinitis pigmentosa therapies now in trials.[33,34] Early-stage clinical trials of in vivo editing techniques, targeting easily accessible tissues such as the eye,[35] or the liver, begin to show results. In vivo therapies move to experimental clinics. CRISPR corrects for mitochondrial genetic disease in IVF procedures. Next-generation "one shot" genome editors in vivo show long term safety data in clinical trials.[36] Base editing gets into major tissues.[37]

### 10-YEAR HORIZON

**Safer germline editing blurs boundaries between therapy and prevention**

Inhaled and other new delivery methods move into the clinic. Epigenome editing has its first trials targeting chronic diseases. New nonviral delivery techniques reduce the need for large doses, reducing cost. Adenosine transversion editors expand the capabilities and applications of base editing.[38] Heritable gene editing begins to gain limited acceptance, although not everywhere, as a consequence of successful somatic techniques and preclinical safety data. Base and prime editing enable in vivo therapeutics, bringing costs of therapy down.

### 25-YEAR HORIZON

**Polygenic editing erodes boundaries between therapy and enhancement**

In vitro derived gametes can be edited safely before implantation. Many forms of gene editing are mainstream. It becomes possible to engineer protection from radiation, chemical warfare and infectious diseases by altering single genes, enabling military applications as well as casual space travel. We use gene technologies to correct, slow down or even reverse processes linked to premature ageing to increase healthspan. A sleep-shortening gene is the first popular enhancement. Up- and down-regulating some specific genetic elements enhances some aspects of cognition.

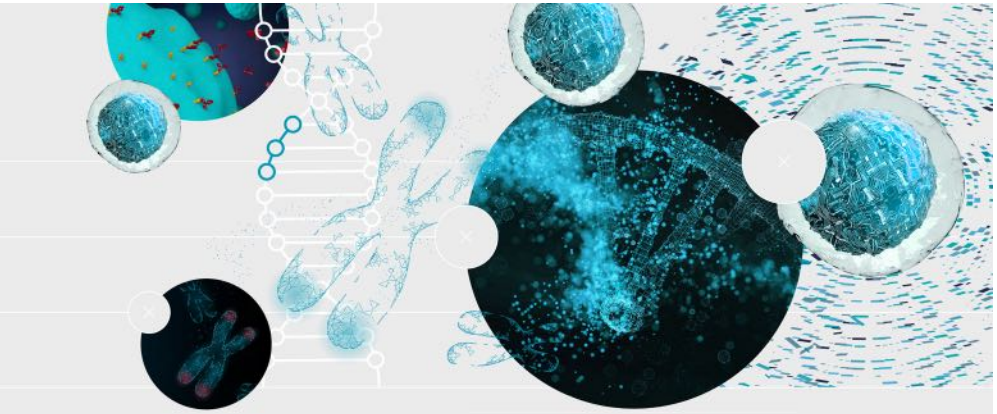
## 2.2.3 Engineered organisms and AI-based tools

**AI promises to accelerate drug discovery.[39] Synthetic organisms and AI will help advance genome editing for human applications in several crucial ways, including improved ways to deliver the editing payload to the cell and experimental organisms that provide a better proxy for human testing.[40]**

AI will help to quickly scan whole genomes and then design vectors that can be used more universally. Work is also under way in AI design of entirely new proteins and editors.[41] However, human screeners are still needed to identify the small percentage that will work as they are meant to. This situation may improve with access to more training data. Generally, advances here will require more collaboration between mathematicians and biologists.

Furthermore, machine-learning algorithms may help identify the relationships among genes, gene networks and other variables (such as epigenetic factors) involved in disease, as well as the potential consequences of edits to these.[42] AI-enabled searches through microbial data obtained from uncultivated samples may reveal more suitable enzymes — helicases, nucleases, transposases or recombinases — that solve the problems of currently available editors.

Recent rapid advances in stem-cell engineering, stem-cell-derived embryo models, organoids (artificial and simplified versions of an organ) and tissue engineering are helping research move towards providing experimental organisms based on human physiology that will help predict the functionalities of genome editors outside the human body and before clinical applications.[43,44]



### 5-YEAR HORIZON

**Synthetic biology circuits go in vivo**

Extremely rapid progress in machine learning and AI solves many obstacles to engineering proteins and enzymes. AI helps create de novo gene editors. Genome reading and writing allows us to build large genetic circuits composed of many repeated guide RNA sequences that enable us to simultaneously target multiple genes. AI leads to engineered proteins and enzymes.

### 10-YEAR HORIZON

**Chimeras, synthetic viruses and other models become mainstream**

Synthetic biology circuits, now in mammalian cell cultures, find applications in vivo and for enhanced control of genome editors for gene therapies. Chimeras generated by injecting human stem cells into animal embryos grow organs for xenotransplantation or grow human-like brain structures to study the effects of gene edits. Improved synthetic viruses and genome editors knock out genes in animal organs to supply the increasing need for organ donation without the risk of rejection. Engineered cells and tissues serve as novel delivery systems to easily grafted tissues such as bone and skin.

### 25-YEAR HORIZON

**Universal editors emerge**

Engineered cells and tissues are grafted into complex tissues like brain or the endocrine system. With prime and base editing, plus tissues grown outside the body and reimplanted, modification becomes easier and cheaper, rivalling in vivo. Genetically modified viruses, synthetic viruses and large genetic circuits are widely deployed for pre-emptive “gene surgery” on otherwise healthy people, directly linking genetic circuits to genome editors. We see the first demonstration in humans of universal cells carrying gene circuitry.

## 2.2.4 Alternatives to direct gene editing

**Existing approaches to gene editing are all-or-nothing: gene sequences are altered, removed or added. However, some diseases manifest through inadequate gene expression that is dialled too far up or down rather than turned on or off. This means that, in some cases, techniques such as editing the epigenome may be a better option.[45] Simply adding or removing the chemical tags that adorn DNA, for instance, could dial down or up expression of certain genes or variants without the risk of dangerous mutations. Epigenetic mechanisms include histone modifications and DNA methylation; manipulating the factors that control these can be both tuneable and reversible, and could be especially useful for controlling more than one gene.[46] Once considered a dark art, epigenome editing is now rapidly advancing.[47]**

Another approach, editing RNA, could open up much more common diseases like chronic pain. Some drugs are already in clinical trials.

### 5-YEAR HORIZON

**Disease spread is monitored through metagenomics**

Metagenomics advances make it possible to monitor the emergence (or re-emergence) of viral diseases with the goal of containing their spread. Epigenome editors alter epigenetic state at precise locations within the genome, lowering the chance of immune response, and are fine-tuned for first use on disease genes and tissues, and tested in vivo. New sequencing methods identify epigenetic modifications while preserving the accuracy of genome sequencing. Insights are gained into how interventions like diet and exercise alter gut microbiome.

### 10-YEAR HORIZON

**Epigenome editors are fine-tuned**

Metagenomics becomes a standard tool for microbial ecology laboratories, using methods similar to gene fingerprinting to profile microbial communities. Epigenome editing becomes titratable.

### 25-YEAR HORIZON

**Cosmetic gene editing becomes possible**

Delivery methods of enzymes and editors — whether gene or epigenome — become straightforward and open to dynamic control. Epigenome editing helps people temporarily mute some genes or express others, making for temporary alterations including night vision and resistance to radiation, viruses and chemical weapons. Cosmetic mutations, such as temporary eye-colour changes, are popular in body-hacking subcultures. Fundamental alterations to the microbiome make humans capable of digesting cellulose or extracting nutrition from plastic.

2.3

# Healthspan Extension

CO CHAIRS:
**Brian Kennedy**
Distinguished Professor, Department of Biochemistry and Physiology, Yong Loo Lin School of Medicine National University of Singapore

**Vera Gorbunova**
Doris Johns Cherry Professor, University of Rochester; Co-director, Rochester Aging Research Center

CONTRIBUTORS:
**Jay Olshansky, David Weinkove, Nir Barzilai**

**Rather than accept the ageing process as a natural facet of life, scientists and regulators are working out how to treat the process as a risk factor for disease in its own right and target it for treatment.[1] This pursuit is being formalised into the discipline known as fundamental geroscience.**

Ageing is the greatest risk factor driving both morbidity and mortality. While research has yielded few solutions to chronic diseases of ageing — such as cardiovascular diseases, most cancers, and neurodegenerative and metabolic syndromes — in the past few decades, findings point to the existence of underlying biological pathways that unite the diseases associated with ageing.

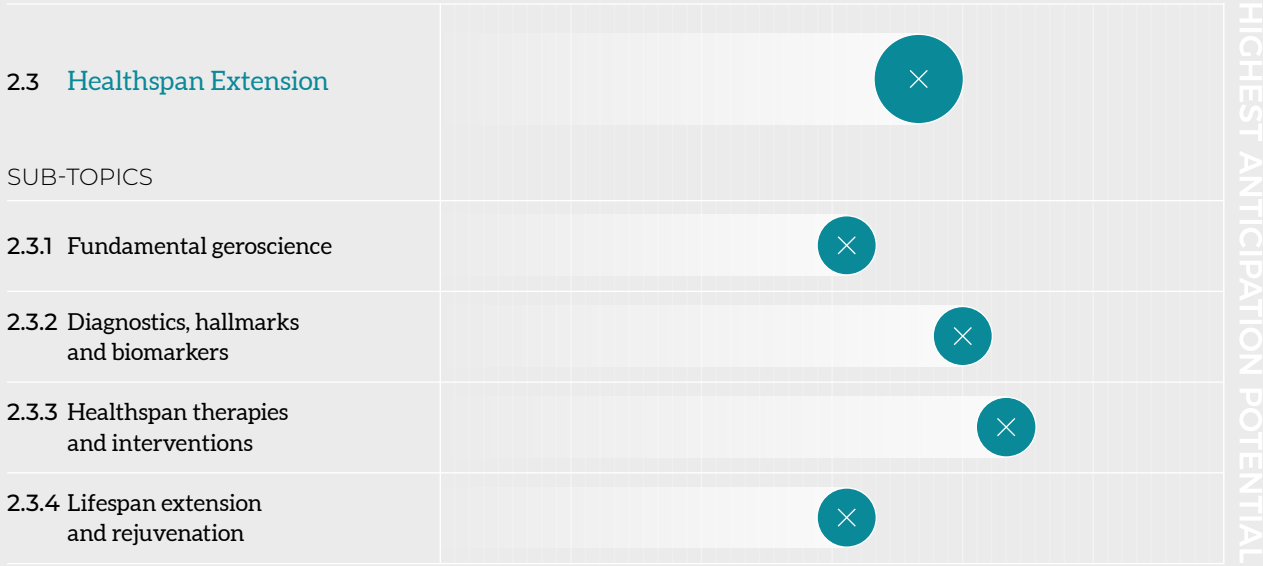
Even while basic questions around such fundamental processes are being explored, there are already therapies in clinical trials. As with fundamental geroscience, here the goal is to reduce the health impacts of ageing. A range of interventions, from small-molecule drugs to gene therapy, are now in various early stages of investigation. Their endpoints are necessarily specific disease outcomes, more with an eye toward prevention, and, importantly, these trials will yield insights that are predicted to inform a range of interventions in the ageing process, from lifestyle changes to technologies to, eventually, pharmacological and even gene therapies that will lead to longer, healthier lives.

A fundamental shift is under way. This foundational reconceptualisation of ageing as a disease will lead to a new kind of public-health programme based on “healthspan extension”. The endgame of such a programme is a society-wide eradication of frailty, high late-life health expenditures and of low quality late-life. These are crucial aims in an ageing global population: the primary goal is not years added to lifespan, but to “healthspan”, where health, wellbeing and quality of life remains high until death.[2]

KEY TAKEAWAYS

Advances in our scientific understanding of ageing are making it clear that there is no reason to treat it as an untreatable process. Breakthroughs in **Fundamental geroscience** are revealing many of the processes associated with ageing in the human body and opening up possible ways to slow, halt or mitigate their effects. As a result, research has begun to identify important **Diagnostics, hallmarks and biomarkers** of ageing. This is leading to a new frontier opening up in **Healthspan therapies and interventions**, which are aimed not primarily at prolonging life, but at extending the length of time for which an individual has a healthy and enjoyable experience of life. There are suggestions, though, that it might be possible to extend healthy lifespan and possibly to reverse processes associated with ageing. Such efforts at **Lifespan extension and rejuvenation** remain controversial, but techniques such as gene therapy and epigenetic reprogramming are being explored and may yet prove to have value.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Topics under Healthspan Extension all receive high Anticipation Potential scores across all variables. These areas still require investments in fundamental interdisciplinary research, with major breakthroughs more than a decade away — though with major transformative effects for science and society. Lifespan extension and rejuvenation are more likely to see advances in 20 years, but will require less coordinated international action than the other topics covered. Healthspan therapies and interventions gets the highest value overall because its impact and the scope for action are rated higher.

MORE INFORMATION:

**go.gesda.global/2-3**

Healthspan Extension

## 2.3.1 Fundamental Geroscience

**Fundamental geroscience, a groundbreaking new basic public health science, investigates the foundational systems involved in the process of ageing itself based on the premise that ageing is inherently modifiable.**

Understanding the mechanisms of how we age could lead to interventions that can alter them, which could lead to "compression" of the period of disability relative to age — essentially delaying its onset so people stay healthy until end of life. Benefits of insights gleaned from this study won't accrue only to old people. Finding ways to mitigate these processes is important across the life course. Ageing processes get under way the moment we are born and their fingerprints are being found in surprising places, from pregnancy complications to childhood cancer treatment to the long-term effects of prophylactic HIV drugs.

Research is currently illuminating the workings of some of these ageing mechanisms, including age-related build-up of defective proteins, dwindling of adult stem-cell reserves, transcriptional slowdown[3] and an age-related increase in the number of senescent cells — which, among other events, drives an increase in chronic inflammation. In all, 12 interrelated hallmarks of ageing have now been identified.[4] Additionally, there are genetic factors: recent research has identified a gene in naked mole rats that extends both lifespan and healthspan in transgenic mice, for example.[5] There are also suggestions that gut-microbe composition matters, as it changes differently in healthy versus unhealthy ageing.[6] The main goal is to understand how all of these factors are connected to chronic disease, and how these in turn are connected into the central system that regulates the ageing process.

### 5-YEAR HORIZON

**Identify specific levers in ageing**

Researchers identify more genes in ageing, to see if they extend lifespan in animals beyond mice. More investigations detail the specific role played by gut microbes in ageing. Research begins to elucidate the interplay between the processes of ageing in the larger system. The knowledge gained is used to develop multiscale AI network models that incorporate the relevant physiological changes.

### 10-YEAR HORIZON

**Ageing is understood as a disease process**

The idea that ageing is a disease gains traction. Machine-learning algorithms help to identify the many genes involved in healthy or less-healthy ageing and how they work together.

### 25-YEAR HORIZON

**A better understanding of why we age**

Science arrives at an explanation of ageing. Personalised ageing regimens allow adjustment of "ageotype", while a major medical shift occurs, moving from treating the symptoms of ageing to treating its cause.

## 2.3.2 Diagnostics, hallmarks and biomarkers

**One essential requirement for extending healthspan will be a set of tools for quantifying both age and the impact of interventions on ageing processes.**

Current technologies such as smart watches, apps and fitness trackers already give some indirect measurements of health, and these indicators may reflect likely healthspan. They assist interventions to some degree, helping people adhere to the only activities known to optimise ageing: exercise, diet and sleep regimens. However, much more granular information is required if meaningful increases to healthspan are to be achieved.

New methods — blood[7] or urine tests[8] — can purportedly reflect age-related variations in blood markers, measuring objective indicators and revealing differential "ageotypes", and potentially warnings of premature ageing.[9] These biomarkers are not yet validated in humans but, when they are, they will provide measures of "biological age" — a more useful indicator of how long a person can expect to remain in good health than number of years alive. We now know that certain genes can slow ageing in centenarians and lead to healthier old age than their age in years would suggest.[10] Furthermore, the body's different tissues can age at vastly different rates due to genetic or environmental factors.

The goal is a biomarker of age whose manipulation restores good health, the way blood pressure does for heart disease. Many candidates exist, including transcriptomics, metabolomics, proteomics and DNA methylation. "Omics" analysis of existing studies of gerotherapies — including rapamycin, metformin and senolytics — is now under way with a view to finding consequent changes in age-related biomarkers. The recent discovery of three senolytics using machine-learning algorithms trained solely on published data is just one way in which AI is helping the search for new biomarkers.[11] Machine learning will be used to search hundreds of datasets and previous trials to identify other useful factors and patterns.[12] Population-level work is aiming to expose the relationships between these "age clocks" and disease risk.[13]

### 5-YEAR HORIZON

**Validation and standardisation of biomarkers takes off**

Healthy longevity intervention trials interface with ageing biomarkers and traditional markers of physiologic age in a process of cross-validation. Measurements of "omics" reveal how other drugs, including SGLT2 inhibitors, senolytics and supplements affecting metabolism, impact aging processes. Clinical trials validate measures of premature ageing, while multiple companies' methods converge on standardised, validated diagnostics of real age.[14] Unhealthy ageing can be identified with greater precision. Biological ages of individual organs begin to predict disease risk in those areas.[15]

### 10-YEAR HORIZON

**Age clocks are validated**

Multi-omics biomarkers emerge. Some specific age clocks that predict morbidity and mortality and are responsive to interventions are validated and brought into alignment. AI mines proteomic and functional molecules to establish patterns. Personalised health assessments integrate information on various organs' ageing processes. Comprehensive evaluations, based on multi-omics biomarkers, identify abnormal ageotypes and suggest gene- or pathway-targeted drugs. Age diagnostics and epidemiology combine to halt specific aspects of the ageing process.

### 25-YEAR HORIZON

**Age profile and prevention strategies are personalised**

Interlinked and fundamental ageing processes are revealed as root-cause contributors to many disorders and diseases. Morbidity is compressed profoundly in a significant amount of people. We understand the relationship between organ-specific and systemic ageing.

# 2.3.3 Healthspan therapies and interventions

**Cognition comprises elements including executive function, focus, cognitive flexibility and working memory. While these can be impaired by a variety of disorders, the most common pathway of deterioration is through ageing. For older individuals, cognitive enhancement can delay or compensate for cognitive decline, prolonging autonomy.[3]**

Healthspan extension can already be achieved through several approaches, including specific diets, calorie restriction and exercise,[16,17] but drugs are being developed to mimic the effects of these interventions.

These include drugs that target sirtuins and drugs that inhibit the mechanistic target of rapamycin (mTOR) networks, whose signalling is increasingly understood to influence longevity and ageing. mTOR inhibition has been shown to increase lifespan in animal models and elderly humans.[18,19,20,21] Two such drugs under investigation are the immunosuppressant rapamycin[22] and metformin, a drug originally prescribed for type-2 diabetes and other metabolic diseases which had the "side effect" of reducing the incidence of other diseases of age compared with the purportedly healthy, non-diabetic controls against whom they were compared.[23]

Trials of metformin and rapamycin[24] suggest that these small-molecule drugs can change the biology of ageing in tissues to a younger profile. The first big, multi-centre trial is about to start.[25] Another approach is senolytics, which target senescent cells before they can damage tissues, and many more drugs and natural products are being developed. Gene therapy and stem cells are other rapidly developing approaches to systemic and organ-specific rejuvenation.

## 5-YEAR HORIZON

**Anti-ageing drugs and regimens begin clinical trials**

Tests begin to validate anti-ageing drugs and regimens. Approved measures of indirect effects on the diseases of ageing lead to first clinical trials to delay age onset directly. AI allows people to personalise exercise and diet interventions to maximise their healthspan. Rapamycin and metformin trials, along with canine and non-human primate work, yield results that begin to reveal the cellular mechanisms they act on and elucidate the viability of mTOR inhibition as a single therapy that can knock down the dominoes of age-related conditions. Multiple approaches to senescent cells yield information about which work best under which circumstances.

## 10-YEAR HORIZON

**Clinical trials clarify promising drugs**

Health plans begin to prescribe validated age-delaying therapies. Research from comparative biology of long-lived species, including naked mole rats, is tested in humans via gene therapy or pharmacological intervention. The first gut microbiome interventions are tested in humans to slow onset of age. Trials begin to combine two or more drugs like metformin and rapamycin. All findings feed back into fundamental geroscience, adding new insights.

## 25-YEAR HORIZON

**Early preventative interventions see success**

The traditional medical model of "one disease, one treatment" is disrupted by drugs that have multi-modal effects. Rather than picking up age-related problems like cancer and dementia in their late stages, preventative interventions stop people getting ill in the first place. Prescriptions for drugs that have been validated in trials are dispensed for some people at particular risk of abnormal ageing early in life, say in their 20s, preventing the ageing process rather than trying to reverse it later.

## 2.3.4 Lifespan extension and rejuvenation

**Recent evidence suggests that the fundamental upper limit for human age is around 120,[26] but the question of what determines maximum human lifespan, and why it differs from other species, remains. Blue whales live to 200, for example. Naked mole rats can live more than 40 years, more than six times the lifespan of rodents of similar size, with very little signs of ageing — they avoid neurodegeneration, cardiovascular disease and cancer. This may be transferable: naked-mole-rat genes have been used to extend a transgenic mouse's life.[27]**

Some researchers speculate that these observations suggest we can extend healthspan through extending lifespans. Others speculate that ageing can actually be reversed. A gene therapy has been mooted to treat multiple age-related diseases, restoring youthful function in some systems, for example.[28] Animal experiments have identified age-associated biomarkers which can be delayed, stopped and even in some cases reversed.[29] Stem cells can be reset to age 0 — these have been used to regenerate a crushed optic nerve in rats.[30] Gene therapy has reprogrammed epigenetic information to reverse glaucoma in a mouse model.[31] Organ replacement and next-generation drugs also may reset the body's clock to an earlier state.

According to a more ambitious theory of ageing, a loss of epigenetic information is a reversible cause of ageing and accelerates its hallmarks.[32] Proponents claim that such changes can be reversed by epigenetic reprogramming, driving the entire system of ageing backwards. These techniques include partial reprogramming (which erases a cell's identity and reverts it back to a stem-cell-like state)[33] and gene therapy,[34,35] the delivery of genetic instructions for making proteins that can travel in the blood to multiple tissues.

### 5-YEAR HORIZON

**Some drivers of ageing are identified**

People will create a geographical area designated as a longevity state.[36] Scientists investigate why different species age differently and identify the pathways involved. Researchers establish the degree of conservation between ageing hallmarks among different species.

### 10-YEAR HORIZON

**Cell and gene therapy used to slow ageing**

Improvements in the tools and techniques of cell and gene therapy reduce the cost and widen the availability of treatments that slow ageing. Interventions target the system responsible for the differential pathways in ageing. Genome maintenance and DNA repair become accepted. Investigations commence on whether mesenchymal-stem-cell administration affects biological age.

### 25-YEAR HORIZON

**Gene transfer slows ageing in humans**

Longevity genes transplanted from different species into humans, in unlicensed clinics, may begin to yield limited data that can speak to the validity of the approach. Slowing the rate of ageing yields new information on whether that has significant impact on lifespan. Stem-cell delivery methods mature, allowing the targeting and rejuvenation of a range of tissue types. Organ derivation and replacement becomes a possibility. Results from cellular rejuvenation trials determine whether this method plausibly rewinds ageing in humans.

2.4

# Future of Consciousness

CHAIR:
**Itzhak Fried**
Professor of Neurosurgery and Psychiatry and Biobehavioral Sciences in the David Geffen School of Medicine and Brain Research Institute, UCLA, Los Angeles; Professor of Neurosurgery at the Faculty of Medicine, Tel-Aviv University

CONTRIBUTORS:
**Sahba Nomvula Besharati, Olaf Blanke, Patrick Butlin, Simon Brown, Guillaume Dumas, Atsushi Iriki, Ryota Kanai, Christopher Krupenye, Ken Paller, Megan Peters**

**Research over the last few decades has made significant inroads into important issues such as investigating disorders of consciousness, understanding and treating coma and related states, and determining how our biologically evolved consciousness might be augmented using biotechnology and silicon technologies in the future.**

As yet, science can offer no standard, widely agreed definition of consciousness, partly because researchers use the same word to describe a variety of phenomena such as wakefulness, awareness, attention, responsiveness to stimuli and inner life. It is thus a field of broad interdisciplinary study.

There is also significant linguistic and cultural variance in what people understand by the term "consciousness".[1] This is also true of "disorders" of consciousness: the experience of what might be termed delusions or hallucinations by Western medicine can be seen as normal and even valuable in many cultures. Responses to the idea of non-human consciousness are also culturally differentiated.

Currently, there is no agreed theory of how consciousness arises.[2] However, the lack of deep understanding and consensus around specific terminology has not prevented the adoption of technologies and conceptual advances that help make decisions in a clinical setting. We have devised methods to quantify the degree of presence or absence of consciousness (as inner life, awareness or mental response to stimuli), allowing us to define whether a patient is in a vegetative state, for instance, and to evaluate whether their consciousness can be "augmented" — that is, shifted to a more elevated state of consciousness, whether by intervention or through the body's natural healing processes.[3]

As with many medical applications, technologies that spring from a clinical setting will eventually benefit the broader population. This is because the same technologies that diagnose or modulate consciousness when there is a deficit or disorder can be pressed into service to enhance or augment healthy, functioning consciousness. They will also be helpful in more philosophical areas, improving our understanding of free will, the self and the ethics of cases at the edges of sentience.

Meanwhile, work is under way to determine the developmental emergence of consciousness in humans[4] and the extent to which machines and animals can have or develop consciousness.[5,6] Researchers also aim to understand whether organoids and other synthetic biological organisms are capable of developing a kind of consciousness.[7] This is likely to spark debate on the ethics of the field itself and of assignment of moral status and rights.

KEY TAKEAWAYS

Although central to the experience of being human, consciousness has proved difficult to investigate scientifically, with researchers struggling to reach consensus on many aspects of the field. While it is clear that **Human consciousness** is a multi-faceted phenomenon, its relation to brain states — including those induced by injury, degradation and trauma — is dizzyingly complex. Understanding where, when (and whether) **Non-human consciousness** arises, whether in other animals or in machines, together with the developmental origins of consciousness in humans, is a useful path towards further understanding of the brain and of the wider phenomenon of consciousness. Drugs, electrical stimulation, in some cases cell replacement, genetic and other biotech interventions all show promise for **Modulation of human consciousness** for therapeutic, recreational and knowledge-gathering purposes. Eventually, we may be able to extend the phenomenon to create **Beyond-human consciousness** that augments our evolved abilities in ways that might facilitate an existence lived alongside intelligent machines.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Another area of high Anticipation Potential score overall is the Future of Consciousness. Understanding and modulating consciousness in humans, animals and machines remains a huge challenge, with major breakthroughs expected to happen in 15 years. The route to get there remains highly uncertain, which further contributes to the high score. The possibility of augmenting human consciousness and sharing it with other entities is seen as most transformative for society. The consequences of a better understanding of human consciousness across stages in life and medical conditions requires the most coordinated international action.

MORE INFORMATION:

**go.gesda.global/2-4**

# 2.4.1 Human consciousness

**Different kinds of consciousness are at play at different stages of human development, from foetus through to early childhood and beyond. On top of that, injury or disease can compromise human consciousness in a variety of ways, such as that seen in vegetative-state patients and people suffering from dementia. There is progress towards creating tests for consciousness.[8]**

Understanding the difference between all these various types of human consciousness will be a vital part of the effort to treat injury and disease, and to understand various aspects of human-rights issues associated with consciousness. Research efforts are aiming to do this, with some success in the application of diagnostic tools that can differentiate between a vegetative state and a minimally conscious state, for instance.[9] Functional MRI and EEG can be used to demonstrate performance of cognitive tasks in some comatose patients who do not follow verbal commands.[10] Intervention in coma patients, aiming at recovery, is becoming a realistic, if long-term, prospect.[11,12] There is hope that better understanding will help detect and assess early memory loss in ageing and in Alzheimer's disease, and guide treatment and care.[13] At the other end of life the need to assess consciousness "in the cradle" in the prenatal and infant stages is becoming an issue with medical, educational, legal and ethical implications.[14]

Neurosurgical research demonstrates that specific neuronal activity underlies the emergence of concepts, memories and intentions in human consciousness, and further exploration here, with emerging brain-recording and stimulation tools, partnered with AI-based analysis, could help decode conscious and preconscious states.[15,16] Interaction with sleeping humans can also help to explore the space between the conscious and unconscious brain.[17]

Such work could also help with fundamental science, such as developing theoretical understanding of consciousness by identifying areas of interest for probing the neural correlates of consciousness, and contribute to quantification and classification of consciousness in humans.

## 5-YEAR HORIZON

**Diagnosis of consciousness improves**

Brain-state diagnostics improve, and machine learning overcomes individual patient variability to assist in prognosis and guide rehabilitation. Specific tests reliably detect early onset of diseases that disrupt consciousness. Better computational models improve our understanding of the systems biology that contributes to conscious states.

## 10-YEAR HORIZON

**Guidelines for consciousness assessment agreed**

An agreed set of international guidelines (effectively a standard scale) standardises assessment of human consciousness. Improved imaging, combined with AI pattern recognition, leads to more reliable prediction of which patients are aware, which will respond to stimulation and which will require implants to communicate from their vegetative state. Neuroscientific tools give a rudimentary ability to decode the content of dreams in sleeping humans, as well as other contents of conscious experience.

## 25-YEAR HORIZON

**Consciousness evaluation evolves**

Scientifically validated assessment of presence and quality of human consciousness is established, opening up the possibility of significant progress on theories of consciousness. Brain-machine interfaces open up seamless communication with apparently unconscious people, even restoring natural consciousness in some cases. Precision neuropsychiatry uses a suite of new interventions — technological and chemical tools — to steer consciousness away from dangerous or unwanted states.

## 2.4.2 Cognitive capacity enhancement

**The challenge of reliably extrapolating from our understanding of human consciousness, added to the inability to report experience, means that it will always be difficult to determine how to approach the issue of non-human consciousness and when, where and how it exists.**

Interesting advances are being made in the study of machine consciousness.[18] Researchers are making progress in developing methods to assess AI systems for consciousness[19] and investigating machine implementations of neuroscientific theories of consciousness.[20] Efforts to understand whether machine consciousness is possible, and what might constitute it, provide an important anchor for our understanding of consciousness itself.[21]

In animals, the issue of consciousness is more immediate, pertaining to issues of moral status, and with ramifications for agriculture and food economics. A cohort of researchers have suggested there is "strong scientific support for attributions of conscious experience to other mammals and to birds", and that "empirical evidence indicates at least a realistic possibility of conscious experience in all vertebrates (including reptiles, amphibians, and fishes) and many invertebrates (including, at minimum, cephalopod mollusks, decapod crustaceans, and insects)".[22] This is a controversial claim, but one that highlights the lack of agreement about the nature and extent of consciousness in the natural world. Further exploration of the issue can only improve our understanding of the phenomenon, although funding for this work is limited. There is also a growing awareness of the possibility that some rudimentary form of consciousness could arise in brain organoids, which are proto-organs grown in vitro from human brain tissue.[23] However, despite the potential ubiquity of non-human conscious experience, caution is needed due to the possibility that very complex cognitive abilities can unfold without conscious experience.[24]

### 5-YEAR HORIZON

**Debates over non-human consciousness take centre stage**

The capacity of AI systems to mimic human behaviour leads to intense debate about whether they might be conscious. Arguments from a consciousness perspective lead many species' rights to become more closely protected.

### 10-YEAR HORIZON

**Non-human consciousness sheds light on human consciousness**

Animal consciousness is measured and assessed by a wide-ranging set of tests developed for assessment of human consciousness (and adapted for non-verbal responders based on assessment techniques developed for human infants). Machines that display many characteristics associated with human consciousness are probed as tools for understanding how consciousness might arise in humans — in particular, for ascertaining whether embodiment plays a critical role.

### 25-YEAR HORIZON

**Hybrid consciousness improves learning**

Neuro-inspired AI systems (neuro-AI) that help design education curricula are imbued with algorithms that operate on an improved understanding of how humans consciously learn, creating a virtuous loop.

## 2.4.3 Modulation of consciousness

**We can modulate human consciousness by several methods. One is chemical: there has been some significant progress in the use of psychedelics and psychoactive drugs, for instance, to augment and alter consciousness. New imaging techniques demonstrate the neurological details of these alterations: psilocybin, for instance, produces a state of increased chaotic brain activity and induces changes in frontal brain structures that may be associated with the phenomenology of psychedelic experiences.[25] Increasingly, experience with chemical modulations of consciousness are proving useful in medical contexts. Psilocybin and MDMA are being used to treat post-traumatic stress disorder and depression, for example.[26,27]**

Electrical modulation of consciousness is also seeing success in invasive and non-invasive forms. Brain-computer interfaces are developing at pace.[28] Precisely targeted non-invasive technology like tDCS has successfully brought minimally conscious patients back towards higher consciousness.[29] "Closed-loop" neuromodulation is able to act on, and sense, brain state based on feedback.[30,31] There is also growing scope for editing memory, urges and wishes through electrical implants, as the technological tools required are already available.[32]

Stem cells provide another approach to neuromodulation. Rat stem cells, for instance, have restored sensory abilities within a mouse brain that had its own olfactory neurons rendered inert.[33] It seems that stem-cell injection can modify cellular composition of neural circuits, potentially altering conscious experience.

### 5-YEAR HORIZON

**Brain modulation experiments widen their scope**

Drug-control frameworks are loosened to allow PTSD and other disorders of the brain to be treated in wider clinical settings using psychedelics. Electrical stimulation of the brains of coma patients sees some success in re-establishing higher levels of consciousness. Clinical trials in selected neurological and psychiatric disorders accelerate technologies capable of extracting information from the brain, inserting information or closing the information loop — thus enabling direct modulation of conscious states.

### 10-YEAR HORIZON

**AI decodes the brain**

Feedback from wearable technology, electrical implants and new imaging techniques enable patients to modulate their own conscious experience. AI systems decode neural signatures of conscious urge and intention, and inject signals useful for therapeutic treatment, including rudimentary memory editing. Psychedelic drugs altering states of consciousness enter mainstream psychiatry. Brain-machine interfaces move from the clinical environment to the general population, enabling enhancement of conscious states.

### 25-YEAR HORIZON

**Brain injuries are treated with stem-cell therapy**

Stem-cell therapies rewire patients' brains after injury. Engineered, highly specific psychedelics transform trauma treatment and neuropsychiatry and enter selective use in general populations. Memory-editing and selective memory chips become a widely available therapeutic and enhancing option.

## 2.4.4 Beyond-human consciousness

**In humans it may be possible to augment normal consciousness using drugs, neurotechnology or genetic interventions, as evidenced by experiments in animals.[34] Some researchers have used wearable technologies or implants to give themselves magnetic senses, for instance,[35] or the ability to cross modalities and feel sound.[36]**

Newly developed brain-to-brain interfaces — currently possible invasively in animals[37] and non-invasively in humans[38] — may allow for direct communication between two brains without involving the peripheral nervous system, instantiating intelligence and perhaps consciousness that has a distributed or collective aspect.[39] In addition, two-person fMRI scanning and hyperscanning[40] is opening up new possibilities to investigate shared experience leading to some form of shared consciousness.[41]

Experiments in robotics are indicating that robots might learn the ability to think in abstract terms, planning and estimating the outcomes of prospective actions without the need to physically execute them. This may have application in averting workplace accidents and recovering from damage.[42] Via brain-computer interfaces, robot self-simulation may also open up pathways for humans to augment their experience. There is scope for human-machine hybrid "teams" to improve industrial decision-making and other tasks.[43]

### 5-YEAR HORIZON

**Humans begin to adopt augmentations**

There is greater adoption of wearable or remotely controllable robotic technologies in factories and for special-purpose applications. A new online database of nootropic drugs seeks to track them and make clinicians aware of their effects and proliferation. Brain-computer interfaces move beyond siloed research labs toward new and more diverse use cases. Virtual reality (VR) and augmented reality offer visual overlays representing other people's heart rate and blood pressure, letting willing participants "see" each others' inner emotional state. Brain interfaces allow for direct communication between two brains.

### 10-YEAR HORIZON

**Engineered body enhancements become available**

Targeted gene therapy allows augmentation of sensory scope, such as "seeing" in the infrared part of the spectrum, and a few body-hacking enthusiasts choose to augment their natural senses with new engineered senses. VR- and AI-driven simulation allows us to visit the future and the past by making immersive, realistic "dress rehearsals" for future events, and by putting us into our own memories.

### 25-YEAR HORIZON

**The era of consciousness engineering and meta-humans arrives**

Increasing understanding of the neurobiology of consciousness coupled with major advances in neuro-AI establishes consciousness-engineering as a major discipline. For a sector of society, permanent connections with machines create blurred boundaries between different selves and between natural and artificial realities. It becomes possible to better incorporate the perspectives of other people and other species within an individual's experience.

2.5

# Organoids

CHAIR:
**Alysson Muotri**
Professor, Departments of Pediatrics and Cellular & Molecular Medicine, University of California, San Diego

CONTRIBUTORS:
**Arti Ahluwalia, Paola Arlotta, Pedro Baptista, Denis Jabaudon, Mitsuru Morimoto, Nicolas Rivron, Minoru Takasato, Gilles Weder, Linda Griffith**

**Organoids — simplified versions of real organs — promise to serve as a better proxy for the study of our tissues than either cell lines or animal models, making organoid researchers cautiously optimistic that they can improve the practice of medical research.**

Research on disease and treatment pathways has been hampered by the fact that cultured cell lines do not respond to interventions in the same way that cells do in their natural environment of complex three-dimensional tissues. This is part of the reason why promising in vitro studies must currently be followed up by animal studies, especially to test drugs.

Brain organoids have already shed light on the risk genes that contribute to autism[1] and how Zika inhibits brain development;[2] they can now be probed for electrical activity in a manner analogous to actual human brains.[3] Organoids from other tissues have been used for drug screening,[4] while tumoroids have yielded better cancer models.[5] The future of personalised organoids offers a way to predict treatment outcomes, avoid toxicities and develop targeted therapies.

As yet, organoids remain primitive versions of real organs, crudely recreating their basic features and functions. However, rapid advances in enabling technologies are allowing them to become far more complex, with greater standardisation of procedures facilitating easily replicated results.[6] With further advances, we should be able to use “embryoids” to observe post-implantation developmental events outside of the womb, making it possible to probe fundamental principles of human development and disease.[7] We will also test tumoroids to find the exact medicine that will best kill tumours in the patient. Eventually, we may be able to generate organs for transplantation.[8]

KEY TAKEAWAYS

Organoids are simplified versions of real organs that have the potential to assist in a number of key scientific areas. One is **Foundational research:** growing organoids in the lab will provide insights into genetics, foetal development and some disease pathways, among other fields. By creating **Hybrid organoids** that combine biological material from humans with other animal biology or silicon technology, researchers are able to investigate human biology in entirely novel ways. As well as generalised insights, the opportunity to generate **Personalised organoids** will eventually mean that an individual's cancer treatment can be checked ahead of administration, and organ transplants can use tissue derived from the patient, avoiding the risk of rejection and the need for immunosuppressive drugs. In order for this potential to be realised, a number of **Enabling technologies** will have to be developed, including scaleable and automatable manufacturing protocols.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Organoid research is advancing very quickly and three of the four sub-topics considered will reach maturity in the coming two to three years. Personalised organoids is an area that will require slightly more time to develop but is within reach in the coming seven years. The expected impacts of these technologies are very large, especially on science and technology. The combination of these factors explains the Anticipation Potential scores. Hybrid organoids score lower because of high awareness and lower economic impact.

MORE INFORMATION:

go.gesda.global/2-5

## 2.5.1 Foundational Research

**The combination of genetic engineering and human organoids has created new opportunities for studies of human genetics. It has already revealed some of the secrets of how human brains uniquely diverged from those of other primates,[9] including Neanderthals.[10] Organoids are also being used to investigate novel viruses and emerging diseases.[11]**

Organoids make it possible to study diseases that cannot be exhaustively studied in animals, such as uniquely human neuropsychiatric or neurodevelopmental diseases that affect the whole genome (schizophrenia, for example).[12] Brain organoids are already being used in the study of neurodegenerative disorders such as Alzheimer's[13] and neurological disorders such as epilepsy.[14]

Organoids also promise to help us understand previously opaque processes in early foetal development. Many chronic diseases emerge during the first weeks of development (for example, cardiovascular disease) so understanding these pathways in a more transparent way is crucial for prevention. Embryoids could also help us understand why humans carry fewer pregnancies successfully to term than other animals, which could lead to improved fertility enhancers and contraceptives.

### 5-YEAR HORIZON

**Models and answers become increasingly complex**

Merging organoid and organ-on-chip technologies — the latter being a microfluidic chip that mimics the physiological behaviour of an organ — allows the study of inter-organ interactions. Large databases are developed covering many types of organoids and available data on proteomics. This leads to increased understanding of how perturbations resulting from medicines or genes affect physiology.

### 10-YEAR HORIZON

**Predictive models have proven efficacy**

Several countries launch "organoid banks", used by academia and industry to understand diseases and their variability across different individuals. We increasingly understand the developmental processes involved with morphogenesis for complex structures. Insights into the biochemical pathways of ageing allow researchers to rapidly age a brain organoid to study Alzheimer's disease. Animal and human embryoids are grown in a dish: humans for the first few weeks of development, animal models until organogenesis and further.

### 25-YEAR HORIZON

**Whole human on a chip becomes a reality**

Given the ability to link several organoids and systems together, we find molecules that enhance reproductive health, prevent pregnancy loss and enhance foetal health. Better understanding of human development leads to new insights into how to augment foetal health and prevent diseases. Observing specific organoid cell types affected by specific mutations in one specific gene accelerates understanding of complex developmental disorders.

## 2.5.2 Hybrid organoids

**Researchers are pairing human organoids both with other species and with robotics and computation. Interspecies chimeric organoids, for example, are being investigated for their potential to grow mature human organs for transplantation by aggregating pig-liver organoids with human progenitor cells.[15] Human brain organoids, successfully transplanted into a living animal, have removed a major barrier to using them as models of human disease.[16] Interspecies organoids (from mice) are used to accelerate development of human cells in embryoids. Whole organs have been derived with mouse-rat interspecies systems.[17]**

Organoid pairings are not limited to the organic. Brain organoids have also been paired with silicon technology, driving a robot, to investigate how innate learning networks form.[18] Such machine-organoid connections could yield novel computational learning approaches for hybrid wetware/hardware AI.[19]

A model of human cortical development could underpin novel computational learning approaches.[20] There is also some hope that hybrid organoids will assist in understanding extinction processes and facilitating de-extinction efforts.[21]

### 5-YEAR HORIZON

**Borrowed cellular qualities emerge**

Researchers grow tissues that regenerate themselves, thanks to capacity harnessed from other species or reactivated in our own development pathways.

### 10-YEAR HORIZON

**Augmented abilities arise**

Brainoid-machine interfaces — hybrid systems — are developed, in which part of the computational power comes from biologically grown neurons and the other part comes from traditional silicon.

### 25-YEAR HORIZON

**The era of hybrid intelligence arrives**

Researchers find a pathway to augmenting human cognition with, for example, the more capable short-term memory of a chimpanzee. Hybrid organic intelligence and research with brain organoids teach us how the brain learns, allowing us to boost AI and traditional education with these insights. Brain organoid integration with AI may give robots intuition and the capacity to “notice” things.

## 2.5.3 Personalised organoids

**Organoids will form an increasingly crucial element of personalised medicine. Drug screening for personalised medicine is already a major application in cancer therapy.[22] Patient-derived tumouroids are a more precise way for clinicians to screen drugs to determine the most efficacious treatment.[23] Correlations between organoid responses and patient responses are increasing: a recent study used organoids to test growth-blocking antibodies and prevent metastasis, an approach that is going into phase 1 trials.[24]**

Beyond cancer therapies, organoids could help predict toxicity of drugs and whether a drug will work given a particular individual's genetic makeup. Because they largely preserve the genetic and functional traits of the original internal organs, they are useful for diagnostic purposes and for predicting patients' responses to pharmaceuticals. Immune disorders could also be open to new investigations.

Organoids may also be the future of regenerative medicine, as bespoke organs and tissues would not be subject to the immunological or ethical complications of transplant organs. Organoid culture allows for the generation of specific cell types that were previously impossible in 2D cultures, for example, hepatocytes.

### 5-YEAR HORIZON

**Organoids come to the clinic**

A simple organoid transplant – for example, of a retina — takes place. Other relatively thin and simple tissues move closer to the clinic. Rapid expansion and wider adoption of organoid technology for drug screening yields better understanding of human variation to drug responses, and generates predictions about how cells of the human body will respond to drugs. Drug discovery consequently gets cheaper.

### 10-YEAR HORIZON

**AI predicts drug responses**

AI-assisted predictions can be made about individual response to some drugs. Recapitulation of actual circuits, not just cells that touch each other, is achieved. Mechanistic conduits to human mental traits are discovered. Tumoroids are grown from patients to develop treatments on a very fast, highly efficient turnaround. Organoid-derived cells are used for stem-cell therapies in humans.

### 25-YEAR HORIZON

**High-resolution personalised medicine begins**

Digitally enabled integration of genomic and environmental data for predicting personal mental biographies becomes possible. Connecting the different organoids that scientists are currently developing in isolation results in miniature models of entire sections of human physiology for personalised medicine. 3D bio-fabrication of organs, including self-assembly, produces complex organs such as kidneys for transplantation.

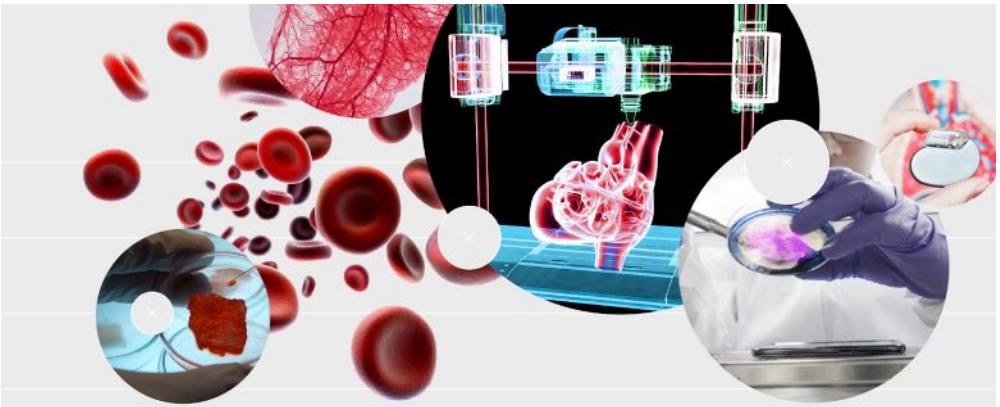
## 2.5.4 Enabling technologies

**Demand for organoids has soared. There is a boom in development tools and several companies have emerged as "app stores" for the mass production of organoids, selling them for research and drug development. However, turning organoids into full-sized organs — along with many other promising potential applications — will require different manufacturing processes to those currently in use.**

The varied protocols researchers use to create organoids result in highly heterogeneous organoids, and so standardisation of tools and protocols, and automated production, will be among the most important drivers of advances in this field. The creation and use of standardised organoids will increase reproducibility of results, replicability and provide the experimental control required for clinical translation. Brain organoids called assembloids now encompass hippocampus, cortex and amygdala.[25]

This will in turn increase the ease of interdisciplinary collaboration, which could help solve lingering problems such as the difficulty of connecting different organoids to each other on a chip, or the development of realistic vascular networks rather than the microfluidic imitations currently used. Here, too, recent advances are promising.[26] Intestinal organoids transplanted into humanised mice have opened the way to better assimilation into chimeric hosts.[27]

After these problems are solved, automation can scale up biomanufacturing: robotically produced organs can have nearly identical numbers and types of cells, for example. This could help with the development of bioreactors that will be necessary for the fabrication of entire organs.



### 5-YEAR HORIZON

**Collaborations ensue**

Microfluidic approaches and lessons learnt from organs-on-a-chip begin to converge on standard protocols. Vascularisation begins to become more successful. Advances in throughput and standards extends how long organoids can live. Consortia lead to interdisciplinary integration. Novel tissue-culture supplies with a stronger physiological basis become more widely deployed. AI improves protocols.

### 10-YEAR HORIZON

**Organoid production scales up**

The transition from cell culture to bioreactors allows scalability of complex organoids. "Microphysical systems" of cells and bioreactors become standardised and ubiquitous. Solutions are found for storing, managing and sharing the massive volumes of data generated by organoid analysis, from gene expression to electrophysiology.

### 25-YEAR HORIZON

**Automation brings industrialisation**

Organs can be created automatically and at scale. The food industry will make meat without animals, using lessons learnt from large-scale biomanufacturing, at scales large enough to be useful for food production. As a consequence, food (for humans and other species) will become more nutritious and cheaper, and can be personalised.

2.6

# Future Therapeutics

CO CHAIRS:
**Michael Lobritz**
VP and Global Head, Infectious Diseases Therapeutic Area, Roche, Basel, Switzerland

**Claire Roddie**
Associate Professor in Haemato-oncology, UCL, London

CONTRIBUTORS:
**James Collins, César de la Fuente, Dimitri Kullmann**

**Gene editing and the growing synthetic biology field promise to change how we conceive of medical intervention. Instead of fixing things after they have gone wrong, it is now becoming conceivable to prevent diseases before birth or before disease processes manifest.**

Engineering the patient's own cells — through adding or subtracting genes — can restore functions that native mutated cells may have lost. This methodology of using cells that are harvested, edited and then re-implanted into a patient's own body has been the source of many recent breakthroughs.[1] The clinical success of using viral vectors and next-generation gene-editing platforms for editing patient cells directly inside the patient (gene therapy) and editing extracted cells which are then replaced (cell therapy) opens the door to broader applications of cell and gene therapies. However, many challenges remain: for example, gene therapy is efficient only in certain areas and organs of the body, and can often be administered only once, due to the body's natural immune response to the viral-vector delivery system that is used to carry the DNA to the cells.

Another challenge facing therapeutics are bacterial and fungal pathogens which are rapidly becoming resistant to existing interventions. The WHO estimates that by 2050, 10 million people will die due to antibiotic resistance.[2]

However, the Identification of potential new classes of drugs is being vastly accelerated owing to recent and multiplying advances in artificial intelligence. Better datasets and better ways of mining those datasets are set to improve alongside AI tools. Metagenomics is yielding new discoveries as well, not only identifying new tricks from existing genomes but also harvesting strategies from extinct species.

Today's cutting-edge gene and cell therapies are united in being highly personalised, which accounts for the tremendous price tag they carry. Bringing down those costs is the only way to democratise these treatments, which will require economies of scale and generalisation.

KEY TAKEAWAYS

Genetic and synthetic-biology approaches are changing our approach to disease treatment and prevention by providing tools that can operate at both the symptom level and deeper causal level. **Future cell and gene therapy** will provide lifelong corrections to errant biology as well as fixing defective or missing genes. Research is making progress in understanding the mechanisms behind immune-system regulation and responses, and by **Hacking immunity** we can not only restore and augment the innate balance of the system when it goes wrong, but also program the system to attack new, precise targets. Developing new **Anti-infectives** is an urgent goal, given the threat posed by antimicrobial resistance, with several promising routes under investigation, including metagenomics and combinational approaches. All these will be aided by new approaches to **Drug discovery** which exploit technologies such as generative AI and machine learning for protein synthesis and data-mining, to offer the promise of vastly accelerated and improved pharmaceutical development.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Future cell and gene therapy and the areas covered by Hacking immunity are seen as the most transformative, with survey respondents highly confident about major advances in the coming five years. However, work towards the next generation of Anti-infectives is more uncertain and is not expected to reach maturity within 15 years. Cell and gene therapy gets the highest Anticipation Potential score overall because of the perceived lack of coordinated international action.

MORE INFORMATION:

**go.gesda.global/2-6**

# 2.6.1 Future cell and gene therapy

**Novel gene-editing platforms like base and prime editing,[3] and new delivery methods including lentiviral vectors, have treated a wide range of genetic blood disorders,[4] which now opens the door to broader applications of cell and gene therapies. After the success of mRNA vaccines, other RNA-based therapies are being explored, including antisense oligonucleotides (ASO), which bind to RNA targets, preventing them from producing harmful proteins, such as those which cause Huntington's disease in the brain.[5]**

The next frontier is selectivity. The health risks of taking immune cells out of patients for editing can be avoided with therapies that act directly on tissues within the body. But these rely on the ability to ferry gene editors into specific tissues or cells. The most commonly used viral delivery method, adeno-associated virus (AAV), can reach accessible tissues such as the eyes and blood, but have more difficulty in penetrating muscle, specific locations in the brain and solid tumours.[6] However, new site-specific gene-editing methods can infiltrate tumours and preferentially target brain areas linked to focal epilepsy.[7] Engineered immune cells can now contain logic gates that selectively target leukaemia cells.[8] Other disease-sensitive approaches could target metabolic signatures of diseased cells.

To affordably advance regenerative medicine, immunotherapy and cancer therapies requires moving from personalised therapies to greater generalisation.

## 5-YEAR HORIZON

### Editing gets specific

Gene-transfer technologies, including AAV vectors and lipid nanoparticles, are repurposed to deliver epigenetic effectors. First human trials begin for gene therapy that targets only affected neurons, treating treatment-resistant epilepsy.[9,10] Oligonucleotides are approved to target more rare diseases. Clinical trials on RNA antisense therapeutics reveal whether the therapy can help people with ALS and other neurodegenerative diseases.

## 10-YEAR HORIZON

### Delivery gets specific

First human trials on gene therapy against Parkinson's disease that targets excitability in ion channels in neuronal circuits take place.[11] Non-viral delivery methods succeed in inserting payloads into the DNA-containing nucleus of the cell. Lentiviral vectors combined with Crispr-Cas9 and other gene-engineering tools becomes a way to destroy solid tumours. The range of clinical indications for bone-marrow-derived stem-cell-based gene therapies expands widely; allogeneic hematopoietic-stem-cell transplantation (HSPC) is phased out in favour of autologous gene therapy.

## 25-YEAR HORIZON

### Selectivity gets specific and therapies become general

Glycosylation or other metabolic markers offer more specific targets for immune-cell-based therapy.[12] Research pivots towards editing and delivery methods that can be batch-produced for many patients across different diseases. Engineered-immune-cell therapies such as CAR-T cells become standardised.

# 2.6.2 Hacking immunity

**There has been gradual progress in our understanding of immune regulatory mechanisms, thanks to the discovery of a diverse range of immune cells — from anti-inflammatory "brakes" on the system to pro-inflammatory "accelerators". The goal for all immune modulation, whether boosting anti-inflammatory or pro-inflammatory cells, CAR-T (the modification of immune cells to target cancer cells) or other manipulation, is re-establishing and supporting the body's natural homeostasis.[17]**

Immunotherapy (adding specifically curated receptors to the T-cells of the immune system and others to recognise cancers and other desired targets, commonly referred to as CAR-T cell therapy) has delivered on its early promise against cancer. But it remains more effective for cancers like leukaemia, lymphoma and melanoma than for inaccessible and immunosuppressive solid tumours. Even for non-solid cancers, CAR-T can fail or induce cytokine toxicity. Lentiviral vectors, derived from the HIV-1 retrovirus, are showing promise to deliver gene editors to tumours and against other immune disorders.[13,14] Trials are also now beginning in England[15] and the US for cancer vaccines that work by stimulating a patient's immune system to recognise and destroy any remaining cancer cells — and stop their reappearance.[16]

Immunotherapy is not just being investigated for cancer. For people with gene errors predisposing them to immune dysfunction, gene-editing techniques show promise to precisely correct T cells wrongly targeting the body's own healthy cells. CAR techniques being used against multiple sclerosis[17] as well as myasthenia gravis,[18] stiff-person syndrome[19] and even intractable lupus[20] are showing promising early results, along with strategies against other autoimmune disorders.

However, all this is fighting symptoms. A future medical approach to address the underlying cause of immune-system dysregulation will require a more precise understanding of the triggers for autoimmune disease.

### 5-YEAR HORIZON

**The roots of autoimmune disorders are understood**

Clinical trials build evidence that cancer vaccines induce an immune response that prevents cancer from returning after tumour-removing surgery. Reduced immune toxicity makes CAR-T therapy safer and more accessible for patients of all ages. Results of lupus immunotherapy trials deliver new insights into mechanisms by which immunotherapy is resetting the immune system.

### 10-YEAR HORIZON

**Immunomodulation becomes supercharged**

Synthetic biology approaches are developed to deprogram the immune system. Microfluidic devices, models used to recapitulate tumour complexity, start to decipher the molecular mechanisms driving treatment inefficiencies and to evaluate new targeted immunotherapies. New treatments are developed for a rare disease of the white blood cells that control the immune system and guard against repeat infections and cancer; insights from this development inform new research into the broader immune system.[21]

### 25-YEAR HORIZON

**Immune hacking gets local**

Therapeutic approaches scout immunity locally instead of making systemic changes: localised rewiring, with RNA, and local delivery tools like nanoparticles. This ends systemic side effects. A better understanding of the immune system leads to precise gene editing of immune cells, making it possible to identify errors in specific types of cells and optimise or personalise treatment that gives optimal function of the immune system. A one-time cure for HIV — that does not require being on lifetime medication — is developed using CAR-T cells to purge the viral reservoir.[22]

# 2.6.3 Anti-infectives

**The widespread use of antibiotics, antivirals and antifungals has driven the evolution of antimicrobial resistance, set to kill 10 million people a year by 2050. Besides antimicrobial resistance, other challenges to combating infectious diseases include, for example, that of tuberculosis, with immune tolerance which makes it extremely hard to target with a single strategy,[23] and the chronic fungal infections immunosuppressed patients often develop.[24] But new drugs are hard to discover and develop, as they do not make much money competing against cheap generics, such as current antibiotics on the market.**

One such recent candidate, zosurabalpin, overcomes existing antibiotic-resistance mechanisms in a major hospital-acquired pathogen, carbapenem-resistant Acinetobacter baumannii (CRAB), and is now in human trials. Although AI holds the promise to speed up drug-screening processes, a major challenge in developing new antibiotic medicines remains the progression of new chemotypes that kill bacteria effectively in vitro into human medicines that carry well-balanced drug-like properties, including safety profiles.

It will be necessary to embrace entirely new ideas. First, existing antibiotics may be made more effective by using them in combination with non-antibiotic drugs. The use of bacteria-infecting viruses known as phages can treat bacterial infections and reduce resistance to antibiotics by removing physiological barriers — biofilms — which contribute to resistance. However, infrastructure is underdeveloped for clinical trials and research is still needed to answer important questions about the specific actions of phages against bacteria, and how bacteria develop resistance against phages.[25] Regulatory infrastructure also needs to be updated for the research into phages to advance.[26] Research is also under way to develop microbiome strategies to cultivate gut flora to outcompete pathogenic strains. In addition to faecal transplants, more sophisticated RNA-based sculpting of the microbiome can selectively kill certain bacteria.[27] Immunotherapy is also being investigated for deployment against bacterial infections[28] and fungus.[29] The more alternatives to defeating antimicrobial resistance the better, to minimise the chance of pathogens evolving mechanisms to evade the treatment — that is, resistance.

## 5-YEAR HORIZON

### Diagnostic technologies improve

Development and implementation of diagnostic technologies that can rapidly identify infecting pathogens, and the antibiotics that are effective against a particular strain, allow healthcare professionals to make informed decisions about which antibiotics to use. Machine-learning models predict “dual function” treatments — ways to kill pathogens while simultaneously boosting immune properties. Phage therapy begins to be adopted in agriculture instead of antibiotics to keep livestock infections in check.

## 10-YEAR HORIZON

### Choice of available therapies improves

How bacteria build resistance to phages starts to be understood and can be modelled using AI. Gene therapy begins to be deployed against pathogenic bacteria to target their survival strategies (including propensity to form biofilms and transition into “persister” states). Autologous prophylactic faecal transplants become a routine precursor to taking antibiotics. Phage therapies move into the clinic.

## 25-YEAR HORIZON

### Research develops a cure for HIV

Purging the viral reservoir of HIV totally eliminates the disease in a one-shot cure. Sustainable chemical-synthesis strategies are employed in small-molecule synthesis, dramatically reducing time and cost of delivery of new medicines.

# 2.6.4 Drug discovery

**Finding new small-molecule drugs is a multi-billion dollar, multi-year effort that often fails.[30] AI-based drug development promises a faster, more effective path and has yielded novel drugs, some of which are now entering trials.[31] It is poised to become an increasingly valuable tool.**

First, machine learning can identify the complicated "lock and key" relationships between new compounds and the relevant disease-related proteins they may affect. AI systems like AlphaFold, which can predict a protein's 3D structure from its sequence, are teaming up with major pharmaceutical companies to hasten the discovery of small-molecule therapeutics.[32] AI also holds promise for synthesising new chemical compounds not seen in nature, which bacteria therefore have not had a chance to build defences against.[33]

Second, AI can mine the metagenome — the diversity of all existing natural molecules[34] — and beyond: one project is mining the genetic information of all available extinct organisms, from extinct human relatives such as Neanderthals to ice-age animals like the woolly mammoth and giant sloth. These have identified previously employed defence mechanisms, now extinct, that contemporary pathogens have not evolved to evade.[35]

Third, machine learning can be deployed to find patterns in other complex datasets, for example in the heaps of data generated during clinical trials, whether they succeed or fail.

But AI and machine learning are not magic tools, and are useless without good data. Data generation requires well-curated and standardised public data sets, and functionalising AI also requires next-generation manufacturing and regulatory approaches to bring synthesis into line with discovery.

5-YEAR HORIZON

**Humans and AI align in drug discovery**

New dataset-generation proposals are developed. AI begins to mine data taken during clinical trials to get a better look at hidden patterns related to trial outcomes. Discovery and proteome mining speeds to identify new candidate drug compounds in minutes. Clinical trials on the first AI-designed drugs begin to yield mid-term results.

10-YEAR HORIZON

**AI deployments improve therapeutic success**

Larger data sources are planned at the nation-state level. AI clinical-trial data-mining links targets to diseases where no links had previously been identified. Frameworks and new chemical-synthesis systems are put in place to more quickly and robustly turn AI discoveries into compounds.

25-YEAR HORIZON

**AI becomes a reliable drug-discovery partner**

AI-mined trial data has now identified disease targets as intervenable nodes and generated proteins and small molecules to intervene. Drug-discovery time is shortened to days instead of years. Sequencing and synthesis is automated, reducing costs such that rare-disease drug treatments become viable.

INVITED CONTRIBUTION

# Growing Embryo Models: Challenges and Future Promise

**Jacob Hanna**
Professor of Pluripotent Stem Cell Biology and Synthetic Embryology, Weizmann Institute of Science, Israel

MORE INFORMATION:

go.gesda.global/2-IC-1

**The human embryo makes all of its organs during the first 40 days of pregnancy. It is during this extremely sensitive period that most pregnancies fail, most developmental defects form and drugs such as alcohol have the most toxic effects. It is also the part of pregnancy that we know least about, with obvious implications for our ability to develop medical interventions.**

There are many reasons for our ignorance, both technical and ethical. Studying this period in human development requires obtaining ex utero samples at the termination of a pregnancy. However, women often do not realise they are pregnant during these first few weeks, and even if they do know and would be happy to donate their embryo for research, voluntary termination often only requires taking a pill. That means tissues extracted during surgery are rare, and tissues of sufficient quality to be used for research are rarer still.

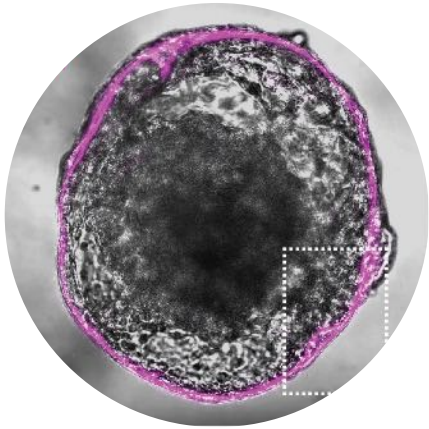
The few samples that do exist provide the current gold standard for researchers working to understand human embryo development. But to really understand a system, thousands of examples are required and all the normal variance between individuals must be understood. Besides this, researchers would ideally be able to engineer the system, labelling or mutating its components to test different hypotheses. This is impossible with embryos derived from actual pregnancies (that is, from the fusion of an egg and sperm).

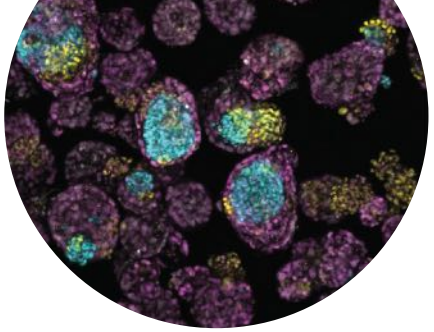
An alternative was required. Stem cells are a particular type of cell with the potential to divide to produce a range of different types of cells. Over the last few years, researchers have managed to steer stem cells to produce the functional units of an entire embryo, and subsequently to develop most of the structural organisation of a real embryo. By 2023 these "embryo-like entities", or "model embryos", had reached a point which allowed early human embryogenesis to be studied for the first time.[1]

Getting to this point required a huge multi-researcher effort over many years. The first challenge was that the stem cells needed to be highly plastic in order to give rise to both the embryonic tissues and the cells around the embryo, such as the yolk sac and placenta. Conventional stem cells are not capable of this, but around 10 years ago[2] we found a way to derive improved stem cells with extended potency, which were able to do just that.

Second, we needed to be able to grow an embryo outside the uterus. We were able to develop this capability using animal models such as the mouse and rabbit. This was in itself a huge breakthrough for the field: such ex utero systems allow you to monitor the same embryo every day with your own eyes, which had never been possible before. This system gives researchers increased control, access and ability to observe and manipulate developing embryos.

But what happens if you take naïve stem cells and put them into the ex utero system? Using mouse cells and genetic engineering, we showed that you can grow embryo models that very closely resemble an 8.5 day-old embryo,[3] meaning that they complete gastrulation — the process of making organ progenitors — and start making organs. Using human naïve stem cells turned out to be much easier, requiring no geneticmodification steps to encourage the formation of the different parts of the embryo. As well as being a pleasant surprise for the field, this was an interesting discovery in itself, demonstrating that human naïve stem cells are more plastic than those in mice.





However, only about 1 per cent of human embryo models develop to the standard needed for useful research. Improving this efficiency remains one of the field's biggest challenges, with optimisation of both the cells and the artificial uterus device required. How cells self-assemble into an embryo is primarily an architectural problem, and reliably replicating this in an artificial system will require advances in biomaterials science, bioengineering, metabolomics and microscopy. Physical constraints provided by the uterus are known to be important but are not well understood, and even the embryo's own size is critical to development: many processes are directed through signalling molecules which diffuse through the embryo and organise it along different axes. If the embryo is too large, then the molecules may not reach far enough; if it is too short, they will be too concentrated to provide useful information to the cells.

There are also other fundamental biological questions, thanks to our ignorance of early embryonic development. For example, the placenta is essential to embryonic development in mice, but might not be in humans. As the models are used to try to answer some of these questions, the results in turn can be fed into improving the model system; the result is a positive feedback loop in which we both improve our understanding of human biology and refine our tools for investigating it.

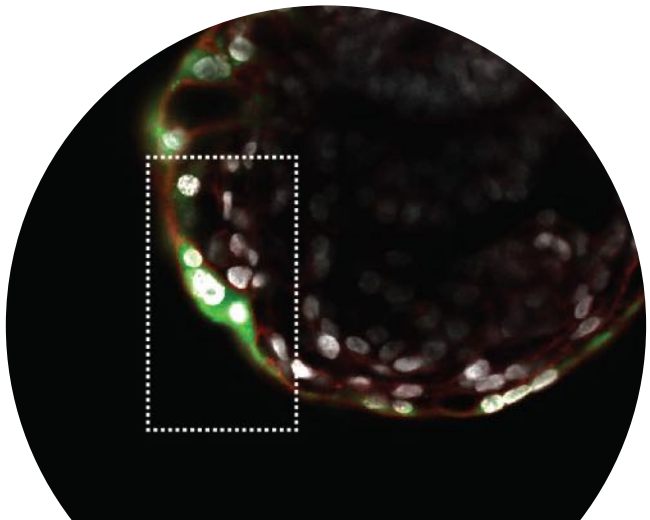
In parallel to developing model embryo systems, scientists are also slowly building atlases of human embryonic development, collecting all possible data from the rare natural embryos obtained through pregnancy termination. These samples provide anatomical information about the developing embryo and can also provide information about which genes are turned on in its different cell types. Given how precious these samples are, it has become imperative for scientists around the world to deposit their data in shared, openly accessible repositories to maximise their value to research, both for the donor's sake and for the public who fund this research.

Often when people hear about synthetic embryo models, they assume that researchers are trying to create embryos and replicate the whole course of pregnancy outside the womb. That is not the goal, nor is it actually achievable in any readily foreseeable timeframe. Embryo models are just that, models of structure and function, not viable entities that could become fetuses or babies. So looking ahead to the next 10 to 15 years, the dream would be to be able to take cells from a consenting adult and from these grow embryo models to day 40 with 80 per cent efficiency. Although only around 1centimetre long, 40-day-old embryos are sufficiently developed for researchers to study the different embryonic structures and how organs originate. By using embryo models which can grow up to the same stage, we can knock out different genes to find out which are important for different processes, such as human liver development. We could also add alcohol, tar from smoke or administer different drugs to see how each affects the development of the embryo models. Using embryonic models from different species, we could compare human development to that of other animals and understand the similarities — and differences — in their mechanisms. This will give us the underlying principles of mammalian development in general, and also help us to understand data from preclinical trials in other species. Ultimately, synthetic embryo technology could be used in clinical trials to develop medical treatments and public health policies.

Beyond the practical limitations of trying to work with real human embryos, there are also a range of associated ethical concerns which can be addressed scientifically using embryo models. Restrictions on working with human and other primate tissues differ from country to country, making different strands of research more or less feasible depending on local guidelines. However, embryo models are still very different from real embryos, and these differences are not likely to disappear soon — they do not have the potential to grow to full-term pregnancy. This is due to both the technical restrictions of working in an artificial uterine system[4] and how difficult it is to even encourage the cells to grow to a structured model of a few weeks old. Work is also under way to develop "restricted" stem-cell lines which cannot develop brain or heart tissues, decisively limiting their potential. Even if, in many years' time, researchers did develop a way to support embryonic development to full term outside the uterus, the application of this technology would first go to supporting pre-term babies which would otherwise not survive, rather than replacing pregnancy to create embryos outside the womb.

Given the pioneering nature of this field, scientists are actively involved in developing ethical guidelines and policies to guide its future. One recent example is the UK's publication of a voluntary code of practice,[5] commendable for the breadth of expertise and perspectives involved. These guidelines provide good recommendations for the field, but given its fast-paced nature and different cultural considerations around the world, they will need to be interpreted flexibly and updated on a regular basis to take into account the latest research developments. However, development of international guidelines at such an early stage of research into synthetic human-embryo models will bring confidence to those working in the field, facilitate cross-border collaboration to accelerate research discovery, and provide both the transparency and time needed for the field to earn society's trust and participation in decision-making.

This is important because there is an acute need for embryo models not just to satisfy our intellectual curiosity, but to improve human health. CMV infections — caused by the herpes virus — are very dangerous during pregnancy, but cannot be studied in mice, as CMV doesn't cross the mouse placenta. Certain brain-development disorders in children originate during embryogenesis; without embryo models, they are impossible to investigate and understand. And these are just the beginning; given our radical ignorance about early embryonic development, it is likely that embryo models will allow us to discover other, potentially enormously significant, processes and factors in the earliest and most sensitive stage of pregnancy.



INVITED CONTRIBUTION

# Space Technology and Global Health

**Claude Nicollier, Pilar Hernandez, Chadia Wannous, Nicolas Ray, Steve MacFeely, Markus, Reubi, Natália Archinard, Martyn Clark, Ravi Shankar, Santhana Gopala Krishnan, Stefano Ferretti, Roberto Biasutti, Aarti Holla-Maini, Antoine Geissbuhler**

*This contribution is produced in collaboration with the Geneva Digital Health Hub and based on their panel discussion 'Space and Global Health' at the Geneva Digital Health Day, 2024.*

MORE INFORMATION:

go.gesda.global/2-IC-2

**Due to the profound impacts of climate change, the intersection of space technology and global health is emerging as a crucial area of focus. Climate change is fundamentally altering the global landscape, causing extreme weather events such as wildfires, droughts, cyclones and floods. These events reshape our physical world and profoundly impact public health by altering patterns of disease spread and facilitating outbreaks. Space monitoring technology, combined with artificial intelligence, is playing an increasingly important role in tracking these environmental changes, and related disease outbreaks, to improve public health interventions.**

Studies suggest that over 50 per cent of known human infectious diseases may be exacerbated by climate change, with a significant proportion of emerging pathogens being zoonotic in nature. Vector-borne diseases such as dengue, chikungunya and malaria, as well as water-borne diseases such as cholera, are particularly sensitive to environmental changes. The displacement of human and animal populations due to climate-related events further complicates disease dynamics and creates new pathways for disease transmission and outbreaks.

The increasing frequency and intensity of pandemics is largely driven by human-induced changes such as land-use alterations, agricultural expansion and climate change. Consequently, incorporating environmental and animal health indicators into disease-surveillance systems is essential for comprehensive risk assessment. The "One Health" approach, which emphasises the interconnectedness of the health of humans, animals and the environment, is of central importance in this regard, and the Surveillance Outbreak Response Management and Analysis System (SORMAS) is a space-based initiative that demonstrates the potential to integrate animal and environmental data, and provide real-time monitoring based on satellite information, enabling a holistic view of health risks.

The One Health Joint Plan of Action, a global framework for collaboration on the One Health approach, outlines an approach to integrating Earth-Observation (EO) data into vector-borne disease surveillance systems. Initiatives in North Africa exemplify this approach by defining "ecoregions" and prototyping an EO-based vector-borne disease-surveillance system. Collaborations with agencies like the European Space Agency (ESA) or global coalitions like the Group on Earth Observations, and the development of prototypes in platforms like Google Earth Engine, are key next steps. These efforts underscore the potential of EO data to revolutionise disease surveillance by providing precise, real-time environmental data that can inform public health strategies. By integrating satellite data into health-surveillance systems, we can better predict and respond to disease outbreaks caused by environmental changes.

In resource-limited settings, access to emergency health services is a major challenge. Remote-sensing data plays a critical role in optimising healthcare access. In Madagascar, for example, a significant proportion of women live more than two hours away from maternity services, with many lacking access to fully functional facilities. Remote sensing and geospatial modelling can create maps that highlight areas of vulnerability, enabling targeted interventions and facility upgrades. Similarly, in Nepal, nationwide surveys on snake bites have led to the development of probability maps for snake-bite incidents and accessibility maps for hospitals with anti-venoms. These maps are invaluable tools for health ministries and stakeholders, facilitating informed decisions on resource allocation and intervention strategies. The integration of geospatial data, population distribution and infrastructure mapping through ESA's Earth Observation missions exemplifies the transformative potential of space technology in health planning.

Data governance is a critical issue that intersects with numerous global concerns, including national security, human rights, environmental sustainability and economic stability. As data becomes a central pillar of our technology- and information-driven society, international data governance frameworks are essential. The fragmented nature of the global data ecosystem, characterised by differing ideologies on data management across regions, necessitates cooperative governance. Space systems produce vast amounts of data, particularly from Earth-observation satellites, which are crucial for linking health, environment and climate. Effective data governance will ensure the responsible and sustainable use, storage and dissemination of data, safeguarding the benefits of the digital revolution while mitigating its risks.

Space technology plays a critical role in supporting the UN Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being). Satellite-based tools for investigating aquatic ecosystems, rapid mapping of disaster-affected areas and collaborations with space agencies highlight global efforts to use space technology to improve health. Initiatives like the ESA International Charter Space and Major Disasters, or the UN Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER), exemplify how space-based solutions provide real-time support in crisis situations, enhance telemedicine, improve rescue operations and ensure effective communication. Human space flight also contributes to medical research, providing unique insights from microgravity experiments and astronaut-health management.

The integration of space technology and global health represents a frontier of opportunities to address climate-sensitive diseases, optimise access to healthcare and ensure robust data governance. Interdisciplinary collaboration, capacity-building, and forward-looking technological advances are essential to realise the full potential of space technologies in achieving the Sustainable Development Goals. Synergies created by bridging the gap between the space and health communities will lead to innovative solutions and a healthier, more resilient global population.

CONFERENCE PROCEEDINGS

# Neuro Augmentation: Hype or Hope?

## 2.1 Cognitive Enhancement

Advances in neurotechnology such as brain-machine interfaces or genetically engineered brains could have the potential to augment human cognitive abilities, raising fundamental questions for humanity and society. With such rapid developments under way, what are the opportunities and challenges for science to positively impact the world we live in by anticipating global governance?

MORE INFORMATION:

go.gesda.global/2-1-Diplomacy

PARTICIPANTS

Moderated by:

**Karen Rommelfanger**
Founder, Institute of Neuroethics

Presentations by:

**Jaimie Henderson**
Professor of Neurosurgery, Stanford University, California

**Mu-ming Poo**
Director, Institute of Neurosciences, Chinese Academy of Sciences

With:

**Nita Farahany**
Professor of Law, Duke University, Durham, North Carolina

**Claudia Fuentes Julio**
Ambassador and Permanent Representative of Chile to the UN Office at Geneva

**Marcello Ienca**
Professor of Ethics of AI and Neuroscience, Technical University of Munich, Germany

TAKEAWAY MESSAGES

*"From the invention of the wheel to the current era of generative AI, humans have relied on technology to enhance their cognitive abilities since ancient times and the recent trend of neurotechnologies is no exception. Both public and private investment in the technology has grown rapidly and the neurotech devices market is expected to reach $24.2 billion in 2027."*

*"Technology for reading and writing signals of the brain is predicted to become wireless within five years. Within 10 to 25 years, brain-computer interfaces are likely to provide better readouts of brain states and, combined with closed-loop neurostimulation, may help patients coping with issues of dementia, sensation and bowel control. The speed of neurotechnology development is moving so quickly that it is almost outpacing our scientific understanding of the brain. The technology itself has been demonstrated but better understanding of how language and cognition are represented in the brain, and even consciousness, could help to advance it even further."*

*"The advent of devices that can measure and influence brain activity and the nervous system are on the cusp of widespread adoption across society, raising profound questions ranging from human rights to data privacy. What is now needed is a global consensus of ethics that balances frontier scientific pursuit with societal needs."*

*"The governance landscape is trying to keep pace with the development of neurotechnology and can currently be broadly categorised into three areas: self-regulation by the scientific community, soft law instruments by international organisations and legally binding frameworks."*

# Tackling Tomorrow's Health Challenges Today

## 2.2 Advanced AI

From designer phages that could allow one to engineer viruses that augment human, animal and plant health to improvements for mental health in the metaverse through shared virtual spaces, science for health is advancing at a rapid speed. How can organisations best be prepared to anticipate tomorrow's trends?

PARTICIPANTS:
Moderated by:

**Tolullah Oni**
Clinical Professor, University of Cambridge, UK

With:

**Mariam Ezz El-Arab**
iGEM Ambassador for Africa, Egypt (winner of the 2023 GESDA Youth Anticipation Initiative)

**Mubeen Goolam**
Stem Cell Researcher, Department of Human Biology and Neuroscience Institute, University of Cape Town, South Africa

**Ryan Morhard**
Senior Director for Policy and Partnerships, Gingko Bioworks, Boston, Massachusetts

**Chorh Chuan Tan**
Chief Health Scientist, Ministry of Health; Executive Director, Ministry of Health Office for Healthcare Transformation, Singapore

MORE INFORMATION:

go.gesda.global/2-2-Diplomacy

TAKEAWAY MESSAGES

*"By 2050, individuals aged 60 and older are expected to comprise 22 per cent of the global population, posing challenges for health and social systems worldwide. The majority of elderly individuals will reside in low- and middle-income countries, necessitating comprehensive preparation for the associated demographic shift."*

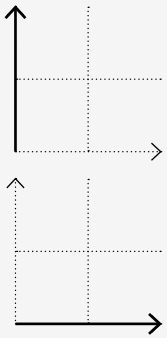
*"Policy-makers face challenges in keeping pace with evolving scientific landscapes, as highlighted during the COVID-19 pandemic. Anticipating future health trends is crucial for shaping policies that maximise benefits and minimise risks associated with innovation, requiring engagement with hard-to-reach populations."*

*"A holistic approach is essential for effective health systems. Emphasis should be placed on preventative measures, including physical activity, nutrition, mental health and smoking cessation. Changing environments to promote healthier choices, beyond individual behaviour change, is necessary."*

# Media-Innovation Analysis

Already among the most relevant topics in public discussion, the emerging areas of Healthspan Extension and Cognitive Enhancement are also driving the innovation landscape in Human Augmentation.

LEGEND:



**YoY PATENT GROWTH**
YoY (year-on-year) growth of granted topic patents[1] from May 2022/April 2023 to May 2023/April 2024

**YoY MEDIA GROWTH**
YoY (year-on-year) growth of topic mentions in news and blogs from May 2022/Apr 2023 to May 2023/April 2024

MORE INFORMATION:

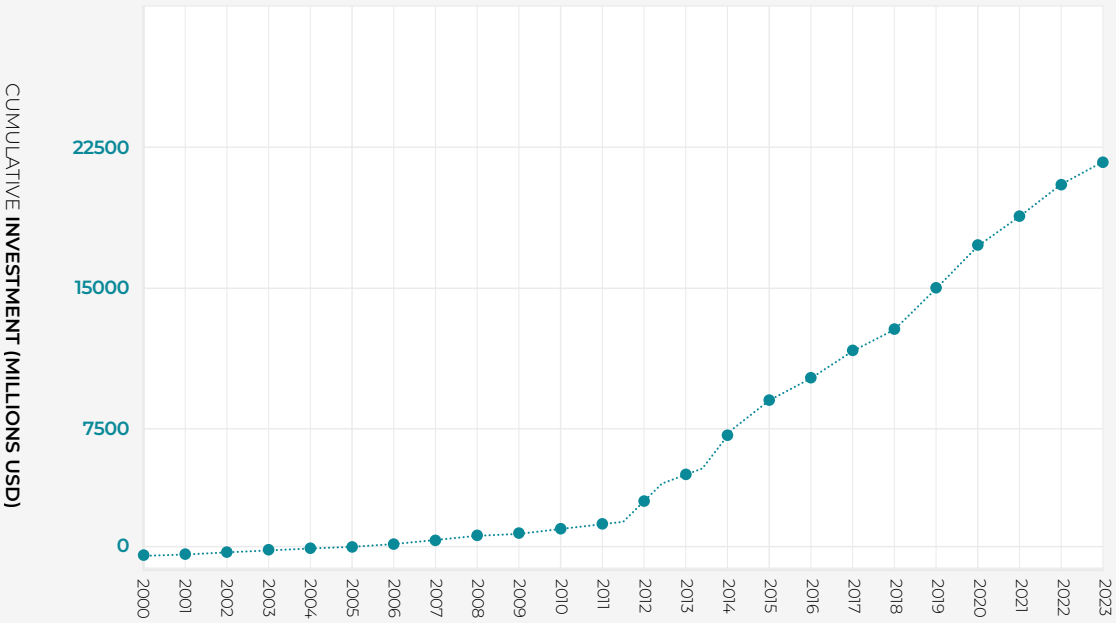
go.gesda.global/Impact

IMPACT FOCUS

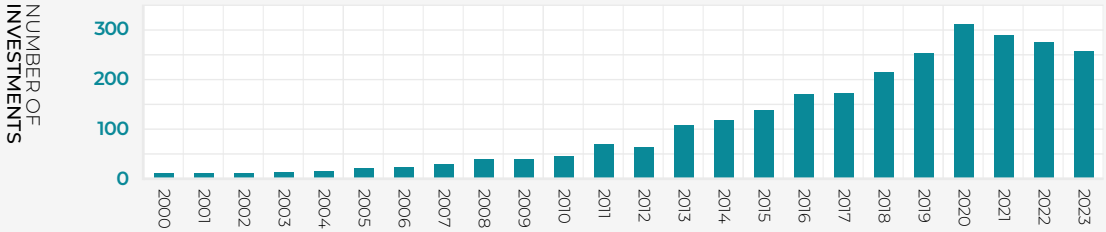
## 2.1 Investment and Company Creation in Cognitive Enhancement

Recent technological advances in electronic miniaturisation, brain-signal detection and artificial intelligence (AI) for data analysis have boosted neuroscience and neurotechnology development, generating large financial investments from the public and private sectors. The yearly investments in neurotech companies have reached USD 2 billion in 2021: a 40-fold increase since the early 2000s. The yearly number of investments has followed a similar trend, reaching 300 per year in 2021.

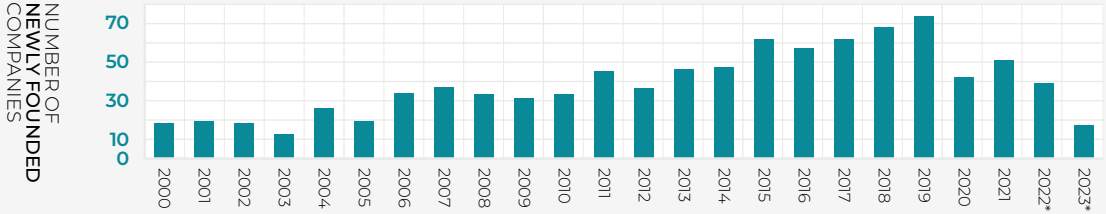
### CUMULATIVE INVESTMENT IN COGNITIVE ENHANCEMENT COMPANIES




### NUMBER OF NEW INVESTMENTS IN COGNITIVE ENHANCEMENT COMPANIES




### NUMBER OF NEWLY-FOUNDED COGNITIVE ENHANCEMENT COMPANIES




Source, facing page: Deep View analysis from 1 May 2022-30 April 2024; (1) YoY media growth = YoY growth of topic mentions from May 2022/April 2023 to May 2023/April 2024; (2) YoY patent growth = YoY growth of granted topic patents from May 2022-Apr 2023 to May 2023-Apr 2024.

Source, this page: Pitchbook

*Data on newly-founded companies in 2023 is incomplete and will be updated once first funding is raised. Projections indicate a minimum of similar levels of company creation to 2021.

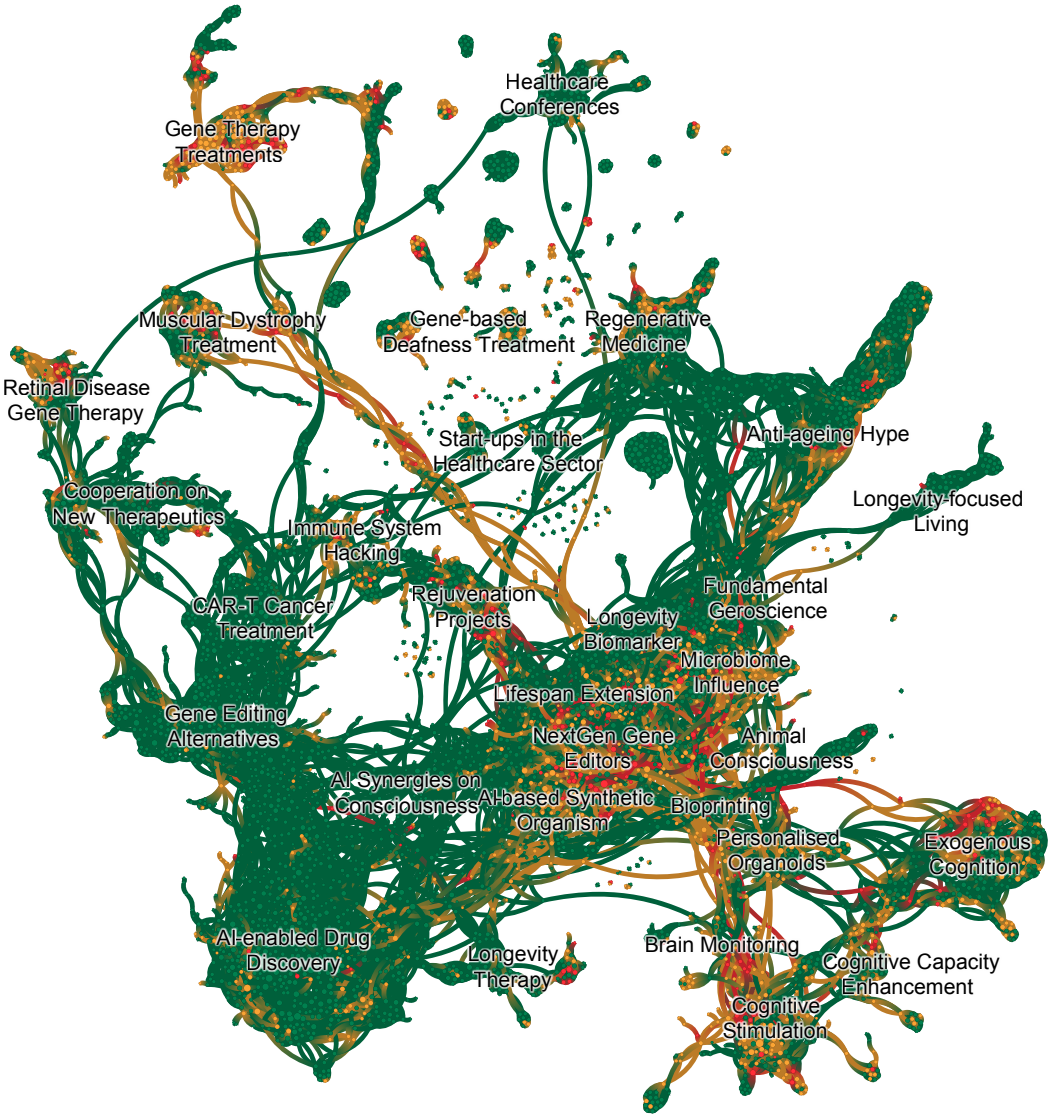
## What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months shows that, while the net sentiment around Human Augmentation is very positive in news, blogs and social media, and continues to rise, the smaller number of negatively framed discussions are focussed on the potential long-term consequences of Human Augmentation and associated ethical questions surrounding new treatments. However, the overarching sentiment surrounding Human Augmentation is highly positive, with a net sentiment of 87 per cent in mainstream media.

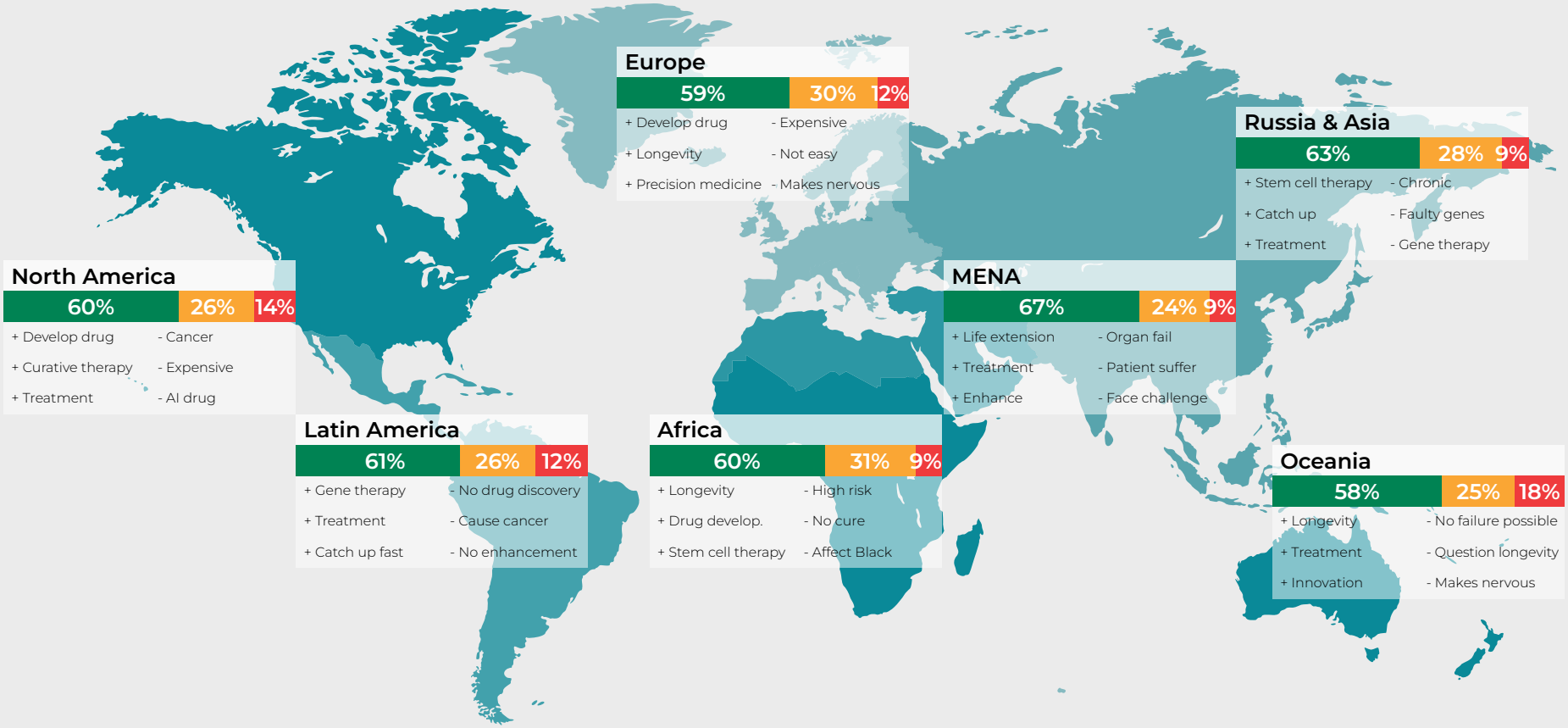
MAINSTREAM MEDIA SENTIMENT

| MAINSTREAM MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| UNIQUE ARTICLES | 385k |
| VISUALISED ARTICLES | 6k |
| NET SENTIMENT | 87% |
| ARTICLE UNIQUENESS | 15% |

| SOCIAL MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| NUMBER OF POSTS | 2047k |
| VISUALISED POSTS | 10k |
| NET SENTIMENT | 65% |
| UNIQUE IMPRESSIONS | 178b |



DEMOGRAPHICS & SENTIMENT PER REGION




GLOBAL SENTIMENT

- The global sentiment towards **Human Augmentation** is **overall positive**, with **exceptional enthusiasm observed in the MENA region**, where positive sentiment reaches 67 per cent.

- In contrast, contributors from **North America, Europe and Oceania express more critical views**, focussing on potential long-term risks and ethical concerns associated with human augmentation.

- Geographical insights reveal the prime contributors to the discussion in each region: **North American sentiment** is predominantly influenced by the US (95%), **Latin America** includes varied contributions from Brazil (20%), Mexico (16%) and Colombia (24%), and **Europe's dialogue** is led by the UK (46%), Germany (13%) and France (12%). In Africa, Nigeria (42%), South Africa (20%) and Kenya (9%) contribute prominently, while discussion across **Asia & Russia** is dominated by India (54%), with notable mentions of China (5%) and Indonesia (7%). **Oceania's discussion** is primarily from Australia (80%), with minimal contributions from other areas.

Source: Quid Social, containing the past 24 months of English language data from 10+ social media sources in 200+ countries.

# Media Analysis

## GROWTH

Within the context of Human Augmentation, 45 per cent of all mentions are attributed to news and blogs on Healthspan Extension. Cognitive Enhancement, growing at a rate of 46 per cent, is by far the fastest-growing topic.

## DOMINANCE

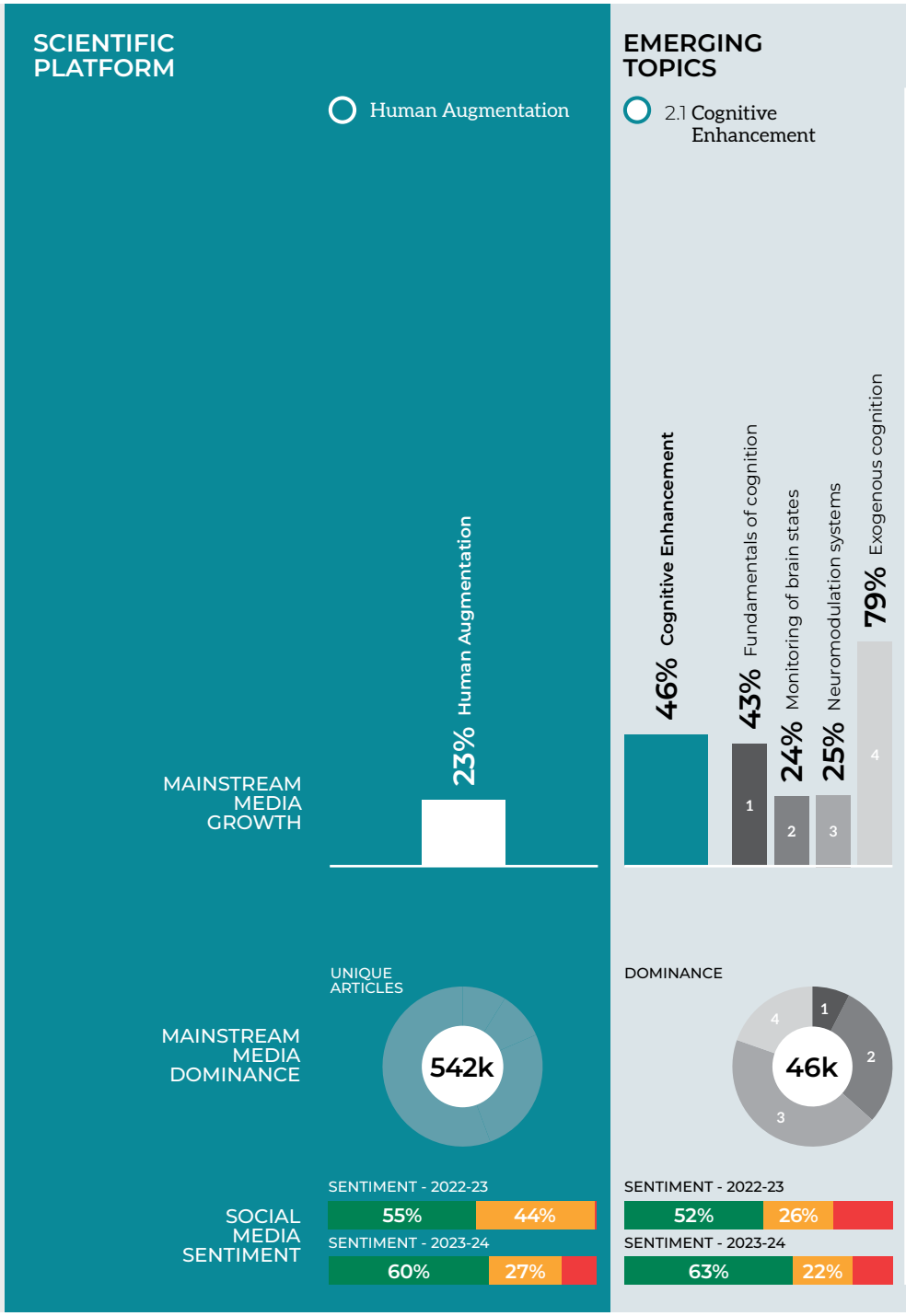
Fast-growing topics are often driven by specific sub-topics, such as Lifespan extension and rejuvenation, which have grown by 45 per cent in mentions, leading to a one-third increase for Healthspan Extension. Organoids is the only topic within Human Augmentation that has decreased over the past year. This is not driven by specific sub-topics but rather by a general reduction in discussions about organoids in news and blogs.

## SOCIAL SENTIMENT

From 2023 to 2024, growing positivity points to greater public acceptance for Human Augmentation, with a significantly increased optimism for Cognitive Enhancement and a slight increase for Healthspan Extension.

MORE INFORMATION:

**go.gesda.global/Society**



## 2.2 Human Applications of Genetic Engineering




DOMINANCE




SENTIMENT - 2022-23

| | |
|---|---|
| 51% | 32% |

SENTIMENT - 2023-24

| | |
|---|---|
| 50% | 35% |

## 2.3 Healthspan Extension




DOMINANCE




SENTIMENT - 2022-23

| | |
|---|---|
| 58% | 28% |

SENTIMENT - 2023-24

| | |
|---|---|
| 63% | 23% |

## 2.4 Future of Consciousness




DOMINANCE




SENTIMENT - 2022-23

| | |
|---|---|
| 49% | 38% |

SENTIMENT - 2023-24

| | |
|---|---|
| 46% | 40% |

## 2.5 Organoids




DOMINANCE




SENTIMENT - 2022-23

| | |
|---|---|
| 61% | 32% |

SENTIMENT - 2023-24

| | |
|---|---|
| 65% | 27% |

## 2.6 Advanced Therapeutics




DOMINANCE




SENTIMENT - 2022-23

| | |
|---|---|
| 62% | 26% |

SENTIMENT - 2023-24

| | |
|---|---|
| 67% | 23% |

SCIENTIFIC PLATFORM

3

# Eco-Regeneration & Geoengineering

Advances in science and technology will be vital for monitoring and mitigating problematic trends in our climate and for establishing new ways for humanity to live on a changing planet — and, increasingly, off it. This is how humans will develop the tools required to decarbonise our economies, establish more sustainable food systems, sustain and enhance our terrestrial, marine and orbital environments and perhaps even mitigate climate change by reducing solar radiation. All of the programmes of research involved offer an important step forward in the story of human progress. Together, they create a portfolio of discovery and action that could be transformative for all our futures.

**THE 2024 VILLARS ANTICIPATION WORKSHOP ON ECO-AUGMENTATION** (pages 144-153)
**Shaping Ecosystems:** Anticipating an Age of Eco-augmentation

GESDA **PHILOSOPHICAL LENS** (pages 200-205)
**Eco-augmentation:** Shaping the future of social-ecological systems

PULSE OF **SCIENCE** (pages 154-199)

Containing deep insights into anticipated advances in Eco-regeneration and Geoengineering over the next 5, 10 and 25 years, the GESDA Pulse of Science provides the expert opinions of leading researchers. In addition, the Villars 2024 Anticipation Report reveals anticipated frontiers in the emerging field of eco-augmentation.

PULSE OF **DIPLOMACY** (pages 206-207)

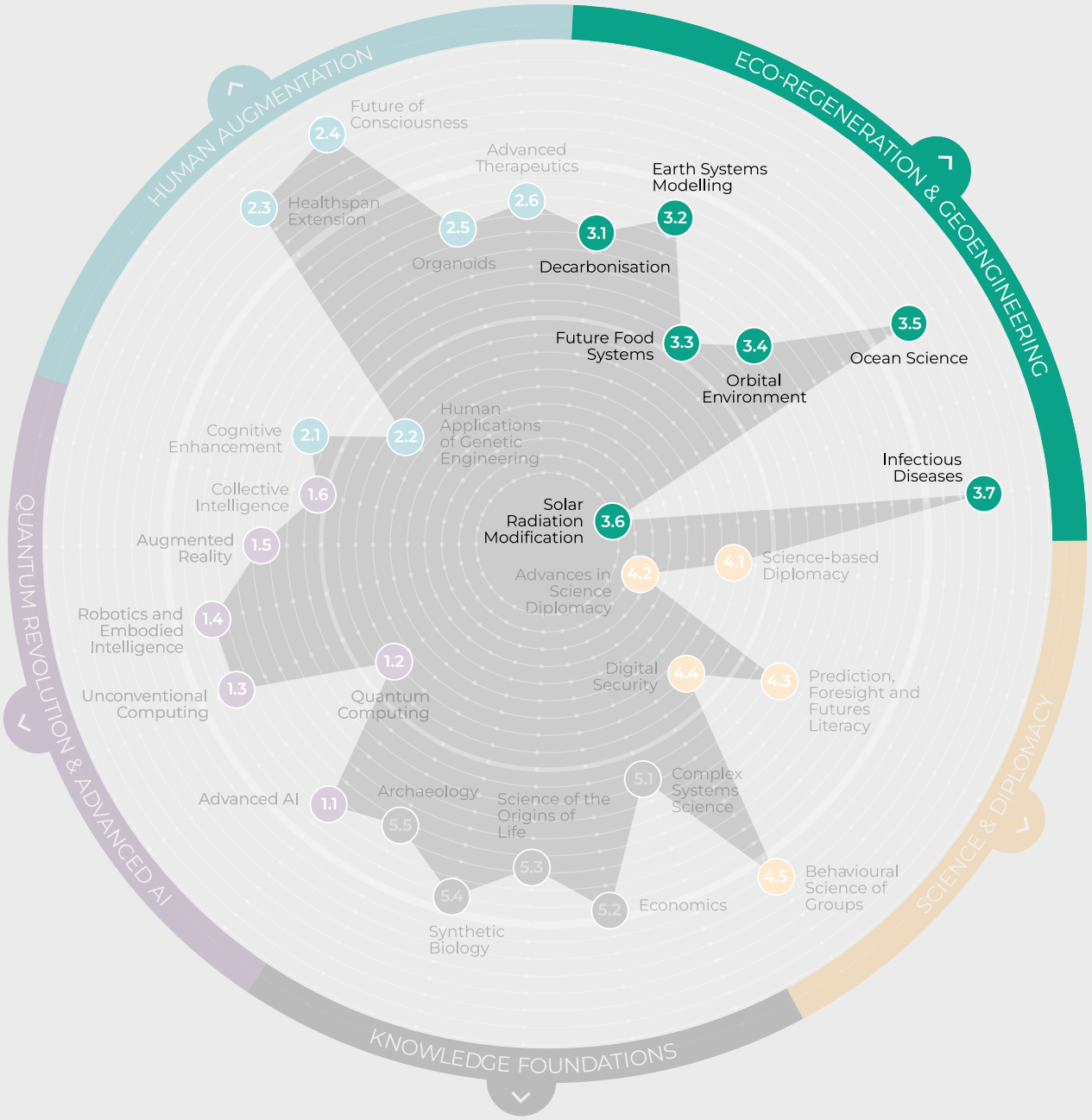
The GESDA Pulse of Diplomacy captures the latest discussions between diplomats and scientists at the 2023 GESDA Science and Anticipation Summit on topics such as Negative emissions technologies, resilient farming, Earth systems modelling and orbital resources.

PULSE OF **IMPACT** (pages 208-209)

Current investment trends and dynamics of company creation highlight Future Food Systems as an increasingly important topic. The GESDA Pulse of Impact provides data detailing private-sector investment, intellectual-property activity and company creation in the area of Future Food Systems since 2000.

PULSE OF **SOCIETY** (pages 210-213)

Powered by AI, the GESDA Pulse of Society's network and dynamic sentiment analysis of both mainstream and social media reveals macro and micro trends in public opinion around the world on topics relating to Eco-regeneration and Geoengineering.



2024 VILLARS ANTICIPATION WORKSHOP

# Shaping Ecosystems: Anticipating an Age of Eco-augmentation

Report from the **GESDA 2024 Villars Anticipation Workshop on Eco-augmentation**
Villars, Switzerland, 25 –27 March 2024

CO-CHAIRS:
**Michael Hengartner**
President, ETH Board

**Bridget Baumgartner**
Co-founder, Designer Ecosystems LLC

**Jacqueline Goordial**
Assistant Professor at the University of Guelph

**Peter Søgaard Jørgensen**
Lead for the Patterns of the Anthropocene research stream at the Stockholm Resilience Centre and Deputy Director of the Global Economic Dynamics and the Biosphere programme at the Royal Swedish Academy of Sciences

CONTRIBUTORS:
**Afshin Akhtar-Khavari, Alexandre Antonelli, Patrick Cai, Junbiao Dai, Michael Dawson, Consuelo De Moraes, Maria Dornelas, Luis Eguiarte, Kevin Esvelt, Sabine Gollner, Olivier Hamant, Michael Hengartner, Anders Meibom, Mark Mescher, Kate Parr, Beth Shapiro, Yue (Chantal) Shen, Valeria Souza, Gregory Velicer**

MORE INFORMATION:

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## Executive summary

Eco-augmentation can be defined as humans' deliberate and strategic interactions with nature, intended to create more resilient, robust and sustainable ecological systems. This includes activities that lead to increases in the diversity and functions of ecosystems. It is now possible in principle to modify organisms to make them more resilient to environmental shifts such as climate change; to introduce genetic changes that will propagate through a population of pathogens or parasites, and render them harmless; and to create organisms that can restore biological functions that have been lost from an ecosystem, or enhance those that exist. However, these technical advances can also pose severe risks to ecosystems and humans, such as runaway invasive species or even ecological collapse.

On a political and ethical level, there is little consensus about what would constitute augmentation of an ecosystem. Ecosystems are always changing, with species or functions being variously lost or gained, and it is not always obvious whether these changes are "good" or "bad". Arguments can be made that "augmentation" means:

- restoring an ecosystem to its previous state (pre-human or at some point in time)
- reshaping it to suit a "new normal" (such as the effects of a changed climate)
- increasing some measure of productivity (especially in agricultural ecosystems)
- adding new functions (such as processing an additional nutrient)
- boosting dominant species in the hope they will support co-existing rare species
- increasing the diversity of micro- or macro-organisms
- adding functional redundancy to make the ecosystem more robust
- limiting invasive species, pests, pathogens and other undesirable species

Multiple scientific fields are integral to eco-augmentation. Ecology is one: to augment an ecosystem, we must first understand it and have some idea of the ways in which it might be "improved". This includes understanding the microbiology of the ecosystem, including any extremophiles, and the underlying genetics. It also includes understanding the connections amongst and between species and communities of all size-classes and their roles in ecosystem function. Likewise, modelling and forecasting are key to predicting the potential consequences of any intervention.

Another key field is synthetic biology, which allows precise edits to be made to a species' genome, or even the creation of entirely new forms of life. These applications are in their infancy but developing fast, so deliberate or accidental release of synthetic organisms into ecosystems is a real and imminent possibility. Unfortunately, despite considerable progress in the characterisation of ecosystems it remains extremely challenging to predict the impacts of such an introduction. Unintended effects are possible or even likely, potentially including low-probability, high-impact events such as a runaway invasive species or ecological collapse. Improving our ability to predict how ecosystems will respond to an intervention is thus essential.

Eco-augmentation also poses significant ethical and philosophical challenges. Some argue that eco-augmentation should benefit humans, while others believe ecosystems have intrinsic value regardless of their utility and should therefore be enhanced for their own sake. But defining what constitutes an improvement to an ecosystem, or the restoration of a degraded one, is non-trivial, depending on humans' relationship to ecosystems and the ways we conceive of them. These questions rest as much on cultural and political values as on technical questions. These values will derive significantly from the communities who will be most directly affected by any attempt at augmentation — who must therefore be consulted and whose cooperation must be secured, because they will have no way of opting out of the consequences.

## Key opportunities

### Illuminating the biodiversity darkspots

Despite our growing knowledge of the world's ecosystems, there remain many ecological "darkspots" where little or no data is available. These include the deep seas — the largest biome on earth — the McMurdo Dry Valleys of Antarctica, some particularly biodiverse terrestrial regions, and the microbial realm — particularly those microbes we cannot yet cultivate. Our lack of knowledge still hampers our ability to model and understand these ecosystems, and the world-spanning interactions between ecosystems. Filling in these darkspots is critical to our ability to develop key models to understand the effects of change, both passive and human-directed, on our global ecosystem.

### Forecasting ecosystem changes

The same factors — habitat loss, invasive species, climate change and so on — pose similar threats to many ecosystems. That such threats may be as predictable as the weather opens up the possibility of forecasting and early-warning systems. These would enable rapid intervention, mitigation or enhancement when key events are detected or predicted. This requires three advances. First, frequent surveys using multiple tools and collecting multiple forms of data to maintain baseline measurements for an ecosystem. Second, rapid and easy access to this data online, ideally through open-access databases. Finally, the ability to model ecosystem changes and their evolution through advances in computational capacities, artificial intelligence and complex systems science.

### Creating more robust ecosystems

In general, the most robust ecosystems seem to be those which have a high degree of functional diversity. For instance, nutrients can be processed in differing ways, creating a complex web of interactions among species and remaining functional across a wide range of conditions. The tools of modern biology and ecology, coupled with more information and understanding of metabolic function, will give us an opportunity to build this robustness into future ecosystems. One possibility would be to identify preserve those functions that enable ecosystem robustness, reducing the risk of collapses and other harmful events. However, diversity that may seem non-functional at a given time may turn out to be necessary at another, and is thus worth preserving for its own sake.

### Hacking co-evolution

Changing a human society changes the associated ecosystems, and vice versa. Synthetic biology and de-extinction technologies have advanced to the point where we will soon be able to design and synthesise new organisms, or even entire ecosystems, rapidly and cheaply, and release them into the wild. The question then is: what do we want to do with these technologies? Deepening our understanding of human-ecosystem co-evolution helps us to identify ways to bring about positive change for humans and ecosystems, and to understand and avoid the associated risks.

## Introduction to eco-augmentation

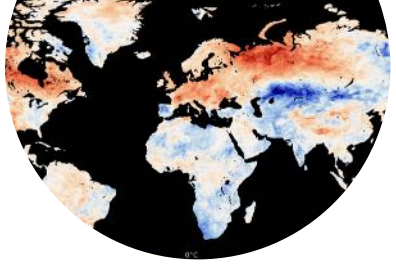
It is now possible, in principle, to deliberately modify ecosystems and enhance their functions: "eco-augmentation". This might include releasing new genes or entire new organisms, with the aim of restoring a lost ecosystem function; making a keystone species more resilient to climate change; or boosting an ecosystem service deemed to be desirable, such as carbon storage. In theory, such eco-augmentation has the potential to undo some of the damage humans have done to ecosystems, to stabilise or restore ecosystem services, and to reduce the risk of catastrophic collapses of ecosystems and of the societies that depend on them.[1]

Existing approaches to eco-augmentation include the introduction of new species, of modified species that can use new resources or survive in particular conditions, or of nutrients in new environments where they are limiting factors (such as iron in the sea). Advances in synthetic biology are now enabling the creation of highly modified and entirely new forms of life, particularly bacteria. Tools like CRISPR allow genomes to be edited with unprecedented precision and thus allow rational design of modified organisms. While this form of biotechnology is still incipient, it is developing extremely rapidly, so synthetic organisms could soon be released — whether deliberately or otherwise — into the wild.

However, the impacts of eco-augmentation are barely understood. Ecologists can make predictions about the likely impacts of a given intervention in an ecosystem, but these predictions often come with enormous error bars. In particular, it is not possible to state with confidence that extremely harmful impacts, such as a new species becoming invasive and dominating the ecosystem, will not occur. The extreme complexity of ecosystems means that we may not be able to predict such low-probability, high-impact events with significant confidence for many decades, possibly indefinitely.

There is already considerable potential for engineered organisms to escape into the wild or to be deliberately released. Some synthetic biologists are working on safety techniques, often focused on making it impossible for these organisms to survive without human intervention: for instance, making them dependent on chemicals that are not found in nature.[2] However, the rapidity with which organisms — especially micro-organisms — can evolve means that such measures may rapidly become ineffective and so are not guaranteed to prevent escape, as happened in the widespread and rapid dissemination of antibiotic resistance among bacteria.

It is profoundly difficult to identify the forms that eco-augmentation should take and its possible environmental consequences. What would constitute a beneficial impact on an ecosystem and what are the acceptable trade-offs? Should ecosystems be restored to a previous state, or radically transformed for a new post-climate-change normal? These questions are about sociocultural values as much as they are about the technicalities of science; they raise profound questions about the relationship of humans to ecosystems, and to the Earth as a whole. A human-centric viewpoint implies that ecosystems should be managed for the benefit of human society, but it is also possible to view the ecosystems as intrinsically valuable, potentially being recognised as having rights of their own — legalistic protections like those recently granted to such geographical features as mountains and rivers. Our legal and political systems have not yet come to grips with these questions.



## Reading and writing ecosystems

Our capacity to read an ecosystem — to identify its constituent organisms, components and processes — is increasing rapidly. Technologies such as efficient environmental DNA analysis, faster and cheaper DNA sequencing, protein and other metabolites analysis capabilities, remote sensing and machine learning have dramatically improved both the volume of data available and the insights that can be gleaned from it. Complex interactions between the behaviours of individual species and the functioning of whole ecosystems are being mapped.

This includes inter-species communication, which is highly prevalent and important for the functioning of ecosystems, and takes numerous, often surprising forms. For instance, bumblebees can cause plants to speed up flower production during times of pollen scarcity by damaging their leaves.[3] Chemical agents, including volatile chemicals that can travel significant distances, also exert strong influences over organisms and ecosystems.[4]

Meanwhile, models of ecosystems are growing in sophistication. It is now possible to simulate the key species and processes in an ecosystem, and to make predictions about shifts such as changing distributions under climate change,[5] but such models can have much wider applications. However, these models will need to be improved in order to analyse not just the supposed key species, but the majority of those in an ecosystem, including the rare ones, since they may also prove critical for the function and resilience of an ecosystem.

The growing range and depth of ecological data opens the possibility of creating "digital twins" of ecosystems, with information on species composition and interaction derived from a range of survey data. However, for the majority of ecosystems, the baseline data needed to feed the models are scarce. Closing the baseline knowledge gap would allow these digital twins to be used to better understand the processes underpinning the ecosystem and to identify stressors.[6]

The range of ecosystems under scrutiny has also expanded. While early ecological studies often focused on large animals and plants living on land, there is growing understanding of remote marine areas, including previously under-surveyed areas like the deep sea,[7] and the microbial ecosystems which form the basis of all food webs.[8] But even on land, there are still many darkspots where little information has been gathered.[9] One survey of vascular plants identified 32 darkspots, almost all found within biodiversity hotspots such as Borneo and Colombia.[10]

In other cases, data exists but is not readily available in any systematic way. Such "greyspot" ecological data remains locked away in individual papers, often behind paywalls. However, initiatives are under way to increase accessibility and to create large, open-access databases of basic information and analysis, along the lines of the very successful NCBI GenBank model. These initiatives have the potential to greatly increase our understanding of ecosystems. For instance, the BioTIME database hosts over 8 million abundance records for over 40,000 species, drawn from over 500,000 locations.[11]

Alongside this, there is growing potential for "writing" ecosystems. Molecular biology and synthetic biology are providing a growing range of tools which can be used for this purpose: for example, CRISPR-Cas9, which allows precision editing of an organism's DNA. Meanwhile, synthesis of DNA is becoming faster, cheaper and more accurate. Taken together, these allow us to modify existing organisms or design entirely new ones.

The potential is exemplified by the Synthetic Yeast Genome Project (Sc2.0), the aim of which is to produce the first eukaryotic organism with a wholly synthetic genome.[12] Sc2.0 researchers aim to replace all the existing "natural" chromosomes in a yeast cell with synthetic ones. The consortium has synthesised all the chromosomes individually and is now focusing on their integration.[13] Other researchers have engineered micro-organisms that produce biochemicals not found in nature, such as "non-canonical" amino acids.[14]

While most such research has been lab-based, the same technologies can be applied in ecosystems. The Mice Against Ticks project aims to reduce the numbers of people infected with Lyme disease on the islands of Nantucket and Martha's Vineyard. The disease is spread to humans by ticks, which are first infected by white-footed mice. The researchers aim to use CRISPR to create mice with heritable immunity against Lyme disease — meaning that their offspring will also be immune, thus permanently cutting the chain of infection if such immune mice interbreed with wild populations.[15]

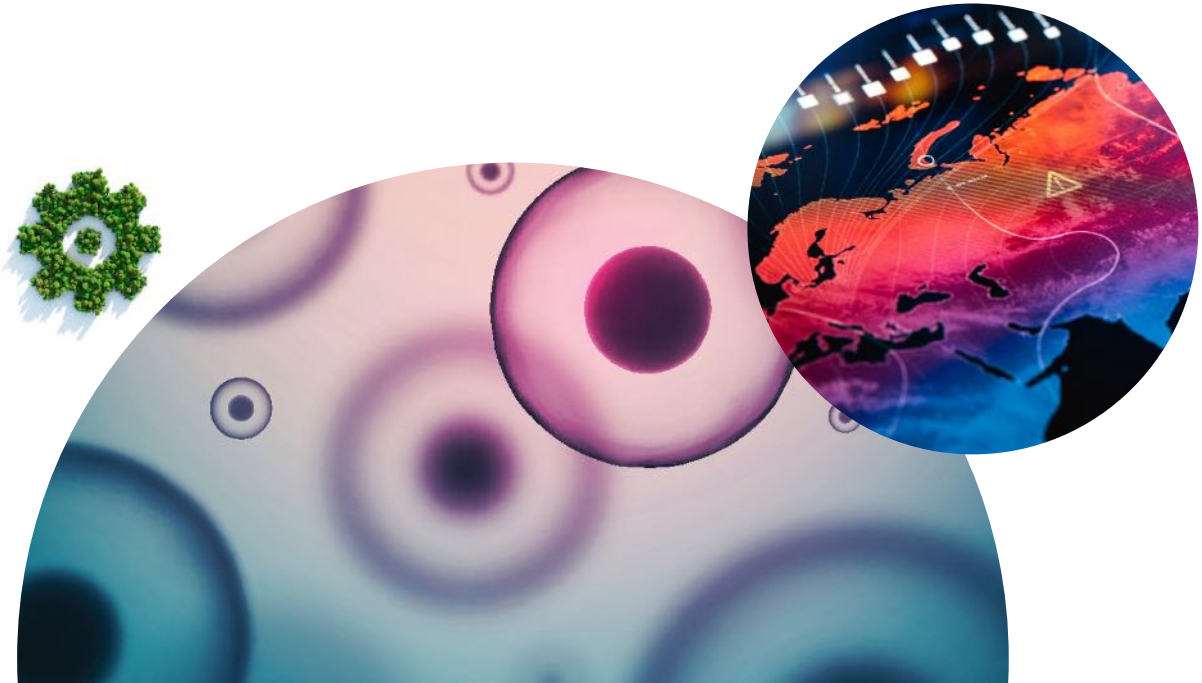
Mice Against Ticks has been designed in consultation with community members and is intended to be geographically contained. Other proposals envisage organisms which depend on particular environmental or nutritional conditions, thus restricting their potential spread. But not all approaches to eco-augmentation can be readily constrained, meaning that they may affect people or ecosystems who were not initially considered. For example, gene drives — suites of genes edited to "override" natural selection and spread rapidly through a population — could spread widely once released.[16]

There is precedent for how to handle such open-ended possibilities. The 1975 Asilomar Conference on Recombinant DNA established guidelines for managing the risks associated with DNA editing, including the prohibition of certain types of experiments.[17] The widespread adoption of these guidelines built trust among policy-makers and the public, enabling the growth of the biotechnology industry. Analogous guidelines could similarly build trust in synthetic biology and eco-augmentation.

Unfortunately, there is no tradition of communication between the fields of synthetic biology and ecology. In particular, there have been few well-controlled experiments in which synthetic micro-organisms are released into realistic laboratory ecosystems to monitor their effects, and even fewer field experiments. Synthetic biologists have instead focused on designing organisms that depend on highly specific conditions and are thus unlikely to survive in a wild ecosystem.[18] This yields a different, more technological, way of providing assurance that experiments or deployments are unlikely to have dramatic unforeseen consequences. However, since organisms have evolved many ways to escape imposed constraints, there may not be a safe way to provide containment at the desired level of confidence.

### 5-YEAR HORIZON

- Advances in the design of warning systems and of conservation genomics for threatened species and systems, based on multiple monitoring tools and sensors, perhaps using AI to inform and accelerate decision-making.
- DNA sequencing and synthesis that is many times cheaper and more accurate than today's. Further improvements to cost, accuracy and accessibility of other "reading" technologies, such as single-cell sequencing and spatial omics.
- Design of multiple, widely applicable safeguards to help prevent synthetic organisms from surviving in the wild if they escape.
- Creation of a single-celled eukaryote (yeast) with wholly artificial chromosomes.
- Development of large collections of viable bacteria, seeds, embryos and so on. to preserve their genomic resources prior to the release at large scale of genetically engineered organisms.



### 10-YEAR HORIZON

- Implementation of early-warning systems for threatened species and systems, based on multiple monitoring tools and sensors, perhaps using AI to inform and accelerate decision-making.
- DNA synthesis primarily done using enzymatic techniques, replacing existing chemical-based techniques. Development of efficient, cheap benchtop synthesisers for long DNA.
- Implementation of multiple, widely applicable safeguards to help prevent synthetic organisms from surviving in the wild if they escape.
- Designer chromosomes for eukaryotes.
- Automated construction of synthetic genomes and insertion into host organisms.
- Widespread use of DNA molecules to store massive amounts of information.

### 25-YEAR HORIZON

- Portable DNA synthesisers
- Systematic methods for culturing "microbial dark matter" — the vast majority of micro-organisms, whose favoured growth conditions are not well understood today
- Writing of other "omics", such as proteomics and 3D cellular structures.
- Customised organisms leading to new biodiversity resources.

## Transitioning ecosystems

Ecosystems are constantly changing. New species evolve, others become extinct, others enter from outside, and environmental conditions alter, with knock-on effects on all the constituents. Ecosystems are always in transition. But these processes used to take thousand or even millions of years to occur. Today, due to human activity, they are taking place at a much faster rate, exceeding the rate at which the ecosystems' constituents can adapt .

Remote and extreme ecosystems are among the most prone to fast transitions because they exist in precarious states. For instance, the Antarctic McMurdo Dry Valleys are the coldest and driest habitat on Earth, and the closest analogue we have to Martian conditions.[19] Yet they are inhabited by a considerable diversity of micro-organisms.[20] While the productivity of these ecosystems is low, they have a high level of functional redundancy and have survived for at least 100,000 years even as Antarctica has undergone major climatic shifts. It is essential to study these ecosystems: they are likely to undergo transitions in the near future, the potential effects of which remain unclear.

There is also a need to better understand why some organisms and ecosystems are particularly prone to dramatic transitions while others are highly resilient. Corals are a notable example: even a small rise in average temperatures can trigger bleaching, in which the corals expel their symbiotic algae, leading to mass death. This means corals are extremely vulnerable to climate change. Global coral-reef cover fell by 50% from 1957 to 2007, and only 10 per cent of coral reefs are expected to survive past 2050.[21] However, corals in the Red Sea are more temperature-resistant than those elsewhere, so might be preserved if non-temperature stressors are minimised.[22,23]

On the other hand, the extremely diverse oasis of Cuatro Ciénegas Basin in Northen Mexico — an analogue of early Earth due to the diversity and abundance of stromatolites — is deeply endangered. The deep aquifer that feeds the ponds is under extreme pressure due to the bad management of alfalfa agriculture in the desert. This is particularly poignant, since this site has survived isolated for hundreds of millions of years, allowing the evolution of many new lineages in the tree of life.[24,25]

The BioTIME database has already acted as a valuable sense-check: it indicates that, contrary to popular belief, species richness is not declining globally, but that there is considerable regional variation, with some ecosystems declining in species richness while others are increasing.[26] BioTIME also shows that many species and communities are shifting to smaller body sizes.[27] There is an urgent need for more such open-access ecological databases.

This kind of knowledge is enabling ecologists to identify warning signs of imminent changes or collapses in ecosystems. Just as weather forecasts provide advance notice of extreme events, ecosystem monitoring could be operationalised to give early warning of dramatic shifts. This would enable interventions to protect or strengthen threatened ecosystems, such as swapping in a new organism to perform an ecological function that is being lost.[28]

Such models and related simulations should be used to help identify harmful unintended consequences of eco-augmentation interventions. It is distinctly possible that a synthetic organism or gene could achieve exponential growth in a particular ecosystem, essentially becoming invasive. While some ecosystems might be resilient against such invasions, we do not know which ones. The precautionary principle suggests that we should consider all ecosystems to be vulnerable.

### 5-YEAR HORIZON

- Massive open-access online repository for diversity and ecosystem data, analogous to GenBank for genomes.
- Remote sensing using, for example, hyperspectral imaging — imaging areas at many points on the electromagnetic spectrum simultaneously — to identify ancient grassy ecosystems at large scale.
- Screening systems based on volatile chemical cues to detect disease outbreaks and ecological shifts.
- Detection of ecosystem tipping points, aided by AI, through monitoring of variables such as spatial patterns of vegetation or fire spread.
- Study of the stratosphere in order to understand the dynamics of aerosols, as well as the ozone hole and the effect of nitrogen oxides and rocket fuel at such high altitude.

### 10-YEAR HORIZON

- Widespread automation of biodiversity monitoring, reducing global blind spots.
- Development of “digital twins” for ecosystems around the globe.
- Advances in identification and monitoring of small-organism and underground biodiversity, for example, using passive acoustic monitoring.
- Rapid and quantifiable marine ecosystem monitoring via deep-learning techniques to interpret audio and video.
- Significantly expanded mapping of deep-sea and sea-bed ecosystems.
- Biobanks for ecosystems.

### 25-YEAR HORIZON

- Reliable predictions of ecosystems’ ability to withstand multiple stressors, integrating global climatic change and atmospheric and geochemical processes.
- Ability to fully reconstruct or repair complex ecosystems, with a focus not just on lists of species but on functional interactions such as nutrient flows.

## Hacking co-evolution

Ecosystems — including the physico-chemical environment, microbes, plants and animals — have been co-evolving for millions of years. And in many cases, these ecosystems and human biology as well as culture continue to co-evolve. Human activity is changing these co-evolutionary processes, often inadvertently and sometimes to the detriment of our own interests. In a dramatic example, humanity's widespread use of antibiotics and pesticides has created selection pressure which has caused many organisms to evolve resistance, so they are once again threatening our healthcare and food systems.[29]

By using multiple techniques, ranging from traditional surveys to sequencing of environmental DNA, ecologists are now able to monitor such co-evolutionary processes over large areas and many years. In theory, it should be possible to intervene intentionally and rationally in order to obtain desirable outcomes — such as ecosystem restoration or improved human health — to "hack" co-evolution. For instance, urban communities often have elevated rates of allergies and other immune-mediated conditions, but Finnish children in kindergartens with higher levels of biodiversity showed enhanced immunoregulatory pathways.[30]

Such "beneficial" interventions could be considered as eco-augmentation focused on the human ecosystem. A key challenge for such interventions is that evolution is known for its capacity to produce surprises even in the simplest ecosystems. For instance, simply growing two bacterial species at 32°C instead of 22°C was enough to upend their ecological relationship: the predatory species became the prey.[31] Such complex and unpredictable outcomes are not the rule, but ecologists do not yet have a means of predicting when they are more or less likely to occur. Interventions may also be more or less effective depending on the organisms involved, the kind of intervention and the complexity of both the environment and of the intervention.

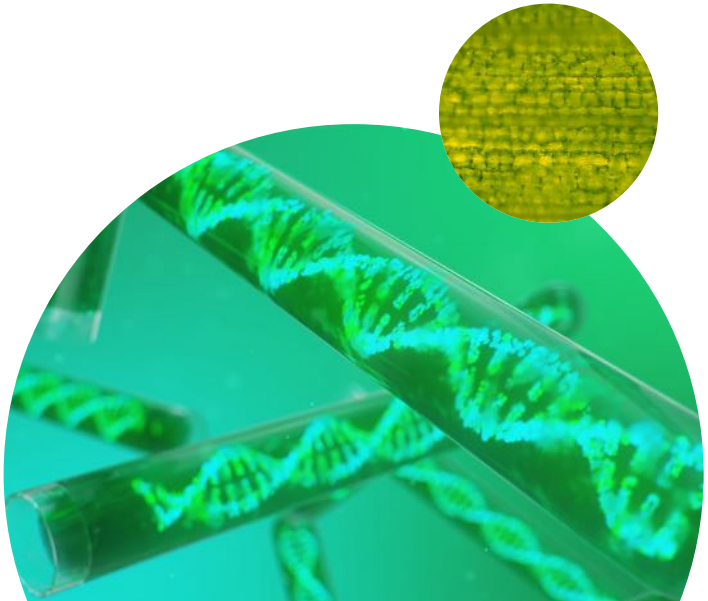
Complex-systems theory offers some guidance, because it indicates that the underlying architectures of ecosystems are often relatively simple, but even in these systems the results can be complex and even chaotic. Ecologists have also identified many emergent rules that apply across ecosystems: for instance, the majority of species in any ecosystem are rare. However, even the best models struggle to identify "tipping elements" in ecosystems, where a small push can cause a big change — yet it is precisely these elements that offer both the greatest opportunities and the biggest risks.

Further challenges arise around the ethics of such interventions. There is little consensus on whether it is acceptable to alter ecosystems for the benefit of humans, what the criteria for deciding would be, or who of the different human (or animal or plant) groups in a given ecosystem deserves to benefit. While concepts like ecosystem services can be interpreted as identifying the ways ecosystems benefit humans, ecosystems have their own intrinsic value independent of humanity in some philosophies such as "deep ecology".

Consent may prove to be a critical issue, but may be different to reach them if different human groups have very different values, and also because the lack of data. The history of conservation suggests strong engagement with affected human communities is essential to any eco-augmentation project during both design and implementation. Restoring an ecosystem is not simply a technical task, but is also about the people who do the work, whose relationship with nature is often profoundly changed by the process.[32]

## 5-YEAR HORIZON

- Systematic understanding of which ecosystem and human-health outcomes are supported by biodiversity and relative effect sizes.
- Capacity to fully “read” and understand any accessible ecosystem: complete description of genomic composition, as well as other “omics” (transcriptomes, epigenomes, proteomes and so on) plus data on its single species (population biology), community and ecosystem ecology, physiology and interacting with the environment, in particular in face of global change and so on.
- Advances in detailed understanding of how biochemical and metabolic processes like bacterial metabolism link to ecosystem-scale effects.



## 10-YEAR HORIZON

- Experimental interventions in controlled environments to promote human health by promoting and augmenting biodiversity.
- Large-scale meta-analyses of co-evolution, and experiments involving interactions between several species, offering estimates of how predictable evolution is and the distribution of rare evolutionary events.
- Detailed computer simulation of ecosystems becomes a general practice, using detailed descriptions of candidate gene pathways and responses to major drivers, and of the results of the interaction between species and their populations, community and ecosystems dynamics, augmented by more powerful computing systems and AI.
- Detailed, well controlled and replicated experimental management of particular ecosystems, for instance to analyse how to maintain their robustness or to increase a chosen ecosystem service.
- First “de-extincted” animal (a modern animal with some traits of an extinct species, rather than a revived but truly extinct animal).

## 25-YEAR HORIZON

- Large-scale experimental interventions to promote human health by promoting and augmenting biodiversity.
- Biodiversity experimental interventions for intergenerational human-health outcomes, such as changing the environment of a parent in order to reduce asthma risk in their descendants.
- Active management of ecosystems, for instance to maintain their robustness or increase a chosen ecosystem service.
- Automated and rapid (perhaps seasonal) assessments of ecosystem species diversity, interactions, genomics and health.
- “Meta-models” linking detailed biochemical processes like bacterial metabolism to ecosystem-scale effects.

3.1

# Decarbonisation

CHAIR:
**Matthew Green**
Associate Professor in Chemical Engineering, Director of the Center for Negative Carbon Emissions, Arizona State University.

CONTRIBUTORS:
**Carlos Abanades, Berend Smit, Nicolas Bauer, Martin Patel, Gonzalo Guillén Gosálbez, Peter Styring, Zhu Liu, Dawid Hanak**

**Greenhouse gas emissions in 2023 were the largest in history: humanity released 35.8 gigatonnes of carbon dioxide ($GtCO_2$). However, this is just 0.1 per cent more than 2022, raising hopes that emissions are peaking.[2]**

The major emissions sources are:
- Energy supply: 34%
- Industry: 24%
- Agriculture, forestry and other land use: 22%
- Transport: 15%
- Buildings: 6%

In 2023, levels of atmospheric $CO_2$ reached 419 parts per million, about 50 per cent higher than pre-industrial levels.[3] As a result, Earth has warmed 1.18°C above the 20th-century average.[4] There is now an 80 per cent chance that the annual global temperature will be more than 1.5°C above pre-industrial levels for at least one year between 2024 and 2028.[5] To give a 50 per cent chance of limiting global warming to 1.5°C, we can emit no more than 275 $GtCO_2$: at 2023 rates, we will use up this carbon budget in seven years.[6]

In the 2015 Paris Agreement, governments agreed to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels".[7] Existing policies are insufficient and are likely to lead to 2.5°C of heating by the end of the century.[8] However, current policies and pledges represent a significant advance on the position 10 or 20 years ago. It may be that we will soon hit tipping points where first pledges, and then policies, are sufficient to achieve the 2°C target. A number of science and technology-based strategies exist that will assist in achieving this goal.

KEY TAKEAWAYS

Decarbonising the global economy presents a significant technical and sociopolitical challenge. To limit warming to 1.5°C or 2°C, global emissions must peak by 2025 and fall rapidly. To achieve 1.5°C, net global emissions must fall 43 per cent from 2019 levels by 2030 and 84 per cent by 2050.[1] **Renewable energy** such as solar and wind has a significant part to play and is rapidly becoming cheaper. There are also considerable opportunities in reducing **Energy demand**, particularly from buildings, transport and certain industries. However, there are some **Hard-to-abate emissions**, notably from agriculture and from certain forms of manufacturing such as steelmaking: reducing these emissions requires the development and/or scaling of new technologies. Finally, there are a number of **Negative emissions technologies** (NETs) that can remove $CO_2$ from the air. These may prove useful later in the century but their scale is too small to offer a substitute for rapid emissions cuts.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Negative emissions technologies are still more than 15 years away from being scaleable, and it is highly unclear whether future breakthroughs will resolve current bottlenecks. Their effects on society and the global economy could be transformational, however, explaining the high Anticipation Potential score for this topic. The path towards Renewable energy appears to be much better defined and major transformations are already happening. As a result, this requires less attention and therefore the score for this field is much lower.

MORE INFORMATION:

**go.gesda.global/3-1**

Decarbonisation

## 3.1.1 Renewable energy

**In 2022, about one-seventh of our overall energy came from renewables.[9] This represents rapid growth: as recently as 2010, solar and wind were just 1.7 per cent of global energy.[10]**

Much of this growth is due to rapidly falling costs. Solar and wind are now routinely cheaper than fossil fuels.[11] This has occurred despite ongoing government subsidies of fossil fuels, which may become indefensible as battery technology improves and undermines the argument that fossil fuel-based generating capacity is necessary for when there is no wind or sunshine. A number of promising developments in materials science offer hope of increased efficiency for photovoltaics.[12]

There has been considerable disagreement about the role that can be played by hydrogen.[13] In theory, hydrogen produced by renewable energy ("green hydrogen") is entirely renewable. In practice, the high demand for renewable electricity means that there tends to be little left over for hydrogen production. Hydrogen may have a relatively limited role to play as "blue hydrogen", generated as a by-product of fossil-fuel combustion. Though it will not be a zero-carbon fuel until carbon capture can be achieved at commercial scales, blue hydrogen could nonetheless help mitigate "Hard-to-abate" emissions. Related "power to X" technologies, such as synthetic fuels made using renewable electricity, are promising, but face efficiency challenges.

Nuclear fission and fusion may also have roles to play. Small-scale nuclear-fission reactors are also under development, although their chances of commercial success remain difficult to predict.[14] Commercial-scale fusion plants are still probably decades away.[15]

### 5-YEAR HORIZON

**Solar overtakes coal in electricity production**

Cost and efficiency improvements mean that solar becomes a larger global source of electricity than coal. Improvements in battery technology allow short-term storage of energy from renewables, but intermittency remains a problem. Algorithmic innovations improve control of supply and demand in electricity markets, freeing more renewable energy to create green hydrogen. Small-scale laboratory fusion successes in privately funded companies stimulate further investment in research. Improved stabilisation enables wind turbines to be built further offshore in deeper waters.

### 10-YEAR HORIZON

**Energy storage innovations grow renewable market share**

Half of global electricity comes from renewable sources. Seasonal and long-term energy storage, such as power-to-gas, flow batteries and liquefied hydrogen and air, becomes a commercially viable output of wind and solar energy sources. Shipping begins to decarbonise, using hydrogen and, in some cases, experimental sail-based propulsion. Accelerating cost declines, due to factors such as falling steel prices and an increase in offshore wind turbine installations, further decarbonising many countries' energy production and use.

### 25-YEAR HORIZON

**Fusion investments begin to pay off**

Small-scale pilot nuclear-fusion plants begin to come online. Electrical grid interconnectors span all of Eurasia. Significant improvements in the energy efficiency of synthetic fuel manufacture enable its use for zero-carbon aviation and shipping.

## 3.1.2 Hard-to-abate emissions

**A significant fraction of our carbon emissions comes from hard-to-abate sources such as aviation, industry, agriculture and forestry. Part of the solution will be on the demand side:[16] diets that feature less red meat will cut emissions, as will reducing food waste and improving cultivated meat. There are also improvements to be made on farms, for instance in soil management, selective cattle breeding for low methane production[17] and anaerobic manure processing.[18]**

In steel manufacture, carbon is typically used to transform iron ore into iron, but newer "direct reduction" processes use hydrogen.[19] There is potential to use "oxyfuel" — air with most of the nitrogen removed — to create emissions that are easier to capture. This may help cut emissions from cement production.[20]

Research on sustainable aviation fuels is progressing slowly because powered flight requires fuels with a high energy-to-mass ratio — batteries can certainly not yet match kerosene. Solar-powered planes remain small. Some companies are experimenting with replacing fractions of their jet fuel with biofuels or chemically engineered synthetic fuels, but these initiatives are not market-ready.[21]

### 5-YEAR HORIZON

**Innovation slows the growth of emissions**

An appetite for climate-change mitigation in agriculture creates a rapid cycle of innovation that slows the growth of emissions. Government programmes begin to support decarbonisation of heavy industry.

### 10-YEAR HORIZON

**Bioprocessing cuts food-waste emissions**

Innovations in bioprocessing mean that global emissions from food waste are half those of 2023. Cultivated meat protein becomes widely available, but cannot satisfy the rising global demand for meat.

### 25-YEAR HORIZON

**Industrial processes achieve significant carbon-emission reduction**

Steel and cement manufacture are close to carbon-neutral, thanks to progress in chemical research that generates cleaner industrial processes. A quarter of people adopt vegetarian diets. Low- or zero-carbon aviation fuels become available.

## 3.1.3 Energy demand

**Reducing demand for energy can have a significant effect on carbon emissions. There is huge scope for demand reduction: for example, the UK could cut its energy demand by more than half by 2050.[22] The International Energy Agency (IEA) estimates that intensive efforts towards increased energy efficiency could cause global energy demand to fall by 8 per cent by 2050, even if the economy more than doubled in size and the population grew by 2 billion.[23]**

Operation of buildings, which consumes 30 per cent of the energy generated globally, is ripe for innovation.[24] For example, a large fraction of that energy is used for temperature control. Improved construction and design, combined with the use of technologies such as ground-source heat pumps, can virtually eliminate this need.

There is also great scope to reduce energy demand through greater use of public transport and improvements to industrial processes.[25] New designs of cars and skyscrapers are reducing the amount of steel and concrete needed, for instance. Improvements to recycling systems, and the gradual transition to a circular economy, also reduce the need for manufacture of new materials.[26]

### 5-YEAR HORIZON

**Electric cars begin to dominate the new car market**

Electric cars become cheaper than petrol in most developed countries, and innovations in battery technology make them more practical to use. Developments in grid technology enables stored energy in electric car batteries to be sold into national electricity grids when demand is high.

### 10-YEAR HORIZON

**Building standards assist decarbonisation goals**

Reforms to building standards and other regulations promote lower energy demand and renewable installation. World steel demand peaks, creating a significant reduction in industrial energy use. Sustainable fuels begin to be available as “drop-in” solutions, helping to abate emissions from heavy transportation.

### 25-YEAR HORIZON

**Global energy demand has peaked**

Heat-pump innovations, combined with smart meters and building regulations, mean that new buildings in most developed countries use minimal energy and are net suppliers of energy. Massive expansion of high-speed rail reduces demand for cars and aviation. Global energy demand is 8 per cent smaller than today but serving an economy twice the size. Electric cars outsell petrol cars globally. New low-temperature industrial processes reduce the energy demand of heavy industries.

## 3.1.4 Negative emissions technologies

**An important element in decarbonisation is negative emissions technologies (NETs). These are technologies for drawing greenhouse gases out of the air and permanently storing them. To limit global heating to 1.5°C, it is estimated that we will need to remove around 810 $GtCO_2$ between now and 2100 — equivalent to 15 years of 2017 greenhouse-gas emissions.[27] Most scenarios for achieving net-zero emissions, and for limiting global heating to 1.5°C or 2°C, include the future effect of NETs that are predicted to mature later this century.**

Some NETs are natural climate solutions. Reforestation can be a NET, because trees take carbon dioxide from the air. Other natural climate solutions include restoring wetlands and kelp forests, which are also carbon sinks. Natural climate solutions could mop up at most 23.8 Gt $GtCO_2$ per year.[28]

Other NETs are highly artificial. Enhanced weathering entails crushing minerals into powder, which reacts with $CO_2$ and water to form a new mineral that can be used or buried. Lime can be thrown into the ocean to react with dissolved $CO_2$ to produce calcium carbonate that sinks to the seabed.

Direct Air Capture (DAC) uses machines that contain chemical "sponges" that draw $CO_2$ out of the air. This $CO_2$ can be sequestrated in underground repositories such as aquifers or depleted oil and gas reservoirs. Alternatively, it can be converted into fuels, fertilisers or construction materials — though this does not necessarily reduce emissions.

All these technologies face problems of scale, cost and geopolitics, and all require certifications and proof of long-term reliability for the market to "trust" them.

### 5-YEAR HORIZON

**Research innovation assists carbon capture and use technologies**

Investment in new direct air capture (DAC) technologies reinvigorates academic research in the field. AI-based chemical innovations begin to find applications for repurposing captured carbon. Advances in DAC technology, combined with rising carbon pricing, spur further investment in research.

### 10-YEAR HORIZON

**NETs begin to scale**

Testing of ocean liming and iron fertilisation gives indications of whether these projects have potential. Advances in DAC technology, combined with rising carbon pricing, spur further investment in research. The first large-scale BECCS (bioenergy with carbon capture and storage) project begins. Construction materials that include captured carbon become commonplace.

### 25-YEAR HORIZON

**Carbon capture becomes a widely used technology**

DAC is implemented on a large scale. AI helps to find new uses for captured carbon. Long-term storage solutions are agreed and implemented.

Climeworks direct air capture plant to sky image is © Climework, Image by Julia Dunlop

3.2

# Earth Systems Modelling

CHAIR:
**Gavin Schmidt**
Director, Goddard Institute for Space Studies, NASA

CONTRIBUTORS:
**Govindasamy Bala, Henrique Barbosa, John Dearing, Katja Fennel, Luciana Gatti, Ray Weiss**

**Researchers seeking to understand environmental shifts such as climate change have incorporated ever more components of the Earth system into their models. This is because of a growing understanding of the significance of the interactions between elements of the Earth system: oceans, atmosphere, land, Arctic and Antarctic ice (the cryosphere) and biosphere.**

The concept of the Earth system can be traced to James Lovelock's much-discussed Gaia hypothesis, which posited that all of Earth is a self-regulating whole. While aspects of Lovelock's proposal remain controversial, the core notion has proved correct.

As an example, by including explicit models of the cryosphere, researchers can better predict the extent and speed of sea-level rise. In addition, the models must incorporate the effects of feedback loops, where small changes in one component can trigger effects in others, which then in turn alter the state of the first component, amplifying or diminishing the original change. The Earth system paradigm has also led to the identification of "tipping elements". These are components of the Earth system that can undergo effectively irreversible change given a sufficiently strong stimulus.

Earth system models that can handle these interactions are necessarily extremely complex. One key enabler is the development of ever-more-powerful supercomputers. However, a crucial task is to ground them in observations of real-world systems, and in process-oriented studies that capture the mechanisms of the Earth system. This requires significant increases in monitoring capacity, using both terrestrial and space-based sensors. Strategic improvements in Earth remote sensing would bolster our understanding of the Earth system and ability to forecast societally relevant changes.

KEY TAKEAWAYS

Earth systems models are a set of extremely complex models of the various interacting systems operating on our planet. They provide a means of anticipating future trends and events. However, their complexity means that the models are far from perfect, despite the powerful supercomputing resources now available to run them. One of the challenges lies in the **Modelling of feedbacks in the Earth system**. An example is the increased global warming through absorption of solar radiation that results from receding sea ice — the recession itself is a result of global warming. Such feedbacks may eventually lead to "tipping elements", such as the potential for the Amazon rainforest to be suddenly transformed into a savannah. **Tipping element modelling and forecasting** is also a significant challenge. It is, however, a vital one to address, since uncertainties here leave our models exposed to sudden and potentially catastrophic deviation from real-world scenarios. Also significant are the **Interactions between Earth systems**. Understanding the links between climate change and biodiversity loss, for example, can assist in the timely and effective management of habitats. While all the computational models of Earth's systems have flaws, these can be mitigated in part by **Model intercomparison**. This can improve model reliability by comparing the performance of ensembles of models and weighting their contributions accordingly.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Modelling and predicting Earth systems tipping points is a very hard problem that will require major advances in many fields. This pushes the time to maturity of the field to 20 years from now, though with potentially important effects on society and science. The interactions between different Earth systems is the area that will require most international coordinated action.

MORE INFORMATION:

**go.gesda.global/3-2**

# 3.2.1 Modelling of feedbacks in the Earth system

**Modelling Earth's climate with any fidelity requires considering its interacting network of feedback loops. For example, rising temperatures are causing Arctic sea ice to shrink. This changes the planet's reflectivity, or albedo: white ice reflects sunlight back into space, while dark blue seawater absorbs it. As a result, the retreating sea ice means Earth warms up even faster. Similarly, the warming that atmospheric $CO_2$ causes also allows for more water vapour in the atmosphere, itself a powerful greenhouse gas.**

In recent years, there has been more concern about cloud feedbacks. High-resolution climate simulations show that low-lying stratocumulus clouds will break up in a warmer climate, reducing their shading effect and allowing for greater warming.[1] This is significant, because these clouds are common in the tropics, shading 20 per cent of low-latitude oceans.

Better modelling of such feedback mechanisms, especially through refinement against observational data, can help us understand these risks and improve the fidelity of our climate models. In recent years, for example, researchers have successfully reconstructed the history of the Atlantic Meridional Overturning Circulation (AMOC) going back over a century.[2] This means it is now possible to put observations of current AMOC changes into their long-term context — and this suggests that the AMOC is indeed slowing.[3] This may, in the near term, increase the overall warming at the surface.[4]

Models also need to take more account of ecosystem feedbacks, such as those from the melting of permafrost (an event that could release large quantities of greenhouse gases, potentially accelerating and increasing the warming trend[5]), climate-induced human migration and coral bleaching, all of which can have feedback effects on climate systems.

### 5-YEAR HORIZON

**Models' uncertainty is reduced**

Improved climate models, checked against observational data, reduce the range of uncertainty on equilibrium climate sensitivity. We gain a better understanding of impacts of climate change on the El Niño-Southern Oscillation (ENSO).

### 10-YEAR HORIZON

**Models include cloud influence**

Tighter constraints on process-level cloud feedbacks are incorporated into climate models. Researchers gain a better understanding of ENSO predictability.

### 25-YEAR HORIZON

**High-resolution modelling and exascale computing improves prediction**

Researchers achieve more explicit inclusion of complex feedback systems encompassing the biosphere, cryosphere and more highly resolved surface and atmospheric heterogeneity.

## 3.2.2 Tipping element modelling and forecasting

**One of the most important outcomes of Earth systems modelling in recent years is the demonstration of various "tipping elements", where sudden, irreversible — and undesirable — changes might occur with relatively small changes in particular climatic elements. Furthermore, in the last decade it has been postulated that the tipping elements could interact with one another, raising the possibility of a planet-wide domino effect.**

In the cryosphere, one of the most immediate risks is to the Greenland ice sheet. Recent evidence suggests that this system could be near its tipping point, with about 7 metres of sea-level rise likely to ensue over the coming centuries.[6] However, as with all tipping points, limited real-world data combined with the weaknesses of current climate models leave a high degree of uncertainty over exactly how much of a "push" is required.

Models also show that the Amazon rainforest can irreversibly "flip" from forest to savannah. This would be a catastrophic shift, accelerating climate change[7] and fuelling more warming.[8] The permafrost regions of the far north are also thought to be a tipping element and recent studies indicate this tipping point may be closer than thought.[9] Collapse of the permafrost will release large quantities of greenhouse gases, accelerating and increasing the warming trend.

The current generation of Earth system models struggle to adequately resolve these tipping elements in many cases.[10] Some models omit them entirely, making the accurate inclusion of tipping elements an important focus for reducing the ambiguity of model-based climate predictions. The best-modelled tipping elements are those, like the Greenland ice sheet, that primarily depend on inanimate physical objects: tipping elements that include biosphere components, such as the Amazon, are a significantly bigger challenge and require substantial ground-truthing with observations.

### 5-YEAR HORIZON

**Permafrost influence is better understood**

Research in modelling achieves clarification of whether the permafrost is truly a tipping-point element or has a linear response. Tipping-element theory is refined through better mathematical modelling constrained by observational data, leading to a convergence of viewpoints on their nature and importance. The Atlantic Meridional Overturning Circulation's history is reconstructed going back several centuries, clarifying whether it is undergoing a slowdown.

### 10-YEAR HORIZON

**AI assists tipping-event analysis**

Scientists using AI-based analysis provide specification of the climatic limits in which the Amazon basin can retain a rainforest. Modelling identifies the West Antarctic Ice Sheet tipping point to a useful degree of precision, allowing it to be explicitly included in climate targets. Physiology studies reveal temperature-humidity limits for key domestic species like crops.

### 25-YEAR HORIZON

**Model-based monitoring of tipping-event warnings**

Earth Systems models are reliable enough, and sensor networks extensive enough, to use real-world data to check models and to make predictions about imminent ecosystem tipping events. Scientists achieve detailed global analyses and forecasts of species movements and ecosystem shifts.

## 3.2.3 Interactions between Earth systems

**The various Earth systems cannot be fully understood in isolation. For example, humanity's greenhouse-gas emissions are heating up Earth's climate, and this is having knock-on effects for the biosphere, the great ice sheets of Greenland and Antarctica, and wildfires. Furthermore, these systems then feed back into the climate: plants and microbes, for example, exchange gases with the atmosphere.[11,12] Therefore, climate change is inextricably bound up with other environmental issues such as biodiversity loss and pollution. Understanding these linkages is essential: for example, improved spatial and temporal understanding of regions likely to become uninhabitable has enabled prediction of forced migrations.[13]**

This means that an essential part of Earth systems modelling involves exploring the interplay across different systems and developing models that take all of the systems into account. This requires integrating data from a wide variety of systems — and from a variety of sources, such as field measurements and remote-sensing technologies.

One of the most high-profile attempts to quantify whole-Earth processes is the concept of "planetary boundaries". This aims to identify a set of Earth systems, each of which is essential to human survival and wellbeing. An initial assessment in 2009 identified nine, ranging from biosphere integrity and freshwater use to land-system change.[14] It further concluded that humanity had already pushed past three of the boundaries, taking our species outside its "safe operating space".[15] However, there are large uncertainties around the size and rate of change we are causing, whether the current list of boundaries should be amended[16] and how the different boundaries interact. The "boundaries" framing has also been questioned: in the absence of tipping elements, Earth systems degrade gradually so hard limits are difficult or impossible to specify.

### 5-YEAR HORIZON

**Planetary boundaries are better understood**

Researchers gain a clearer understanding of the interdependence between planetary boundaries and significantly improve estimates of the safe limits for pollution.

### 10-YEAR HORIZON

**An array of sensing technologies feed into modelling of system exchanges**

Improvements in LIDAR, satellite-based sensing and infrared spectroscopy provide more reliable data on gas exchanges between biosphere and atmosphere, which improves Earth Systems modelling.

### 25-YEAR HORIZON

**Computing advances improve climate interventions**

Exascale computing allows data from all Earth systems (including their interactions) to be integrated into the best sets of models at high resolution. This enables ensemble-based predictions and deeper, more reliable understanding of where interventions will have the greatest impact on climate change.

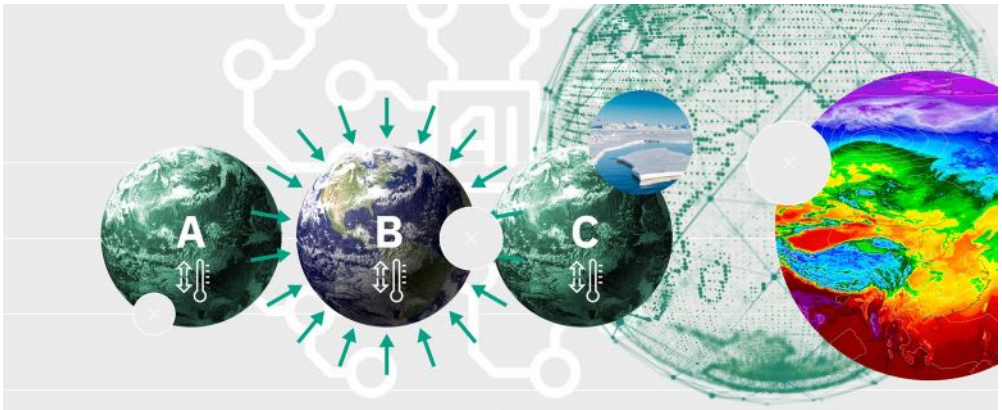
## 3.2.4 Model intercomparison

**There is no single "best" model of how Earth systems interact to create our environment. All the various models in existence have strengths and weaknesses in different areas. This is partly because of a lack of understanding of the details of many Earth system processes, and partly because of necessary compromises in resolution and complexity: running these models is computationally expensive. Because the models are built using a range of strategies, their performances diverge in complex ways.**

An essential component of Earth system science is therefore systematic comparison of "ensembles" of models.[17] Efforts such as the Program for Climate Model Diagnosis and Intercomparison co-ordinated at Lawrence Livermore National Laboratory have made headway in systematising the comparison process.[18] This has enabled the use of the models in the Intergovernmental Panel on Climate Change (IPCC) assessment reports. In the most recent round of intercomparisons, CMIP6, researchers found that it was necessary to weight some models more strongly than others to give a more accurate ensemble than a simple average:[19] optimising such weightings is a significant research problem.

An ongoing challenge for Earth system modellers is to understand in which circumstances the Earth system is stable and resilient, and when it instead behaves chaotically or changes violently. Palaeoclimatologists have documented many sudden shifts in the climate: these include the 4.2ka BP event (a widespread east Mediterranean drought that may have lasted a century 4200 years ago) and the rapid temperature shifts known as Dansgaard-Oeschger events that punctuated the last glacial period. Consequently, some climatologists have suggested the models are unrealistically stable, although a lack of suitably configured models means that these conclusions are premature. It remains uncertain just how much natural instability the system possesses and how to represent this in models.

All these uncertainties would be reduced by improved gathering of observational data, better anchoring the models in reality. This seems a particularly urgent task because 2023 was exceptionally warm, to an extent that has so far eluded quantitative explanations.[20]




### 5-YEAR HORIZON

**Leading models become more integrated**

Insights into what makes some climate models more accurate than others facilitates the creation of weighted ensembles of models that show marked improvement in performance.

### 10-YEAR HORIZON

**AI accelerates performance and reliability of models across Earth systems**

Researchers converge on a constructed set of constrained models that work reasonably well across all Earth systems, capturing uncertainty in a structured way. AI-based model improvements begin to accelerate performance, for example by improving parameterisation of processes too complex to be explicitly modelled. AI is also used to estimate outcomes of scenarios for the Earth system, without the need for full simulations.

### 25-YEAR HORIZON

**Model uncertainties are significantly reduced**

Growing alignment between models' predictions gives a clear indication of climate instabilities and tipping elements.

3.3

# Future Food Systems

CHAIR:
**Nam-Hai Chua**
Andrew W. Mellon Professor Emeritus and Head of Plant Molecular Biology, the Rockefeller University, New York

CONTRIBUTORS:
**Rodrigo Ledesma Amaro, Kellye Eversole, Jonathan Jones, Jiayang Li, Lone Dybdal Nilsson, Rajeev Ram, Michael Strano, Yuexin Yang, Cuilin Zhang**



**Suitably managed and directed, a set of ongoing and future science and technology breakthroughs offer an opportunity to sidestep likely problems with food supply, improve food quality and make the production of food more sustainable.**

These opportunities come at an important time. The global population continues to grow, topping 8 billion in 2022 and forecast to reach over 10 billion by the 2080s.[1] According to the World Bank, feeding a global population of 9 billion in 2050 will require a 70 per cent increase in food production over 2021 levels.[2] Clearly, agricultural yields must increase, and distribution improve, to ensure adequate nutrition for all.

Scientifically informed policies to change global diets, including major decreases in red meat consumption (as suggested in the planetary health diet), can help to improve environmental and food system sustainability. Agricultural practices can be improved, both to reduce their impacts and to become more resilient against stressors like extreme weather. Genetic-engineering technologies such as CRISPR, along with more traditional breeding practices, are being used to enhance crops and livestock, both in their nutritional value and their environmental resilience.

Artificial intelligence is emerging as a key technology for managing complex systems such as farms and soils. These advances in AI will be complemented by the development of smaller and cheaper in situ sensors, as well as remote sensors, to closely monitor farms. Approaches in nanotechnology can have applications in agriculture, improving soil quality through nano-engineered additives, for example.[3] This will be vital in mitigating the effects of environmental crises such as climate change and ecosystem degradation. This is particularly important because, in many cases, agriculture already operates with unsustainable practices, the impact of which will only be increased by the impending environmental issues.

On top of these problems is the issue of food quality. Here again, science and technology breakthroughs can help. We know that even in countries where people have access to sufficient calories, diets are often nutritionally sub-optimal, and must be improved if we are to avoid perpetuating significant health problems. According to the Global Burden of Disease report 2020, 22 per cent of all adult deaths in 2017 were associated with poor diet, with cardiovascular disease as the leading diet-associated cause of death.[4] Type-2 diabetes, also associated with poor diet, was the ninth leading cause of premature death globally in 2017. This is particularly troubling because the situation is getting worse: in 1990, type-2 diabetes was only the 18th leading cause of premature death. Ongoing improvements in the methodology of nutritional studies will help to uncover causal mechanisms behind healthcare problems, however, and to create strategies for optimising and personalising nutrition to take into account the highly individual nature of physiological responses to different types of diet. Science-led personalised nutrition is set to be increasingly important, at least in countries with the infrastructure to support it.

KEY TAKEAWAYS

Bioengineering can bring more, new and better food to the global market. **Engineering crops and livestock** will be vital as we face the growing nutritional requirements of the large future global population. **Reformatting the ecosystem** involved in food production is also an option. Possible strategies include consideration of pollinators, soil quality (including the soil microbiome) and the use of chemicals and biotechnology for improving yield and reducing the impact of weeds and pests. On top of this, suitably directed research will enable a reworking of the long-standing traditional processes and practices of agriculture. **Reimagining farming** will help to dramatically increase food production. Technologies such as AI-led decision-making and vertical farming are examples of potential paths forward here. As well as increased food quantity, there needs to be consideration of food quality, with a view to giving individuals more opportunities to personalise their nutrition and creating foods with higher nutritional value generally. **Optimising nutrition** in this way could have profound impacts on personal health and significantly reduce the expenditure on healthcare provision in these societies, which have generally been impacted by widespread prevalence of diet-related health problems such as cardiovascular disease and type-2 diabetes.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Transformational advances in food systems are still a decade away but the path to get there is relatively well-defined. Reimagining farming is the sub-topic that contains innovations that are judged to be most transformational for society. Reformatting the ecosystem is the area that will require most international coordinated action.

MORE INFORMATION:

**go.gesda.global/3-3**

# 3.3.1 Engineering crops and livestock

**A combination of conventional breeding and newer technologies such as CRISPR genetic editing may significantly enhance the resilience of crops and livestock to changing conditions, and the nutrient availability they offer.[5]**

Biofortification, where conventional plant breeding or modern biotechnology techniques bolster the amount of iron and other essential minerals and vitamins on offer, is an increasingly promising option.[6] Although the factors influencing both the nutrient content of crops and the scale of their absorption by human bodies remain incompletely understood,[7] many successes in biofortification have already been achieved through conventional breeding, and the potential of genetic engineering technologies (gene stacking, where two or more novel and useful genes are introduced into a single plant line, is one example) remains largely untapped.[8]

Genetic engineering can also boost crop yields, for example by re-engineering photosynthesis to boost energy capture.[9] This can be coupled with improved crop resilience to help cope with droughts,[10] pests and disease, which together account for 43 per cent of global crop loss.[11,12] Domestication of resilient wild species[13] could increase agricultural resilience to changing environmental conditions.[14] RNA sprays, which deliver RNA-based vaccines against diseases to crops, have considerable potential for improving resilience against pathogens.[15]

Engineering the plant bacterial microbiome can enhance crop production and resilience.[16] That is especially true for the rhizosphere microbiome associated with plant roots, which can help crops resist disease.[17] There is also similar potential to engineer livestock. Already, researchers have used genetic engineering to develop fast-growing AquAdvantage salmon (which have been commercialised), pigs resistant to viral infections and dairy cattle resistant to mastitis.[18]

### 5-YEAR HORIZON

**Genetic engineering of plant metabolism improves efficiency**

Advances in fundamental understanding of photosynthesis processes enable genetic engineering of the system to improve efficiency. AI identifies optimal targets for genetic engineering of the plant microbiome.

### 10-YEAR HORIZON

**Engineering approaches become mainstream**

Crops with enhanced photosynthesis efficiency are routinely engineered. First commercial RNA vaccines for crop diseases are created. Meat from genetically engineered livestock is widely available. First food proteins are derived from $CO_2$ by genome-edited micro-organisms.

### 25-YEAR HORIZON

**New foods come to market**

Multiple new strains of cereals are domesticated by genetic engineering from wild species. Understanding of the plant microbiome allows symbiotic relationships to be engineered to maximise crop resilience and yield. Global lab-grown meat that replicates the sensory experience of animal meat achieves price parity.

## 3.3.2 Reformatting the ecosystem

**Science and technology breakthroughs can help to improve the ecosystems in which crops, livestock and agriculture exist. Research identifying the threats to pollinators, for instance, allows the development of interventions.[19] Genetic engineering has been used to modify symbiotic micro-organisms living in honeybees, protecting them against *Varroa* mites[20] and the *Nosema* parasite.[21] It may also be possible to engineer plants towards being more efficiently pollinated.[22]**

Research is increasing the specificity of pesticides, reducing unintended effects on non-target organisms, and thus mitigating harm to crucial parts of the food chain and natural pest controls. Alternatives to pesticides, such as RNA sprays, are in development.[23] There is also growing attention being paid to gene drives. These are heritable edits to the genes of a specific organism that will spread through a population when the edited organisms are released into the ecosystem. They can be used to render populations incapable of spreading disease or to control the reproduction of invasive species,[24] although further research is required to avoid unintended consequences.[25]

Novel means of enhancing soils with nutrients, such as the addition of biochar (a charcoal-like substance made from anaerobic burning of organic material), are being explored.[26] Understanding the soil microbiome, including competition among microbes, is key.[27] Conserving or restoring the soil microbiome is also important, and has been shown to accelerate plant biomass production by more than 60 per cent, making it a priority task.[28] Knowledge gaps in the role of cropping systems in soil health remain,[29,30] but improving understanding of fundamental ecosystem properties, especially feedback mechanisms and complex interactions, should help close them.

### 5-YEAR HORIZON

**Technology helps improve soil health**

Analyses of soil microbiome identify key species and interactions, while cheaper and smaller sensors enable more systematic monitoring of soil health. Effective microbial and multiple genome-editing tools enable microbiome engineering. Blight-resistant potatoes are developed.

### 10-YEAR HORIZON

**Research gives deeper understanding of pests and pollinators**

Further development of gene-drive technology allows the risks they bring to be mitigated. Understanding of pollinators and their role in ecosystems is sufficient to develop a global strategy for pollinator conservation. Stable synthetic microbial communities are developed.

### 25-YEAR HORIZON

**Small-scale interventions preserve productivity**

The interactions between farms and their ecosystems are tracked through a widespread rollout of monitoring systems, allowing interventions that enhance agricultural productivity and prevent degradation of the natural environment. Gene-stacking and AI enable editing of organisms within the soil microbiome, significantly boosting its utility.

## 3.3.3 Reimagining farming

**Researchers are following a number of approaches to re-engineer the mechanisms of food production. One involves incorporating automation, artificial intelligence and other novel technologies into traditional forms of agriculture.[31] For example, tools like deep learning can accurately identify the presence of weeds and signs of disease from drone footage, enabling targeted intervention[32] and decreasing unnecessary pesticide use.[33] Similarly, engineered plant nanosensors and portable Raman spectroscopy could potentially detect stresses and track the health of crops and soil.[34]**

Such high-tech approaches to traditional farming can be complemented by the use of agro-ecological tools,[35] such as microbe-based bespoke fertilisers,[36] evidence-based crop choice and rotations.

Precision fermentation with engineered micro-organisms can provide nutrient sources and improvers for food products such as cultured meat, improving texture and palatability and helping move towards viable large-scale production.[37] Microbes and enzymes are already being used as factories that produce fats and proteins for nutrition products.[38]

The controlled release and targeted delivery of fertiliser ingredients manufactured at the nanoscale may also improve sustainability by ensuring more efficient use of nutrients.[39] Combining these approaches with "climate-smart agriculture", an acknowledgement of the need to take changing climatic conditions and their increasing variability into account,[40] will be especially important in developing economies where farms often lack resilience.[41]

Vertical farming, in which crops are grown indoors, close to population centres, under artificial light, could have a number of significant benefits. These include reduced food miles, reduced water use (watering systems are closed) and cuts in chemical pollution from fertilisers.[42] Making vertical farming economically viable remains challenging, however.[43]

### 5-YEAR HORIZON

**Research improves new approaches to farming**

Studies of the economics of vertical farming identify the key chokepoints currently limiting the technology. Improved characterisation of biochemical interactions between plants enables rational design of mixed-cropping systems. Nanotech sensors monitor crop plants for stressors and other key variables. Biomass fermentation is used to enhance the nutritional value of plant-based foods and improve taste and texture.

### 10-YEAR HORIZON

**Farming technologies create new processes for food production**

Cultured meat reaches price parity with conventionally-produced meat via precision fermentation of micro- and macro-nutrients that help reproduce conventional texture and mouthfeel. Technologies such as AI and the Internet of Things radically improve farming practices.

### 25-YEAR HORIZON

**Nanotech and biotech provide foundation for efficient farming**

Nanotechnology delivery systems for pesticides and other interventions see widespread use. Biofertilisers replace chemical fertilisers in many countries. Farmers have access to predictive analytics that guide all practices, as well as seeds and products designed specifically for their own complex systems. Cultivated meat is available in structured forms, such as steaks. The reduced cost of producing highly nutritious and palatable fermented products and cultivated meat means that traditionally undernourished groups are better fed.

## 3.3.4 Optimising nutrition

**Research has made clear that, depending on factors like genetics and lifestyle, people may require a different mix of nutrients and eating habits for optimal health and well-being.[44] Unpicking these details is key to elucidating the causes of a number of significant health problems.**

Scientists are now making progress in shaping the requirements of "personalised nutrition". Gaining such insights involves monitoring individual responses to particular foods — including considerations of the age at which they are introduced and of the role of the individual's gut microbiome. This has already shown potential to aid the development of a number of important health measures, such as tools for preventing the onset of obesity or food addiction.[45]

A key challenge is to understand the interactions between diet and the gut microbiome.[46] Physiologists have learned that the gut and brain are strongly connected, interacting through links dubbed the "gut-brain axis".[47] Alterations to diet can impact the microbiome,[48] with knock-on effects for multiple bodily systems including the immune system and even mental health.[49] People's individual gut flora differ significantly, so understanding the microbiome is key to personalising nutrition.[50]

### 5-YEAR HORIZON

**Research gives a clearer view of the gut microbiome's role**

Focused investigations achieve a systematic characterisation of individual variation in gut flora in multiple populations. AI sees some success in predicting gut microbiome responses to interventions, opening the path to better-informed dietary advice. Precise measurement of individuals' nutrition status and underlying determinants becomes available to a wider swathe of the population.

### 10-YEAR HORIZON

**Links between diet and health are clarified**

Physiological mechanisms linking diet and chronic health conditions are elucidated. Individual variation in hormonal responses to foods is characterised. Individualised nutrition programmes and food prescriptions become more widespread.

### 25-YEAR HORIZON

**Microbiome testing becomes standard practice in nutrition planning**

A gut-microbiome biopsy becomes a standard test during nutrition planning. Researchers achieve greater clarity in developing nutrition plans that can mitigate chronic health risks, leading to reliable, proven interventions.

3.4

# Orbital Environment

CHAIR:
**Lindy Elkins-Tanton**
Foundation and Regents Professor in the School of Earth and Space Exploration, Arizona State University; Principal Investigator of the Psyche mission, NASA

CONTRIBUTORS:
**Kathryn Hadler, Jean-Paul Kneib, Debbie Senesky, Vlada Stamenkovic**

**Our local region of space offers significant untapped resources: an unrivalled view of Earth, almost unlimited solar power, a high-quality vacuum and microgravity in abundance. For the more ambitious, there is the Moon, Mars and various near-Earth asteroids. Between them, these offer water ice, metals, building materials and real estate.**

Earth orbit and rocky bodies are also potential human habitats. NASA's Artemis program, for instance, due to send humans to the Moon in 2025, will eventually create a lunar base.[1] China has similar plans, with the initial phase involving the creation of a scientific facility in the Moon's south polar region by 2035.[2] In the longer term, Mars could also become a human habitat.

Wherever humans go, they will need power and the capability to build the things they need using local resources in exotic environments. Near-Earth asteroids offer potentially valuable resources for those able to exploit them. Space-based manufacturing techniques will need to evolve to make full use of these resources.

Closer to home, Earth orbits themselves are another resource. The advent of commercial launch services is making access to these locations cheaper and easier. This activity is making orbital real estate an increasingly crowded and valuable resource.

One important cargo will be paying visitors. Space tourism is a well-established business, albeit on a limited scale. That looks set to accelerate, with operators such as SpaceX, Virgin Galactic and Blue Origin offering paid seats on flights. The future of human space flight is highly dependent on ensuring passenger safety, however.

So the way the industry maintains safety and deals with accidents will have a crucial impact on growth.

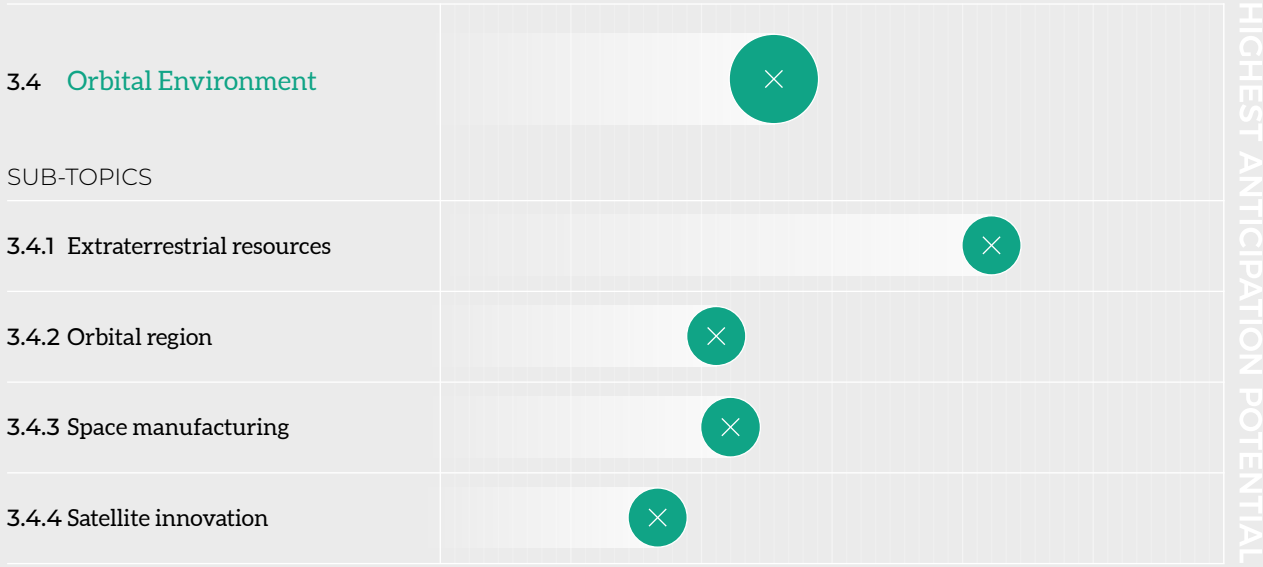
However these fields evolve, the orbital environment will need to be protected, perhaps in the same way as other global commons, such as the oceans or Antarctica.[3] That will require formal global coordination, governance and an appropriate legal framework.

In the 1960s, the space race was driven by geopolitical tensions and played out as a proxy for war. An important question today is how relations between global superpowers will shape the next generation of space exploration, given that the difference between friendly cooperation and antagonistic rivalry is likely to be profound.

KEY TAKEAWAYS

The regions beyond Earth contain a plethora of resources that would be of value both on Earth and in pursuit of human goals in terrestrial orbit and beyond. Harvestable **Extraterrestrial resources** include valuable minerals, resources for fuel, construction and sustenance for space-based communities, as well as solar energy. The **Orbital region** itself is also proving valuable as real estate, hosting ever more satellites that have an increasing commercial and military significance. An area ripe for development is **Space manufacturing**, which could significantly reduce the cost and difficulty of space exploration and habitation, as well as providing means to manufacture items that are difficult or impossible to produce on Earth. The field of **Satellite innovation** is seeing significant progress, with an increasing number of agencies working on the ability to manoeuvre one satellite to inspect, refuel or even disable another. Some researchers in the field have expressed concern about the geopolitical implications of such developments.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Earth's Orbital region is the domain requiring the most global multilateral attention, given issues around the management of space debris and the proliferation of satellites and other orbiting objects. The exploitation of extraterrestrial resources still requires sustained investments, research and technological development over the coming 20 years. Major advances will occur with relative certainty along the way, but the field will require strong coordinated international action.

MORE INFORMATION:

**go.gesda.global/3-4**

# 3.4.1 Extraterrestrial resources

**The resources available in space divide broadly into two categories: those that can be used to support in-space activities and those that can eventually be brought back to Earth[4]. Most of the near-term opportunities involve using resources in situ, with Moon exploration set to become a significant driver of science and technology in this area.**

Operating on the Moon will require locally produced resources, such as water extracted from ice at the lunar poles. This can be broken down into oxygen and hydrogen for propellant and life support, and the first pilot mission to demonstrate this capability will be an important milestone. The lunar regolith is also likely to be a rich resource for building materials and metals, particularly iron, aluminium and silicon for solar-panel manufacture. Characterising the make-up of the regolith and the ice it contains will be an important early goal for these missions.

Near-Earth asteroids are a more distant potential source of precious metals, ores and ices. But the huge cost of such missions is a significant stumbling block.

In 2023, the Space Solar Power Demonstrator (SSPD-1) satellite demonstrated that solar power could be harvested in space and beamed to Earth in the form of microwaves. Future challenges include scaling the panels to the kilometre scale.[5]

A different kind of resource is found on the far side of the Moon: a unique radio silence that astronomers hope will give them access to clear signals from elsewhere in the universe.

## 5-YEAR HORIZON

**Moon landings trigger public debate on lunar resources**

NASA's Artemis programme and commercial landers increase global interest in the Moon with missions demonstrating the first extraction of water and metals from the lunar surface. This work drives an international debate on how best to exploit the Moon, to spread the benefits across all humanity while preserving the lunar environment for future generations.

## 10-YEAR HORIZON

**Energy from orbit comes of age**

The first demonstrations of continuous transmissions of solar power from orbit to Earth provide valuable momentum for net-zero efforts, driven particularly by countries like Japan that have limited terrestrial resources of their own. But the cost of the enterprise raises questions about the ability to scale production to levels that will have significant impact.

## 25-YEAR HORIZON

**The Moon becomes the gateway to the solar system**

Lunar mining facilities begin to continuously produce propellant, metals and building materials on a usable scale. This paves the way for a lunar base that is a self-supporting manufacturing facility for beyond-Earth space exploration.

## 3.4.2 Orbital region

**The orbital region around Earth is a resource of growing importance and strategic value, largely because cheap commercial launch systems have made access easier.**

Humanity uses this environment as a viewing platform from which it can observe the Earth and the universe, as a thoroughfare for spacecraft and as a home for satellites. Satellites provide commercial services such as telecommunications and Earth observation, civic services such as climate studies, and weather-monitoring and military services, such as intelligence-gathering and both offensive and defensive operations.

Nation states have already begun to increase resources devoted to protecting, inspecting and destroying assets in space.[6] The weaponisation of space is increasing tensions and raising the stakes for space-related diplomacy.[7]

Overcrowding is likely to become an important issue, particularly in areas of special interest, such as Lagrange points and low Earth orbit. The prospects of Kessler Syndrome, where a chain reaction of collisions increases debris levels exponentially, are rising. So de-orbiting protocols will become more important, as will efforts to clean up debris in high-occupancy orbits, The European Space Agency has plans to demonstrate the safe removal of large pieces of debris with its Clearspace-1 satellite.[8]

How this orbital hygiene will be organised is not clear but there are calls for a better form of space-traffic control to reduce the chance of accidents, for the planned clean-up of space debris and for an appropriate legal environment to resolve disputes.

### 5-YEAR HORIZON

**Increased pressure for global governance of space commons**

The increased deployment of space weapons increases diplomatic efforts to find global agreement on limiting their use. These talks form part of a move towards global governance of space commons.

### 10-YEAR HORIZON

**In-orbit debris removal begins**

Commercial space debris removal makes Earth orbit safer than at any time since the dawn of the space age. But fears of a Kessler event dominate discussions to better coordinate activities in space.

### 25-YEAR HORIZON

**Space traffic control gets green light**

The world's space traffic control begins operating from Rwanda (a legacy of the Rwanda Space Agency's long-standing role in space diplomacy). This real-time service coordinates on-demand launches to all destinations.

# 3.4.3 Space manufacturing

**Earth orbit is a region of microgravity, high-vacuum conditions and clean energy from the Sun. As such, this region offers the manufacturing industry a site that is conducive to producing high-purity components, experimenting with exotic manufacturing methods and even attempting to create substances that cannot be made on Earth.**

For example, these conditions ought to allow for higher-quality versions of pharmaceuticals, metals or semiconductors that can outperform those made on Earth.[9] That should mean that large spare-part inventories for space-based operations will become a thing of the past.

The most important manufacturing limitation is the availability of power. Kilowatt power sources exist, but megawatts are needed for industrial-scale production. Finding ways to establish these is an important goal for space agencies and commercial operators such as Blue Origin.

Larger power systems will enable the manufacture and construction of bigger structures like remote-sensing antennas, the building blocks for human habitation modules and semiconductor fabrication.

The longer-term goal is to find ways to exploit resources on Mars and near-Earth asteroids, which may be accelerated by construction of a Moon base and the exploitation of lunar water ice, which can be readily turned into oxygen and hydrogen for propulsion and life support.

## 5-YEAR HORIZON

**Power boost for space manufacturing**

The availability of kilowatt power systems in orbit and on the Moon kickstarts research and development of microgravity and low-gravity manufacturing techniques. This allows the prototyping of products and materials that are commercially viable.

## 10-YEAR HORIZON

**Construction of a new international space station begins**

Orbital-construction companies begin assembling a replacement for the International Space Station while manufacturing a kilometre-scale antenna to harvest solar power. With a clear business case for commercially viable materials, space manufacturing begins to scale up.

## 25-YEAR HORIZON

**Lunar habitation approaches feasibility**

Moon-based manufacturing of building materials, propellant and oxygen for life support leads to the prospect of self-supporting lunar habitation. Megawatt power supplies unlock a wide range of opportunities for lunar and orbital manufacturing, allowing space manufacturing to enter the supply chain.

# 3.4.4 Satellite innovation

**Giant networks of communications satellites are already a reality, with constellations belonging to Starlink and Eutelsat OneWeb already in orbit. These fleets will quickly become more capable as companies deploy satellite-to-satellite laser communications. Real-time video feeds from space are also gaining in popularity.[10]**

With launch costs dropping, satellite operators are experimenting with off-the-shelf components for imaging, sensing and communicating at lower cost.

One important limit on satellite lifetime is the amount of onboard fuel. With high-end satellites costing hundreds of millions, refuelling is an attractive way to extend lifetimes. Lockheed Martin[11] and Northrop Grumman[12] are among companies developing a standard refuelling capability for satellites. This will require greater manoeuvrability: changing orbits and rendezvousing with other craft remains difficult, requiring plentiful fuel and agile propulsion systems.[13]

However, Russia appears to have perfected this technique in spacecraft that are able to approach and inspect other vehicles.[14] This technique, known as proximity operations, will no doubt be useful, enabling applications such as automated refuelling of spacecraft. The development of proximity operations also raises security concerns, as it enables the disruption or even disabling of civil and military satellites.

The increased activity on the Moon and in lunar orbit will require a lunar time zone, with satellites proving timing, positioning and communications. That will require significant collaboration to develop international standards.

5-YEAR HORIZON

**Satellite internet services become global**

The competition among commercial companies to offer satellite broadband internet connections drives down the cost of connection and helps solve the long-standing problem of providing rural internet access, particularly in developing countries. International standards agreed for deorbiting spacecraft at the end of their useful lives.

10-YEAR HORIZON

**Innovation in satellite refuelling brings down cost**

The first automated refuelling of a commercial satellite doubles its operational lifetime and once again lowers the cost of operating in space.

25-YEAR HORIZON

**Improved satellite manoeuvrability**

Lunar operations lead to international standards for coordinate systems, for timing, communications and above all safety. The establishment of these standards provides a foundation for a globally representative lunar community.

3.5

# Ocean Science

CHAIR:
**Sabine Gollner**
Senior scientist, Royal Netherlands Institute for Sea Research (NIOZ)

CONTRIBUTORS:
**Diva Amon, Maya Ben-Yami, Elva Escobar, Marcel Jaspars, Pei-yuan Qian, Andrew Sweetman, Jason Sylvan, Moriaki Yasuhara, Erik Zhivkoplias**

**Our growing understanding of the ocean offers enormous opportunities, both for the prevention of harm and the enabling of benefits. By better understanding marine ecosystems, we can do a better job of safeguarding them from human impacts like climate change and pollution. We can also develop a sustainable bioeconomy based on marine resources.**

An array of new technologies and methods are leading to rapid progress in oceanography — the physics and chemistry of the ocean. Automated sensor arrays are enabling us to trace systems of currents and nutrient flows in unprecedented detail. Deep-sea exploration is revealing how the ocean interacts with the solid Earth, notably in hydrothermal vents where mineral-rich water spews up from beneath the seabed. The ocean is becoming understood as a vast engine of currents and chemical flows that is inextricably linked to wider Earth-system processes such as plate tectonics and the climate.[1]

This understanding is crucial because of the sheer power of the ocean. As global average temperatures continue to rise, the ocean is responding in complex ways: sea ice is melting and retreating, currents are slowing and shifting their paths, and stored heat is moving. Our growing understanding of oceanography will enable us to identify the most significant and pressing risks, and to devise ways to mitigate them.

Likewise, our knowledge of marine biodiversity is progressing rapidly, driven by technologies like eDNA and metagenomics. At the same time, our understanding of marine ecosystems and the services they provide is also increasing, enabled by uncrewed vehicles and other tools for large-scale ocean observation.

This knowledge is crucial to the well being and prosperity of society. We already know that non-sustainable human activities pose multiple threats to key marine ecosystems in the deep sea, coral reefs, seagrass meadows and the Arctic sea-ice biota. Our improving understanding of those ecosystems offers an opportunity to find better ways to conserve them — and thus to protect the natural services they provide, ranging from food provision to climate regulation.

The ocean can also offer opportunities, when managed sustainably. Whilst the impact of large-scale industrial implementations is not yet understood and thus must be developed with great caution, the emerging “blue economy” sectors may provide renewable energies, store carbon (marine carbon-dioxide removal, or mCDR, provide food or harvest marine genetic resources.

KEY TAKEAWAYS

Earth's oceans are a major and vital part of the planet's ecosystem, generating 50 per cent of oxygen, absorbing 90 percent of excess heat and capturing 25 percent of $CO_2$. However, much of the detail of their characteristics, contributions and changing properties are not yet understood. The field of **Oceanography** aims to inform our understanding of the physics and chemistry of the oceans, such as those involved in currents, helping us to model and forecast the effects of a changing climate and the potential for tipping points to cause major change. Researchers are still gathering new information on **Ocean biodiversity**, including microbial marine life as well as plants and animals living in the water and on and in the sea-floor (where an estimated 90 per cent of species are yet to be discovered). Research is also uncovering the details of **Ecosystem functions**. The services that the diverse deep-sea ecosystems, as well as plankton, seagrass and corals in shallower seas, bring to the ocean system remain largely unexplored, and further insights will be vital to conservation efforts. All of this can inform understanding of **Human impact and ocean stewardship** and facilitate better outcomes for the ocean environment and dependent life in the face of climate change and other challenges.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Ocean Science is an area with an overall high Anticipation Potential score. The transformational effects of all domains surveyed and the need for international coordinated action are both very high, especially for Ocean biodiversity and Human impact and ocean stewardship. Advances in research on Ecosystems functions are more uncertain, and the field should take 12 years to reach maturity, contributing to a higher Anticipation Potential score.

MORE INFORMATION:

**go.gesda.global/3-5**

# 3.5.1 Oceanography

**We are rapidly improving our understanding of the physics of the ocean, including the mapping of currents, temperatures and flows of chemicals. A major driver has been remote-sensing technologies for sea-surface monitoring, notably the Argo network of nearly 4,000 robotic floats.[2] Researchers can now follow floating debris, such as marine plastic pollution, across oceans.[3]**

For the first time we can track long-term changes. More heat is being transported into northerly waters, for instance.[4] Currents are changing,[5] with some slowing down or speeding up,[6] and vast "gyres" shifting position.[7] Ocean chemistry is also in flux: dangerous low-oxygen zones are growing.[8] Researchers are now watching for evidence of tipping points,[9,10] such as a slowdown or collapse of the Atlantic Meridional Overturning Circulation (AMOC),[11] although timescales remain difficult to determine.

There is still a need for more data on the physical characteristics of the ocean, especially in the deep sea, which is somewhat constrained by gaps in our ability to gather data, whether using survey vessels, moored buoys, Argo floats or instruments tied to animals. If this situation can be improved by acquisition of data from commercial and military vessels, it may be possible (though this is still a subject of debate) to create a "digital twin" of the global ocean that is detailed enough to be useful in oceanographic prediction and intervention modelling.[12]

### 5-YEAR HORIZON

**Ocean history becomes clearer**

Improved palaeooceanographic proxies reveal how ocean behaviours have changed over millions of years. Research gains a better understanding of the physical mechanisms driving changes in the ocean, for example by analysing how freshwater inputs in the North Atlantic affect ocean circulation. The behaviour of the ocean is analysed under a more complex range of climate-change scenarios, including those with overshoots and with net-zero climate actions.

### 10-YEAR HORIZON

**Remote sensing improves**

Cheaper and more efficient remote sensing enables detailed monitoring of ocean-surface currents, temperature and other factors throughout the world ocean. New Earth system models become available, enabling improved understanding of oceanographic processes such as $CO_2$ exchange and saturation, and the stability of circulating current patterns. Longer-term observations lead to improved understanding of the dominant forces driving change in the oceans.

### 25-YEAR HORIZON

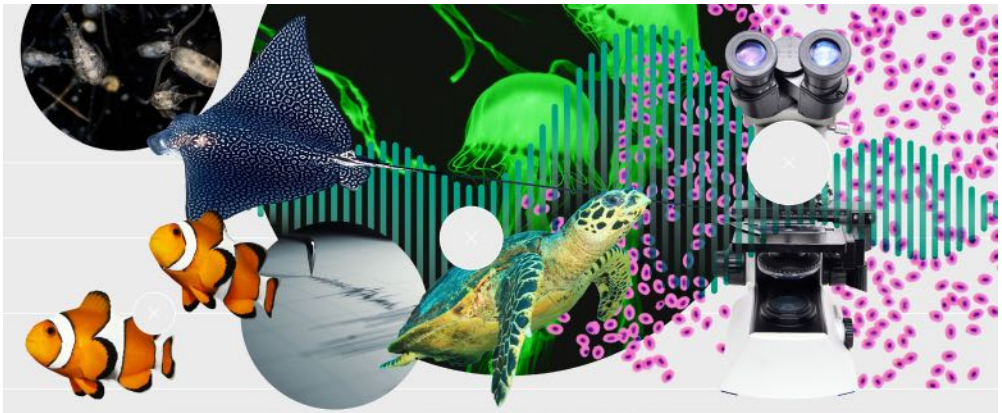
**Data provides capacity to forecast major changes**

Combining data, modelling and physical understanding enables forecasting of major oceanic changes such as shifting currents and upwelling. Higher-resolution models resolve existing discrepancies between models and observations. Observations until 2050 allow us to understand the ocean's reaction to rapid climate change, for example determining whether or not the AMOC is losing stability and how much it can weaken.

# 3.5.2 Ocean biodiversity

**Despite rapid progress, many discoveries about ocean biodiversity remain to be made. Technologies like eDNA and metagenomics are revealing unprecedented diversity in the "ocean genome",[13] aided by sampling programmes like Tara Oceans.[14] Bio-logging enables remote tracking of animal behaviour,[15] while acoustic sensors are increasingly contributing to biodiversity assessments.[16,17,18] Furthermore, machine learning can be used to make sense of vast datasets, for example characterising the functional traits of plankton.[19] There remains a need for consistent identifiers across different kinds of biodiversity data so researchers can make links between databases.**

The immense variety of microbial marine life[20] is only now coming to light[21] — as are the complex ecosystems found in deep-sea water, as well as on and In the deep-sea bed.[22,23,24,25] As the climate warms, some species are moving to new areas, creating an urgent need to understand which are becoming invasive.[26] More broadly, there is a need for more tracking of biodiversity, both to establish baselines and to follow trends as climate change[27] and other human impacts mount up.[28] Although warming is slower in the deep ocean, research suggests that its biodiversity is no less exposed than that of surface waters, because of free-drifting (pelagic) larval stages in many deep-ocean organisms' life cycles and because of most deep-sea organism's adaptation to cold and stable conditions. Indeed, projections indicate that, while mitigation could limit threats to surface biodiversity, deep-ocean biodiversity will face an unavoidable escalation in threat.[29]



## 5-YEAR HORIZON

### Monitoring improves assessment

More comprehensive and wide-ranging assessments of ocean biodiversity are made possible by a combination of monitoring techniques. Improvements in remote tracking of animals enable mapping of long-distance migration routes and identification of key regions such as spawning grounds. eDNA can identify species in a biome. Imaging and acoustic monitoring can recognise large animals to species level. Automated image capture helps monitor species abundance. Research achieves more precise and accurate estimates of the number of species in the ocean.

## 10-YEAR HORIZON

### Biodiversity-tracking aids conservation efforts

Multi-year studies enable tracking of biodiversity trends and inform conservation efforts to establish efficient marine protected areas. International capacity-building and knowledge-sharing programmes enable broader use of eDNA tools for biodiversity monitoring. Improved wet-lab methods and high-pressure aquaria enable more controlled studies of marine organisms and biochemistry, including chemical signalling.

## 25-YEAR HORIZON

### Species-specific forecasting comes of age

Reliable forecasting allows predictions of which species will become invasive. Keystone species are identified, enabling protective measures. Reliable predictions of the chemicals an organism makes, and the roles it plays in its ecosystem, become possible, based primarily on its genome sequence. Humankind benefits from marine genetic resources through applications of biodiscovery of pharmaceutical compounds, and from Inspiration for novel materials and structural design.

# 3.5.3 Ecosystem functions

**The functions of marine ecosystems, and the ecosystem services they provide, are still being studied and are little understood,[30] with major discoveries continuing to be made. For instance, in recent years ecologists have realised the critical importance of wetlands, mangroves, seagrass beds and coral reefs, often operating as a single unit, which supports the recovery of entire ecosystems and their services,[31] and even traps marine plastics.[32] Similarly, the scale of ecosystem services provided by plankton continues to expand under examination.[33]**

Increasing exploration of the deep-sea water column and sea-floor substrate — by submersibles, robotic vehicles and other methods — is revealing complex ecosystems unlike anything at the surface. Hydrothermal vents are emerging as major contributors to the overall marine ecosystem.[34] Researchers are finally able to explore the microbes living in oceanic crust,[35] revealing hidden ecosystems shaped by magmatism and water-rock interactions.[36] Some marine microbes perform metabolic processes, such as degrading petrochemicals,[37] and genetic information from deep-sea microbes and from sponges has aided the development of antiviral drugs and rapid testing for COVID-19.[38] Marine Genetic Resources represent a large, and mostly untapped, source of potentially useful substances.[39] However, the open-water pelagic zone (including the dark ecosystem), the largest habitat on Earth, remains under-explored.

A key challenge is to determine the fluxes of carbon and other nutrients through marine ecosystems, enabling us to track the carbon budget of the oceans[40], including the deep ocean[41], and their ability to remove carbon from the atmosphere.[42] Autonomous platforms can help monitor these biogeochemical processes.[43] Behaviours such as deep diving by large predators like sperm whales are crucial to these fluxes.[44]

Available data on ecosystem function covers less than the last 25 years. Attention has mostly focused on a handful of charismatic groups: notably shallow-water corals, the decline of which is fairly well-documented.[45] Expanding this longitudinal tracking to other species, including in the deep sea, will be crucial for tracking ecosystem responses to climate-driven changes such as ice-shelf collapses.[46] It will also be key for planning how we use and conserve marine ecosystems.[47]

## 5-YEAR HORIZON

**Deep oceans are opened for study**

New technologies and methods arise for studying deep-ocean ecosystems, including microbial ones. Research achieves a better understanding of how marine biodiversity affects ecosystem function. Awareness of the impacts, effectiveness, social implications and governance issues relating to plans for marine carbon-dioxide removal (mCDR) begin to be discussed more broadly.

## 10-YEAR HORIZON

**Multi-year studies expose deep-ocean trends**

Multiple longitudinal studies of ecosystem functioning are carried out, extending to deeper regions of the sea that could previously only be visited intermittently. There are systematic surveys of ecosystem services by different organisms and ecosystems. Researchers collaborate to build interconnected global databases of biodiversity and ecosystem function, and to identify legal and governance gaps relating to mCDR.

## 25-YEAR HORIZON

**Machine learning and other emerging technologies inform marine ecosystem conservation**

A global catalogue of sound, bioluminescence and chemical seascapes in the dark ocean, the chemicals produced by marine organisms, and their functions and interactions predicted by machine learning aid conservation. AI identifies biota from images and video to assist biodiversity assessments and generate an open-access identification library. Research achieves an improved mechanistic understanding of the links between biodiversity and ecosystem function, based on multiple data sources and AI.

## 3.5.4 Human impact and ocean stewardship

**Human impacts on the oceans are considerable, and rising.[48] Climate change is deoxygenating, acidifying and warming the oceans, pollution such as fertiliser run-off from farms threatens many ecosystems, and overfishing is destabilising many ecosystems. There are also emerging impacts, such as the nascent deep-sea mining industry[49] and initiatives to remove $CO_2$ to the ocean to mitigate climate change. These impacts intersect in numerous ways:[50,51] for instance, ocean biodiversity affecting climate.[52] However, with effective knowledge-gathering and policy-making, it should be possible to minimise harms and create a sustainable future for the oceans.[53] Artificial intelligence may have roles to play here, for instance in modelling the impacts of interventions.[54]**

Better understanding of our impacts will come from improvements in monitoring, for instance by robotic surface vehicles,[55] and in expanding our observations to the remote deeps.[56] There is great potential for citizen scientists to contribute,[57] both to ocean observations and to conservation.[58] New blue industries like marine aquaculture may have key roles, both in our economies and in marine conservation.[59] Capacity-building and knowledge transfer will be crucial to understand all parts of the ocean, from the south to north, and shallow to deep.

Managing the oceans is a major geopolitical challenge.[60] A key challenge is to determine, by leveraging scientific expertise and co-design, which kinds of policy interventions will be the most beneficial and have the fewest unintended consequences. The BBNJ (Biodiversity Beyond National Jurisdiction) treaty,[61] once ratified, will regulate the sustainable use of marine genetic resources, environmental impact assessments and area-based management tools such as Marine Protected Areas in the ocean outside national boundaries.[62] Successes in ocean diplomacy, such as with the adoption of the BBNJ treaty, will need to be built upon to assist future ocean science and conservation efforts.[63] Conservationists are increasingly exploring radical ideas such as granting legal rights to nature.[64]

### 5-YEAR HORIZON

**Citizen scientists expand their role**

Low-cost, accessible monitoring devices enable citizen scientists to significantly expand their role in tracking ocean ecosystems. Research is spurred by improved understanding of cultural connections to the sea, including the cultural heritage of the deep sea.

### 10-YEAR HORIZON

**A sustainable blue economy emerges**

Understanding is sufficient for rational design of marine conservation interventions and of regulations for the sustainable blue economy. Standardised and reliable methods for conserving shallower ecosystems are developed. In many deep-sea ecosystems, however — such as hydrothermal vents or the abyssal plains — the pace of recovery is so slow (where possible at all), that the prevention of any degradation remains essential.

### 25-YEAR HORIZON

**AI and systematic analysis improve conservation**

Earth system models and artificial intelligence are used to simulate global-level interactions between the oceans, their ecosystems and the wider Earth system. Systematic analyses of biodiversity-conservation interventions demonstrate the key factors determining effectiveness of initiatives such as Marine Protected Areas. Transdisciplinary research, including social, anthropological, legal and economic expertise, establishes methods for estimating the financial value of ecosystem functions and services.

3.6

# Solar Radiation Modification

CHAIR:
**Govindasamy Bala**
Professor at the Center for Atmospheric and Oceanic Sciences, Indian Institute of Science

CONTRIBUTORS:
**Ines Angela Camilloni, Peter Irvine, Richard Muyungi, Thelma Krug, Janos Pasztor, Isabella Eckerle**



**Solar radiation modification (SRM) is a set of approaches that could fully or partially offset the temperature rise caused by greenhouse-gas emissions, thus reducing some of the harmful impacts of anthropogenic climate change.**[1]

Some options involve nothing more complicated than painting roofs white. Others entail constructing fleets of high-altitude aircraft for spraying reflective aerosols into the stratosphere or even space-based mirrors. The optimal solution may be one that deploys modification technologies alongside other climate responses such as emissions reduction and CO2 removal.[2] Overall, there is growing scientific consensus that this approach would work in a technical sense, with some limitations.[3,4]

However, all SRM approaches raise challenging questions such as who should control the technologies, if and when they should be deployed and what should happen if a deployment goes wrong or fails entirely. Another concern is "moral hazard": the possibility that investing in these SRM approaches would reduce the impetus to cut greenhouse gas emissions.

Given the increase in global mean temperatures, decisions about whether to research and deploy SRM are becoming increasingly urgent. However, there is a pressing need to develop international governance frameworks for deciding whether or not to conduct SRM field experiments, and if they are to be conducted, how — and to prepare for making decisions whether or not to deploy at some point in the future.

Some governments and funding bodies are rising to the challenge, with the European Commission[5] and White House Office of Science and Technology Policy[6] both promoting further investigation and the UK starting a £10.5 million research programme.[7] However, in March 2024, the field suffered a setback when the UN Environment Assembly failed to agree on the establishment of a scientific expert group to advise on SRM. The failure reflected concern in developing countries about the nature of the research and how the results would be used.[8]

KEY TAKEAWAYS

Reducing the amount of solar radiation incident upon Earth's surface could help mitigate global warming, and strategies for reducing this radiation flux are under investigation. **Stratospheric aerosol injection**, which involves injecting chemicals into the lower stratosphere to reflect back some incoming sunlight, is promising, but raises a number of concerns. **Cloud engineering** schemes also show some promise but could lead to localised cooling and regional changes in precipitation pattern. **Terrestrial solar radiation modification** schemes to increase reflection of solar radiation back into space, such as painting more of Earth's surface white, or artificially regrowing Arctic ice, are also under consideration. Further from possible implementation, but perhaps more impactful in the long term, are the **Space-based solar radiation modification** strategies such as radiation-reflecting satellites that carry panels to reflect solar radiation or shade portions of the Earth from the sun's rays. All of these possible pathways require intense scrutiny and international co-operation if unintended adverse consequences are to be avoided.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Solar Radiation Modification is the topic with the lowest Anticipation Potential score overall. The reason for this is the strong awareness generated by the media attention that the topic has received recently. However, its relatively low transformative effect on other fields of science and society is also a contributing factor. Major research on the four sub-topics is still required, with timelines ranging from 13 years for Stratospheric aerosol injection to 37 years for Terrestrial solar radiation modification.

MORE INFORMATION:

**go.gesda.global/3-6**

Solar Radiation Modification

# 3.6.1 Stratospheric aerosol injection

**The most prominent and most-studied approach to SRM is stratospheric aerosol injection (SAI). This entails injecting aerosols into the lower stratosphere to reflect back some incoming sunlight, reducing the amount of solar radiation that the Earth absorbs.**

There is evidence that SAI can offset some of the impacts of climate change, but will come with ancillary risks of its own. Crucially, it would be possible to restore the average global temperature to pre-industrial levels if sufficient quantities of aerosols were injected in a sustained fashion.[9] However, modelling studies suggest that it is not possible to reset temperatures in every region. The same applies to precipitation, wind patterns and other aspects of climate. So, while SAI could lead to a more favourable outcome overall, there would inevitably be some winners and some losers.[10]

Sulphate aerosols are the most commonly proposed substance for SAI. However, sulphur's potential to damage the ozone layer or lead to acid rain is a significant concern and this is driving research into alternative materials, such as calcites or chalk powder. A better understanding of the way all these materials interact with the upper atmosphere is much needed.

The overwhelming majority of studies of the effectiveness and consequences of SAI have been carried out through computer modelling. Most of the field tests that have been proposed have been called off after facing opposition.[11] But a small number have taken place, carried out by independent researchers and funded by entrepreneurs, raising concern over the possibility of unilateral action.[12,13]

## 5-YEAR HORIZON

### SAI conversations begin

An increase in research funding begins to establish a much-needed evidence base to inform discussion. The report of the Climate Overshoot Commission, COP28's global stocktake, UN Environment Assembly and General Assembly considerations, and a special IPCC report on SRM increases the sense of climate urgency, and informed global conversations about SAI to begin. Moreover, they encourage internationally coordinated outdoor SRM research programmes to take place and to better understand the risks, benefits and governance challenges of SRM.

## 10-YEAR HORIZON

### Modelling informs decision-making

Continued indoor modelling research, particularly with advanced machine-learning techniques, as well as outdoor field experiments, result in sufficient information to begin to allow evidence-based decision-making on whether or not to consider SAI as a supplemental option to mitigate and adapt to climate change. Governance frameworks put in place to guide international coordinated research on SAI, as well as further research on governance needs of SAI and the available evidence base, result in beginning work toward an international treaty for the long-term governance of SAI.

## 25-YEAR HORIZON

### Governance of SAI deployment begins

Advances in high-resolution modelling capabilities give better understanding of SAI's impacts at local and regional scale. A global treaty provides a binding framework for long-term governance of SAI deployment as one of many climate-change-mitigation techniques. Its provisions also provide for a global authority to implement AI on behalf of the global community.

## 3.6.2 Cloud Engineering

**A number of SRM technologies involve altering the properties of clouds, causing the clouds to reflect more solar radiation back into space. Marine cloud brightening (MCB) is one form of cloud engineering. The idea is to spray droplets of seawater into the sky, with sea-salt crystals providing additional seed nuclei for water droplets to condense.[14] This would make marine clouds whiter and more reflective, sending more solar radiation back into space and cooling the surrounding region. A range of spray technologies have been considered.[15]**

Various researchers have also proposed thinning and dispersing high-altitude cirrus clouds, which contribute to warming by trapping a disproportionately large amount of terrestrial radiation that would otherwise escape into space.[16] Injecting these clouds with particles of bismuth tri-iodide allows the formation of large ice crystals within the clouds. These large ice crystals fall out more rapidly, shortening the clouds' lifespan. Cirrus reduction can improve the transmission of long-wave terrestrial radiation into space.[17]

In February 2024, researchers at the US National Oceanic and Atmospheric Administration proposed injecting ice-nucleating particles into the troposphere to prevent water vapour reaching the stratosphere, where it usually absorbs outgoing radiation. This "intentional stratospheric dehydration" would help to cool the planet by increasing outbound radiation, although significant technical and practical hurdles would need to be overcome first.[18]

Whereas SAI has a globally uniform effect, cloud-engineering techniques produce more localised cooling, allowing them to be used in a targeted way. For instance, MCB could be used to cool major coral reefs, which suffer bleaching when water temperatures become too high.[19]

5-YEAR HORIZON

**MCB experiments are promising**

Australian MCB experiments yield encouraging results, and result in the launch of a 10-year programme to apply MCB to contribute to the protection of the Great Barrier Reef.

10-YEAR HORIZON

**Small-scale MCB begins**

The first prototypes of automated ships that can spray seawater for MCB are launched. The first official small-scale use of MCB is undertaken over endangered corals. Real-world testing of cirrus modification begins.

25-YEAR HORIZON

**MCB in regular use**

MCB is in regular use over corals and other heat-sensitive ecosystems during heatwaves.

## 3.6.3 Terrestrial solar radiation modification

**Changing the colour of parts of the Earth's surface can affect local heating. This is because dark surfaces absorb more of the Sun's heat, while light-colour surfaces reflect more back into space. As a result, making the surface of the edplanet lighter — increasing its albedo — can have cooling effects.[20]**

One prominent method is to paint roofs white or other pale colours. This can have direct benefits to the local populations, including mitigating the worst effects of heatwaves. Furthermore, the cost is relatively low.[21]

In areas not covered by buildings and roads, plants with light-coloured leaves can also change the local albedo. This is cited as a potential downside of planting additional trees on grassland areas: trees are typically darker than grass, so they lower the albedo and may thus contribute some warming. There is also ongoing research into engineering paler crop plants, a task in which synthetic biology may play a role.[22]

At the more extreme end of the scale, there are proposals to artificially regrow Arctic sea ice, perhaps by spraying tiny particles of silicon dioxide to encourage ice formation, or by pumping huge volumes of cold water up from the deep sea. In theory, schemes like these could restore a large area of reflective ice surface. However, the feasibility and costs are uncertain, and there may be unforeseen negative environmental consequences.[23]

### 5-YEAR HORIZON

**Urgency spurs international research**

Following the COP28 global stocktake, the UN Environment Assembly and the Arctic Council agree that refreezing the Arctic is an urgent priority to avoid a major global tipping point. This spurs major international research efforts to find effective solutions. Small effects of albedo brightening encourage local governments to experiment further.

### 10-YEAR HORIZON

**Building codes embrace albedo brightening**

Albedo brightening is written into legal requirements for new buildings.

### 25-YEAR HORIZON

**Crops assist albedo brightening**

Crops engineered for higher albedo become widely available to farmers

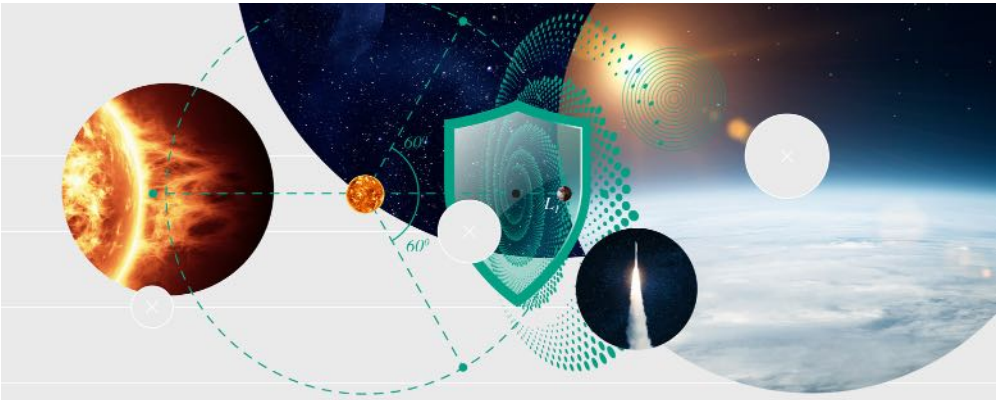
## 3.6.4 Space-based solar radiation modification

**There are a number of proposals for space-based technologies that could mitigate climate warming. In all cases, the technologies would prevent some of the Sun's radiation from reaching the planet, offsetting the additional heat trapped by greenhouse gases.**

The simplest notion is a large occulting disc or "parasol". This would be placed at a carefully chosen position between the Earth and the Sun, in order to produce a permanent partial solar eclipse. The ideal location would be Lagrange Point 1, where the gravitational pulls of the Sun and Earth are balanced.[24]

Researchers have also considered a number of alternative reflectors for reducing the radiation incident on Earth.[25] These include Fresnel lenses, diffraction gratings and mirrors.[26,27] The key considerations are the robustness of the design to meteoroids and other threats, and the mass of the structure — which must be carried into space by rocket, or else manufactured in space, adding to the cost.

All these technologies face considerable technical and economic barriers.[28] For example, an occulting disc at Lagrange Point 1 would need to have a surface area of millions of square kilometres: no structure remotely close to such a scale has ever been constructed in space. Furthermore, such projects arguably also create a dangerous single point of failure in our climate-mitigation strategies: in contrast to Earth-based forms of SRM, the scale of investment and hardware deployment required for a space-based reflector would mean putting all our eggs in one basket, with catastrophic risks if the project failed.




### 5-YEAR HORIZON

**Space-based SRM remains a conversation topic**

Renewed interest in space flight and space colonisation ensures that conversations about space-based SRM continue.

### 10-YEAR HORIZON

**Falling costs spur interest**

Speculative planning by interested parties shows that once-prohibitive costs have been reduced through advances in space-flight technology. Consortia of wealthy individuals begin to talk openly about temporarily alleviating climate issues through space-based means.

### 25-YEAR HORIZON

**Feasibility studies begin**

Governments commission preliminary feasibility studies for space-based SRM. Small-scale, low-orbit tests of solar-reflector technology begin.

3.7

# Infectious diseases

CHAIR:
**Wanda Markotter**
Director of the Centre for Viral Zoonoses, University of Pretoria, South Africa

CONTRIBUTORS:
**Serge Morand, Kris Murray, Rafael Luis Ruiz de Castaneda, Alessandra Scagliarini, Jakob Zinsstag, Samantha Paoletti, Scott O'Neill, Ioan Negrutiu**

**The past century has seen enormous progress against some diseases, with the mortality associated with a few diseases — malaria, for instance — falling dramatically.[1] However, infectious diseases remain a major threat to human health and well-being.**

The current disease load is only a part of the problem.[2] New diseases are continually emerging, with COVID-19 being the most dramatic recent example, as humans come into contact with novel pathogens and global transport networks facilitate their rapid spread. Environmental degradation is a potential contributor to this emergence through human infiltration and destruction of natural habitats for increased trading of wildlife and intensive livestock farming, among other activities.

Alongside this, warming temperatures and other climatic shifts are forecast to move vector organisms, such as mosquitoes and ticks, into new regions.[3] This will intensify disease pressure on communities that are already struggling with other stressors. Thawing of Arctic permafrost due to climate change represents another potential source of new and dangerous diseases.[4]

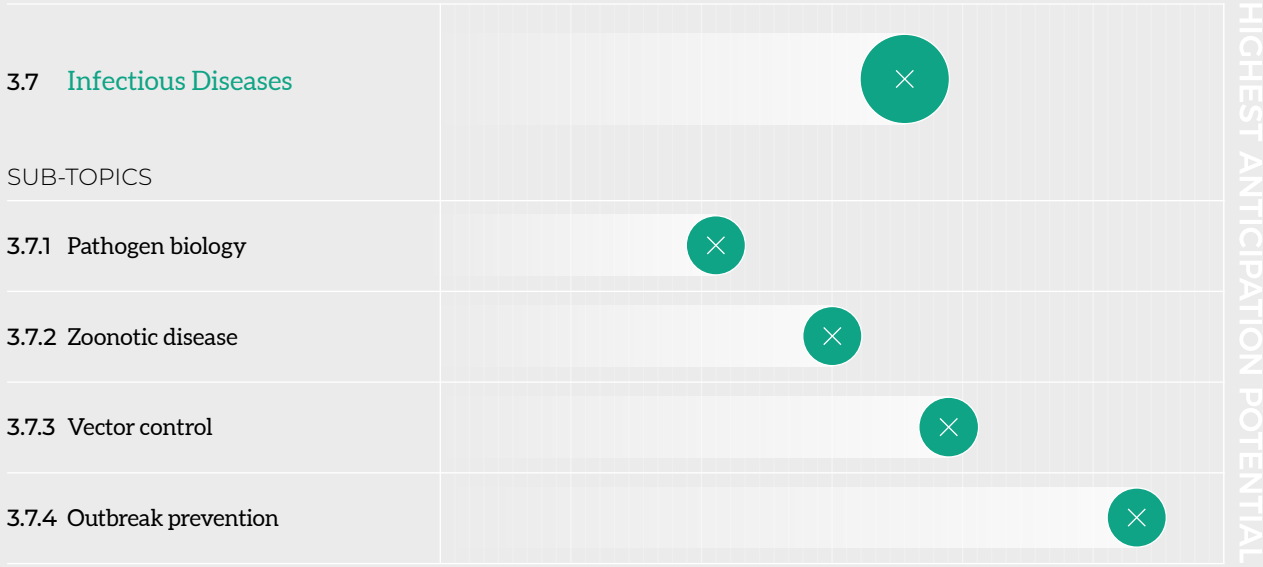
Given the difficulty of addressing these underlying factors in the short term, our overall aim should be to move from treating and managing disease outbreaks to preventing — or at least detecting spillover events early — and containing them. There are many specialised areas of infectious disease science — such as accelerated vaccine development and genetic sequencing in pursuit of vector-control technologies — in which considerable progress remains to be made. There is a tantalising prospect of preventing future pandemics before they take hold.[5]

Doing this will entail tackling infectious diseases in their broader context as part of a social-ecological system: for example, understanding when diseases are likely to spread from wild animals to humans as a result of environmental changes that are in turn influenced by social, economic and political trends; or understanding when socioeconomic conditions promote the spread of infections such as cholera. This is the framework that One Health uses to understand and tackle disease.

KEY TAKEAWAYS

Despite significant achievements in the battle against infectious disease, maintaining human health and well-being remains a challenge across the globe. Research into **Pathogen biology** is helping with this, finding weaknesses in the organisms that pose a threat, and assisting in the development of vaccines. Changing human behaviour and land use means that **Zoonotic diseases**, where humans disease is caused by pathogen originally hosted by other animals, is on the rise. Research is elucidating a number of measures that can be taken to mitigate this threat. Another subject of urgent research is **Vector control**: limiting the opportunities and capability for disease transmission by organisms such as ticks, flies, fleas and mosquitoes. Ongoing efforts to develop and implement systems that can achieve **Outbreak prevention** will help to avert future pandemics.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

In general, all fields covered by Infectious Diseases have high Anticipation Potential scores. Outbreak prevention scores particularly highly because future advances in technologies for more precise disease surveillance will be transformational and require strong international coordinated action but are still more than a decade away. The scope for action in the area of Pathogen biology is relatively low, reducing its Anticipation Potential score.

MORE INFORMATION:

**go.gesda.global/3-7**

# 3.7.1 Pathogen biology

**Great progress has been made in our understanding of fundamental pathogen biology. However, while some pathogens are extremely well-studied, many are neglected. Most notably, before the COVID-19 pandemic, there was little focus on coronavirus research despite two relatively recent coronavirus outbreaks in the form of SARS and MERS.**

Some of the most dramatic progress has been in vaccine development, as evidenced by the success of the COVID-19 vaccines.[6] 2021 also saw one of the biggest successes of recent years, with the approval of the first successful malaria vaccine RTS,S/AS01 or Mosquirix.[7] There are also approved vaccines for the Ebola virus,[8] and several Zika virus vaccines are undergoing clinical testing.[9] If these vaccines can be successfully rolled out to vulnerable populations, the burden of these diseases will be substantially reduced.[10]

A key challenge for pathogen biologists and medical professionals is to understand the multifarious health impacts of pathogens. This has been highlighted by the covid-19 pandemic. While coronaviruses like SARS-CoV-2 are thought of as primarily respiratory infections, in fact their effects range across many body systems.[11]

Finally, pathogen biology must be harnessed for the broader long-term goal of predicting and preventing outbreaks. This means understanding which pathogens are “out there” on a global scale and identifying those that pose a risk to human health.

## 5-YEAR HORIZON

**Vaccine production improvements**

Vaccines can be rolled out within 100 days of the emergence of new pathogens. Research and commercial development puts mRNA vaccines into widespread use for multiple infectious diseases.

## 10-YEAR HORIZON

**Exposome development**

Systematic studies allow the compilation of a full list of pathogens and other compromising agents that the average person is exposed to during their lifetime — their “exposomes”. Effective treatments exist for post-infection conditions like long COVID and ME/CFS.

## 25-YEAR HORIZON

**Pathogen index created**

A systematic global understanding of potentially dangerous pathogens in nature is compiled.

## 3.7.2 Zoonotic diseases

**The COVID-19 pandemic has demonstrated once again the risk from zoonoses: diseases that move from animals to humans. More zoonotic diseases will surely emerge in the coming decades due to human-animal contact, but it is unclear where such zoonotic outbreaks are most likely to happen. Pathogens can come from wild species — as with SARS-CoV-2, which originated in bats — or from domestic animals, as with MERS, which came from camels. Intensified farming systems create significant risk, as evidenced by the recent avian influenza outbreak.[12] While researchers have devised global risk maps showing regions of the world where the risk is highest, in practice the high-risk areas are too large to be practicably managed, so it is vital that we create more finely grained maps.**

Understanding the risk also requires a better understanding of the necessary conditions for inter-species pathogen transmission. For example, it is often hypothesised that the risk is greatest when humans push into a new area and thus come into first contact with species whose pathogens might evolve to use humans as hosts. However, often when humans move into a new area they degrade wildlife habitat, driving out or exterminating many animal species. This might reasonably be expected to reduce the risk of a disease crossing over. Understanding human-animal ecosystem interactions is thus likely to be key.

A vital part of this will involve data-sharing and integrated practice in human and animal health research and treatment. At the moment, human and animal researchers tend to work in parallel, with little contact across the divide. Given the threat of zoonotic disease, this situation is not conducive to the prevention of future outbreaks. More use also needs to be made of social and anthropological science, and local knowledge and insight, especially when resulting from “citizen science” projects, although progress is being made in these areas.[13]

### 5-YEAR HORIZON

**One Health comes closer**

Data demonstrates the benefit of treating human, animal and environmental health together via vaccination and other tools that address the drivers of spillover events.

### 10-YEAR HORIZON

**Risk maps developed**

Fine-grained risk maps of pathogen prevalence that include data on human, animal and environmental factors are developed, illustrating which regions have the greatest potential for zoonotic crossover.

### 25-YEAR HORIZON

**Rabies eliminated**

Rabies is eliminated in Africa through a mass vaccination programme. Integrated One Health surveillance of diseases and drivers of spillover becomes standard practice.

## 3.7.3 Vector control

**Around 80 per cent of the world's population is at risk from infection by viruses or parasites transmitted by vector organisms like mosquitoes, ticks and fleas. These vectors transmit the disease directly into a person's body, often by biting them. Gaining a measure of control over these vectors could have significant benefits for global health.**

A number of emerging tools can directly control vector organisms. For example, altering the gut microbiome of mosquitoes or tsetse flies can make it impossible for them to host the parasites responsible for disease development in humans.[14]

Similarly, genetically modified *Aedes aegypti* mosquitoes have been released in Florida, carrying a gene that kills females in the larval stage.[15] The mosquitoes carry a range of diseases including Zika, but it is hoped that the female-lethal gene will spread and cause the population to dwindle, reducing transmission of the pathogens.[16] Previously, trials have used mosquitoes infected with Wolbachia bacteria, which have successfully reduced the transmission of dengue.[17]

Alongside these control mechanisms, we need to develop indicators of ecological health that influence disease risk: essentially, early-warning systems for outbreaks. A crucial step in devising such systems will be to integrate surveillance of human and animal diseases.[18] At present these are monitored separately, often by distinct agencies.[19]

### 5-YEAR HORIZON

**Success in mosquito control**

Field experiments demonstrate that mosquito populations can be controlled by releasing individuals that are genetically or otherwise modified. Biologically modified vectors reduce mosquitoes transmitting diseases such as dengue fever.

### 10-YEAR HORIZON

**Synthetic biology harnessed**

These methods are validated on other insect-borne diseases — such as Zika and chikungunya. The tools of synthetic biology, including genetics, are in widespread use to control vector organisms.

### 25-YEAR HORIZON

**Vector microbiomes put to work**

Affected countries experience drastic cuts in annual cases of vector-borne diseases, while climate change moves outbreaks north. Researchers learn how to disable or destroy vector organisms through action on the microbiome.

## 3.7.4 Outbreak prevention

**The best way to deal with a pandemic is to stop it happening in the first place.[20] Preventing major outbreaks is possible but will require several major shifts in practice.**

A key research challenge is to understand how outbreaks arise and ultimately to predict them. It is therefore crucial to study each disease in the multiple species it infects and to track it as it moves from one to another. Alongside that, we must gather genomic data so that outbreaks can be traced back to their sources — which can then be monitored.

This information can then be harnessed to predict outbreaks and to rapidly detect them when they occur. Better surveillance and early-warning systems are essential. It will be important to develop cheap, effective and easy-to-use rapid testing tools, ideally able to detect several pathogens with one test. This will be particularly relevant in communities where human and animal populations are in regular close contact.

Our preventative strategies will be most effective if we approach human health in more social-ecological terms. For instance, changing animal husbandry practices will slow down the reshuffling of pathogen genetics and reduce the chances of generating new zoonotic diseases. One framework for this type of approach is One Health, which aims for cross-disciplinary work integrating human health, animal health and environmental health.[21] There is also a framework called Planetary Health, formally launched by the Rockefeller Foundation and *The Lancet* in 2015.[22] This draws on the concept of "planetary boundaries" that should confine human activity. The exact definitions of these concepts are not fully agreed, and it is not clear which provides the better framework, but there is a clear complementarity, and the overarching concept is widely agreed to be a desirable framing for the future of public health.

Alongside this, there is an urgent need to redevelop and modernise public health systems in the face of the threat from infectious disease.[23] In many developed countries there has been considerable focus on developing pharmaceutical and hospital treatments. But while these are obviously essential, they are only part of the picture. For example, many countries have poor capabilities for testing and contact tracing, and their welfare systems do not provide adequate support for containment measures such as self-isolation.[24]

### 5-YEAR HORIZON

**Drivers of disease emergence are tamed**

State agencies roll out improved ventilation and air-filtration systems in key risk areas such as hospitals and animal markets. Large-scale genomic testing of pathogens enables the tracing of outbreak sources. There is global reform of animal markets and other human-animal contact sites to reduce drivers of disease emergence.

### 10-YEAR HORIZON

**Public health systems strengthened**

Aware of previous shortcomings, governments build greater capacity and resilience into public health systems. One Health approaches are integrated into mainstream medicine and public health.

### 25-YEAR HORIZON

**Early warning system established**

An integrated global pandemic early-warning system is established, based on a combination of disease surveillance in both humans and animals, ecosystem monitoring (including land-use change and biodiversity), and tracking of human-animal contacts.

INVITED CONTRIBUTION

# Fungal Pandemics

**Leah Cowen**
Professor of Molecular Genetics at the University of Toronto

**Joseph Heitman**
James B. Duke Distinguished Professor and Chair, Molecular Genetics and Microbiology at Duke University School of Medicine

MORE INFORMATION:

go.gesda.global/3-IC-1

**It may not attract much attention in everyday life, but the fungal kingdom has a remarkable breadth and depth of impact on human and environmental well-being.**

Fungi are integral to health, agriculture, biodiversity, ecology, manufacturing and biomedicine. They are Earth's pre-eminent degraders of organic matter, are among the best-characterised model systems for biomedical research and produce enzymes crucial for fermentation, food production, bioremediation and biofuel production. Fungi have also made invaluable contributions to medicine: they produce a phenomenal diversity of chemicals that we have found uses for as antibiotics, immunosuppressants that make organ transplants possible and drugs that reduce the risk of heart disease.

But while there is still much to be learned about the potential benefits of fungi, they also have detrimental aspects that need to be addressed. Novel infectious diseases caused by fungi are on the increase all over the world, just as they are for other microbes (such as zoonotic viruses) — but fungi are responsible for an increasing proportion of emerging-disease alerts across humans, plants and animals, possibly because as eukaryotes they are more closely related to their host animals and plants than bacteria or viruses are, and thus more difficult to treat. This has grave consequences:

- **Fungi have a staggering impact on human health**. Of an estimated 6 million species of fungi, more than 200 are closely associated with humans. They may live on us harmlessly, form part of our microbiome or, as pathogens, cause infectious and sometimes lethal diseases. These pathogens (including *Candida, Aspergillus*, and *Cryptococcus* species) currently infect billions of people worldwide and cause more than 1.5 million deaths per year — on a par with prominent bacterial and protozoan pathogens, such as those that cause tuberculosis and malaria.[12]

- **Fungi are a serious threat to global food security**. Crop-destroying fungi have been a threat to humanity since the agricultural revolution. Diseases caused by fungi and oomycetes have led to the starvation of populations, ruination of economies and decimation of landscapes. Such diseases have been increasing in severity since the mid-20th century: emerging fungal diseases now pose an unprecedented threat to global food security and ecosystem health,[3] by causing epidemics in staple crops that feed billions and producing toxins that contaminate food supplies and cause cancer. The future will bring new variants of old foes, movement of old adversaries to new areas and entirely new fungal diseases.[4] Further, there is alarmingly open scope for fungi and their toxins to be deployed as biological weapons.

- **Fungi cause rapid species extinctions and loss of biodiversity**. It is unlikely that there is a single animal on the planet that has not been parasitised by fungi, and animals are also subject to novel and re-emerging diseases. Several fungal species have recently become notorious for causing emerging infectious diseases which have led to massive die-offs, population declines and, in some cases, species extinctions. For example, *Batrachochytrium dendrobatidis* (*Bd*) and B. *salamandrivorans* (*Bsal*) cause devastating skin infections in amphibians. *Bd* has contributed to the decline of 6.5 per cent of amphibian species — the greatest documented loss of biodiversity attributable to any one pathogen.[4] *Pseudogymnoascus destructans* causes white-nose syndrome, which has killed millions of North American hibernating bats: mortality can exceed 90 per cent. We have historically been concerned about the emergence of novel diseases from wildlife reservoirs, but novel disease also threatens wildlife conservation and ultimately global biodiversity.

The fundamental challenge in tackling these problems associated with fungi — which is also the fundamental challenge when it comes to harnessing their enormous potential benefits — is to understand the unique facets of their biology that are responsible for their remarkable properties. Currently, science is at an inflection point and uniquely positioned to dramatically accelerate the pace of discovery, thanks to advances in genomics, genetics and the identification of pathogens. However, this acceleration is contingent upon bridging the gaps between research focusing on humans, plants and wildlife. These have traditionally been disparate disciplines, and while there have been seminal discoveries within each, it is now exquisitely clear that an interdisciplinary approach is crucial because solving these challenges is multi-faceted, necessitating a One Health Perspective. We have yet to leverage fundamental discoveries on novel targets required for fungal stress survival to develop a new class of antifungal drug (it has been over 20 years since the last new class was introduced), to develop a vaccine to prevent fungal disease or to develop a resistance-evasive strategy to protect crops from devastating pathogens. That could change if the science focuses on:

- **Understanding the forces driving the emergence, evolution and spread of fungi** including the integration of mathematical models, genetics, genomics and population biology at multiple temporal and spatial scales.

- **Identifying mechanisms of fungal adaptation and interactions with hosts and other microbes** by understanding microbiomes and interspecies interactions through genomic analysis and other approaches, including novel types of tissue, organoid and animal models.

- **Understanding the evolution of resistance to fungicides and antifungals across the fungal kingdom**, including field studies to understand where, how and why resistance develops in farm settings, composting and in patients.

- **Developing novel strategies to thwart fungal disease** including chemical genomics, functional genomics, experimental evolution, small-molecule and natural product screening, and, ultimately, structure-guided drug design.

Addressing these challenges successfully over the next 5 to 10 years could have major implications for the planet. In the context of global health, it is estimated that 1.6 million lives could be saved; in the context of agriculture, sufficient food could be salvaged to support over 8 per cent of the world's population; and in the context of biodiversity, new treatment and protective strategies could be developed alongside agricultural practices that would minimise crops' vulnerability to fungal pathogens.

But improved understanding of the fungal kingdom would contribute to addressing some of humanity's and the planet's grandest challenges. Fungi could solve the world's plastic crisis by targeted degradation both in the environment and in recycling and treatment plants; better control of fungal pathogens that affect trees would increase the biomass available for the absorption of $CO_2$ and better understanding of the role of fungi in our own bodies could help us tackle widespread and persistent health issues, such as autoimmune disorders and gastrointestinal conditions. The challenges posed by fungi are significant and urgent; the benefits they offer are too.

PANDEMIC

# Eco-augmentation: Shaping the Future of Social-ecological Systems

CO CHAIRS:

**Eric Desjardins**
Associate Director of the Rotman Institute of Philosophy; Associate Professor of philosophy at Western University.

**Orit Halpern**
Lighthouse Professor and Chair of Digital Cultures at Dresden University of Technology

**Emma Ruttkamp-Bloem**
Professor and head of the Department of Philosophy, Faculty of Humanities at the University of Pretoria

**Manuel Gustavo Isaac**
Senior Programme Manager, Science Anticipator at GESDA

CONTRIBUTORS:
**Vincent Block, Hayley Clatterbuck, Alyne Costa, Henry Dicks, Maria Paula Diogo, Laÿna Droz, Freya Matthews, Sahotra Sarkar, Kim Sterenly, Leslie Paul Thiele**

An expanded version of this essay can be found at:

go.gesda.global/3-Lens

**The current state of the planet, marked by climate change and biodiversity loss, presents one of humanity's most urgent challenges, further exacerbated by a projected population increase to nearly 10 billion by 2050. Scientific and technological advancements are vital for monitoring and mitigating these issues, offering solutions for humanity to coexist with a changing planet in a sustainable way. In this spirit, the third platform of GESDA's Science Breakthrough Radar® provides an overview of trends and breakthrough anticipations in Eco-Regeneration & Geoengineering over 5, 10, and 25 years, including critical strategies such as Decarbonisation, Earth Systems Modelling, Ocean stewardship, Solar Radiation Modification, and Future Food Systems to ensure nutritional security for all. Amidst these efforts to sustain the planet's health while adapting to accelerating global change, the 2024 Philosophy Lens zeroes in on eco-augmentation.**

GESDA defines eco-augmentation as "humans' deliberate and strategic interactions with nature for more resilient and sustainable social-ecological systems". Thus defined, this concept aims to serve as a platform for the sciences that navigate the fine balance between repairing and enhancing natural systems, focusing on three primary dimensions:

- "Reading and writing ecosystems" captures technological advances in synthetic biology, gene-editing and ecological modelling to monitor, understand, and manipulate ecosystems.

- "Transitioning ecosystems" refers to the constant flux in ecosystems, which must be understood and managed to maintain their good functioning.

- "Hacking co-evolution" means steering the evolutionary dynamics between human societies and natural ecosystems toward beneficial outcomes.

Central to eco-augmentation are questions combining normative and descriptive aspects, such as: why and how should we "augment" nature? For whose benefit is this augmentation intended? Which elements of natural systems should be chosen for augmentation? Such questions probe into the intrinsic, relational and instrumental values of nature underlying eco-augmentation, which will depend on whether the chosen framing is, for example, conservation, restoration or recreation. The perspectives of different stakeholders, whether ecocentric, biocentric, zoocentric or anthropocentric, and the nature of the ecosystems involved are also crucial in this context.

Altogether, these dimensions form the conceptual landscape of eco-augmentation, the subject of this year's Philosophical Lens. To do so, we will focus on the three fundamental questions driving GESDA's anticipation of scientific and technological advancements for an inclusive and global sustainable future:

- Who are we, as humans?

- How can we all live together, as societies?

- How can we ensure the well-being of humankind and the sustainable future of our planet?

These questions will guide our analysis of the key notions at stake in eco-augmentation — namely, humans, nature and their interactions. Environmental philosophy will play an instrumental role in our analysis, characterised as a hybrid discipline that draws on the philosophy of science, epistemology and ethics to examine fields that range from conservation biology to synthetic biology via restoration ecology.

In this process, our approach will be honest knowledge brokering: while mapping the key notions at stake in eco-augmentation, we will always strive for value-neutrality, acknowledging that every position is laden with values without taking a stance. Thereby, we will seek to open the solution space of action and opportunities for society and decision-makers, enabling them to "use the future to build the present."

## Humans and nature

In eco-augmentation, humans are "humans-in-nature", so we should begin by examining the roles and identities of humans within the Anthropocene and the evolving concept of nature, asking: "Who are we, as humans?" and "What is nature?"

First, the human aspect. Eco-augmentation is deeply rooted in the concept of the Anthropocene, a term first coined by Dutch meteorologist Paul J. Crutzen at a meeting of the International Geosphere-Biosphere Programme (IGBP) in February 2000. "Anthropocene" acknowledges the distinct impact that humans are having on the environment, evident in measurable changes such as global warming and biodiversity loss. In so doing, it challenges traditional dualisms about humans, nature and technology, and fosters cross-disciplinary collaborations that span different timescales, from Earth-system science and geology to social sciences and humanities.
As "geobiophysical" transformative agents in the Anthropocene, humans possess unprecedented abilities to shape and sustain new social-ecological environments. This transformative power, coupled with cultural and technological advancements, positions us as the Earth's "ultimate ecosystem engineers", for better or worse. A critical dilemma therefore arises: should we harness or restrain our own human nature? Addressing this dilemma is crucial for responsible eco-augmentation.

Conflicting visions vie for the future Anthropocene, varying from ecomodernist techno-utopism to convivialist degrowth. While the idea of a "good Anthropocene" might still sound like an oxymoron, it can serve as an aspirational goal for transforming human-nature relationships. This will be key for a sustainable living-together in eco-augmentation.

We can now turn to the question of nature. The concept of "nature" is imbued with various meanings and values across cultures and times. Recognising the sociocultural and historical frames that influence how we perceive and relate to nature will prove another essential step in eco-augmentation.

Conceptualisations of nature across cultures generally cluster into three perspectives:

- an inclusive universe where humans are integral parts of nature
- an exclusive environment where humans are separate from nature
- a deified nature with spiritual dimensions

The notion of nature as a static, passive and exclusive environment remains largely a Western exception to global cultural norms. The more prevalent view is of anthropogenic nature, a dynamic and active space shaped by humans. These varying perspectives intersect with how societies value nature, across a spectrum ranging from intrinsic values, where nature is valued for its own sake, to instrumental values, where nature is valued for its utility to humans, via relational values, which emphasise meaningful relationships between humans and nature.

Understanding these diverse cultural conceptualisations and values is again essential when engaging in eco-augmentation practices. Environmental policy frameworks have indeed long rested on a monocultural dichotomy-based conception of nature, unsuited to manage Anthropocenic uncertainties about unpredictable futures. In eco-augmentation, new conceptions of nature are therefore needed. Shifting away from stability to resilience will be crucial.

## Ensuring the future of our planet

Once humans and nature are in place, we can turn to their relationships, asking “How can we ensure the well-being of humankind and the sustainable future of our planet?”

Eco-augmentation targets the coupled dynamics of human sociocultural systems and natural ecological systems. These social-ecological systems are characterised by emergence, where self-organisation among heterogeneous components leads via complex processes to new system-level properties, behaviours and capacities. Feedback between the sociocultural and environmental elements leads to the reciprocal adaptation of both. This process of co-evolution fosters resilient and sustainable systems in the face of ongoing change. Previous views of nature have assumed it to be teleological, mechanistic or deterministic — designed or directed towards a particular, defined set of outcomes. The social-ecological co-evolutionary perspective, on the other hand, takes a view that is open-ended, non-deterministic and inherently unpredictable.

A key driver for such a co-evolution is social-ecological niche construction. Niche construction is the process by which organisms modify their environment in ways which alter the evolutionary selection pressures acting on them. In the context of social-ecological co-evolution, it emphasises causal interrelationships between sociocultural and environmental processes across three dimensions:

- social-ecological causation, which focuses on the symmetric dynamics of niche construction
- social-ecological inheritance, which encompasses parallel inheritance mechanisms within ecological, social-ecological and sociocultural systems
- cross-social-ecological indirect effects, which consider how distant niches influence one another globally

These dimensions highlight ethical considerations of interspecies, intergenerational and intragenerational justice, which further increase as the scale and scope of humans’ activity exceeds our niche construction capacities, potentially leading to self-destruction and social-ecological lock-ins.

In the context of eco-augmentation, niche construction aimed at serving human needs will have to be redirected to serve “others” in addition: “regenerative niche construction”. The key will be hacking social-ecological dynamics through purposefully engineered and self-reinforcing feedback loops that have high-level transformative impacts. Fostering social-ecological co-evolvability will help guide disruptions toward more resilient and sustainable social-ecological systems.

**Deliberate and strategic interactions**

At its core, eco-augmentation consists of strategic and deliberate interactions between humans and nature, combining various strategies to build resilient and sustainable social-ecological systems. These interaction-management strategies reflect varying intensities of human involvement, from observers to participants, stewards and engineers.

Conservation, preservation, restoration and rehabilitation are common interaction management strategies, each with distinct views, ideals and objectives. For example, conservation adopts a “hands-off” approach, protecting nature for its intrinsic value; preservation allows limited human intervention for long-term benefit. Restoration focuses on recovering specific species or ecosystems, whereas rehabilitation aims to restore ecosystem functions.

To manage the unpredictability of emergent social-ecological systems, resilience-driven interactions are increasingly favoured over traditional command-and-control approaches, based on the human-nature dichotomy and leading to vulnerable ecosystems. This paradigm shift emphasises dynamic and adaptive ecosystem-management practices centred on learning and experimentation, aligning with the above view of globally integrated social-ecological systems.

**Resilient and sustainable systems**

Two criteria have typically guided ecosystem-management strategies: historical fidelity to some idealised past condition and ecological integrity focused on robust ecosystem functioning. These criteria are challenged by Anthropocenic eco-augmentation, where technological intervention blurs the lines between fixing and enhancing ecosystems. There are no historical precedents for the resulting novel ecosystems, which can differ significantly in composition from previous systems. Nor are there necessarily readily applicable benchmarks for their functioning. Novel ecosystems thus provide unique opportunities to rethink human-nature interactions. Eco-augmentation efforts must be guided by values, carefully chosen to realise the ultimate goal of eco-augmentation: resilient and sustainable social-ecological systems. Human natural values such as ecosystem services and biodiversity can promote the expected resilience and sustainability.

Resilience captures how systems persist and thrive amidst change. It can take two forms. Engineering resilience focuses on recovery to a steady state within a single stable equilibrium. Social-ecological resilience emphasises robustness to perturbations and continuous development within multi-stable equilibria: this is the appropriate target for eco-augmentation. Relying on diversity and redundancy to enhance self-organisation and adaptability, it prioritises the ability to adapt to current changes and challenges, while preserving the potential to transition to new forms in future.

Sustainability also requires a new construal in the context of eco-augmentation. Traditionally centred on interhuman relationships across time, it will benefit from shifting toward valuing relationality with the environment and interconnectedness across life forms. In this spirit, multi-species sustainability qualifies best, treating non-humans as agents with negotiable needs and interests to ensure the well-being of all for both current and future generations.

Eco-augmentation thereby invites us to move beyond “centric” thinking — whether eco-, bio-, zoo- or anthropo-centric — to the relational habitability of the planet, acknowledging non-human agency to support mutually beneficial evolutionary feedback. The resulting multi-perspectival planetary thinking will position humans as mediators within complex networks of interdependent relationships, materialising environmental justice across species and generations in such a way that human natural and cultural values can only be pursued together.

## Living all together

As all the components, dimensions and relationships concerned with eco-augmentation have been covered, our remaining question is **“How can we all live together?”** in eco-augmentation, with a focus on the two spheres that make our collective life in human societies: the technosphere and the sociosphere.

The technosphere encompasses the technological environment created by humans, shaping and sustaining new social-ecological systems. From this perspective, a key challenge is to move beyond the traditional differentiation of humans, nature and technology to conceptualise how technology informs and affects human-nature interactions within the Anthropocene.

Technology is not merely a human construct: humans are also products of technological evolution. Likewise, nature serves as a model for technology while technology shapes our understanding of nature. Consequently, nature for eco-augmentation technologies cannot be reduced to an object of knowledge but should also be treated as a model to mimic. The resulting natural-technological hybrids will be endowed with autonomous agency and independence together with an element of unpredictability and uncertainty — mirroring the resilient and sustainable social-ecological systems they proceed from.

However, this reciprocal mimesis between technology, humans and nature operating with eco-augmentation in the Anthropocene can lead to an anthropomorphising technological determinism, disempowering humans who either reject any responsibility in shaping the social and natural worlds, or else endorse a narrow-minded technosolutionism that focuses on treating Anthropocenic symptoms rather than the causes.

In this context, eco-augmentation acts like a powerful technological "pharmakon", associating the unprecedented opportunities of altering **"the fabric of non-human life"** with the risk of unintended detrimental and potentially irreversible consequences. Retaining ownership and control over these technologies through new forms of governance will be crucial to repurposing them toward resilient and sustainable futures.

The sociosphere is the sociocultural context within which eco-augmentation takes place, encompassing governance, policy and practice. Achieving resilient and sustainable futures necessitates radical transformations in the sociosphere through new imaginaries for technoscientific governance. Participatory methods, such as constraint-based scenario planning, will help foster the societal imagination needed to shape the future and improve decision-making under uncertainty, by enabling appropriate identification of resilient and sustainable policies. Combining bottom-up scenarios of local changes (often more achievable and controllable but hard to scale up) with top-down, global frameworks for comparing worldviews will be essential to effectively drive eco-augmentation governance.

Eco-augmentation governance, in turn, requires proactive management of change through multi-stakeholder collaboration, balancing short-term adaptive decisions and actions with long-term transformative visions. The main challenge here remains to bridge the "knowing-doing" gap, with many environmental assessments failing to translate into actions. Engaging local practitioners with scientific research to match ecological priorities with social opportunities through knowledge co-production and co-learning is therefore crucial. To do so, eco-augmentation must evolve towards interdisciplinarity, integrating ecological and social approaches via mutual translations, if it is to influence the global trajectory of the Anthropocene.

Overcoming this science-society-policy divide will ultimately culminate in global inclusive diversity, which reconciles Indigenous, local, traditional and scientific ecological knowledge systems across cultural, ontological and linguistic variations. Frameworks for equitable knowledge-sharing environments, like the **"multiple evidence base"** approach, can encourage epistemic cross-fertilisation between stakeholders in different positions of power, while marking a key opportunity for technoscientific diplomacy to represent those disempowered. Once crystallised into legitimate, credible and salient knowledge, global inclusive diversity will enhance the adaptability and transformative capacity needed in eco-augmentation for more resilient and sustainable social-ecological systems.

CONFERENCE PROCEEDINGS

# Keeping Check on Earth's Vital Signs

## 3.1 Decarbonisation

From real-time monitoring of greenhouse gases to modelling the impacts of biodiversity loss, having the right tools to track the current and future health of our planet is critical if we are to remain within safe boundaries. What steps need to be taken to ensure more accurate, integrated and routine tracking of Earth's systems and protect the health of our planet for generations to come?

PARTICIPANTS
Moderated by:

**Anousheh Ansari**
CEO, XPRIZE Foundation

With:

**Johan Rockström**
Director, Potsdam Institute for Climate Impact Research

**Lars Peter Riishojgaard**
Director of Greenhouse Gas Monitoring, World Meteorological Organization

**Dominic Waughray**
Executive Vice President, Climate, Nature and Tackling Inequalities Imperatives, World Business Council for Sustainable Development

MORE INFORMATION:

go.gesda.global/3-1-Diplomacy

TAKEAWAY MESSAGES

*"Despite accurate predictions, events, such as Hurricane Katrina and the European floods in 2002 and 2005 respectively, demonstrate failures in persuading people to heed forecasts and in coordinated decision-making and preparation by nations, even in developed countries."*

*"Over the past 60 years, $CO_2$ concentrations in the atmosphere have rapidly increased from 320 to 420 parts per million, an unprecedented rise over the last 2 to 3 million years. Scientists face challenges in understanding the fate of $CO_2$ absorbed by the ocean, land and atmosphere, highlighting the urgent need for real-time global monitoring."*

*"The World Meteorological Organization's Global Greenhouse Gas Watch, initiated in 2023, aims to provide sustained, routine monitoring of $CO_2$, methane and other greenhouse gases globally. This information is intended to empower negotiators at UN climate summits and compel parties to take action against climate change."*

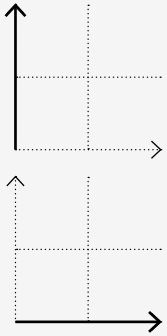
*"Private-sector involvement in climate solutions requires navigating a geopolitical environment that is much more fractured than when the Paris Agreement was made in 2015. Large companies working to incorporate sustainable goals into their financial plans can use prototype science-based targets for nature but must first build up transition plans, end-to-end value chains for accounting or disclosure mixes."*

*"Earth's stability and resilience are quantified through a planetary boundaries framework. Of the nine identified boundaries, six have been transgressed, indicating critical degradation, such as the Amazon rainforest releasing more carbon than it absorbs. A global shift to net-zero emissions by 2050 is needed to avoid catastrophic consequences."*

# Media-Innovation Analysis

Comparing the growth in patents to the growth in news and blog coverage, Future Food Systems has seen the most growth as a topic in the media, but this is not matched by the pace of patent increase. Other topics, such as Solar Radiation Modification and Ocean Science, are not growing in terms of their presence in the media, but are nevertheless experiencing high levels of growth considering patents issued.

LEGEND:



**YoY PATENT GROWTH**
YoY (year-on-year) growth of granted topic patents[1] from May 2022/April'23 to May 2023/April 2024

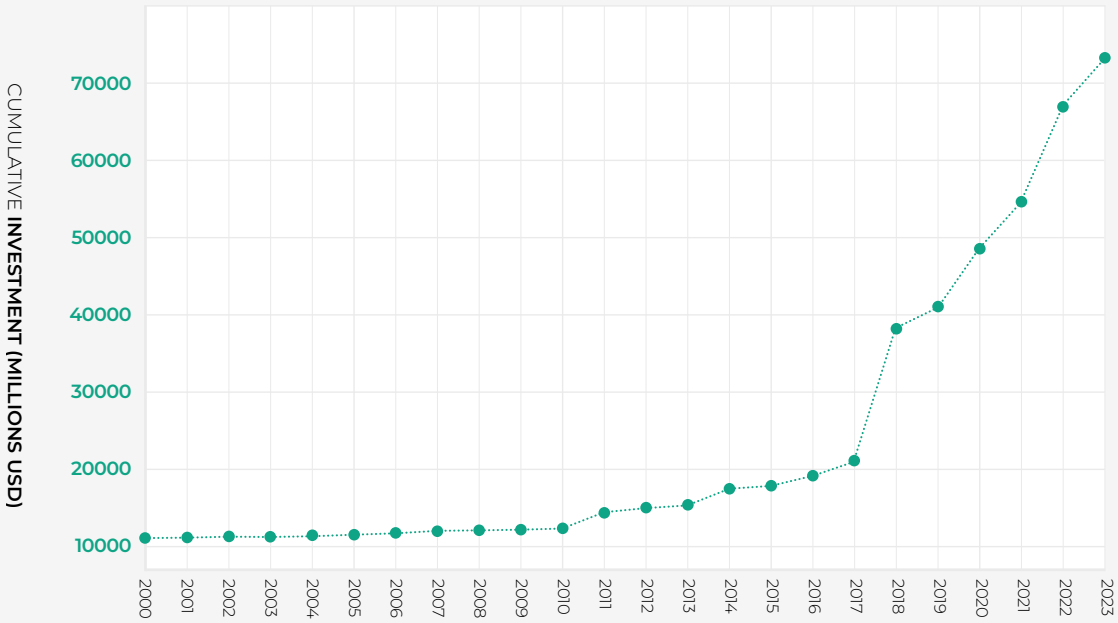
**YoY MEDIA GROWTH**
YoY (year-on-year) growth of topic mentions in news and blogs from May 2022/April'23 to May 2023/April 2024

MORE INFORMATION:

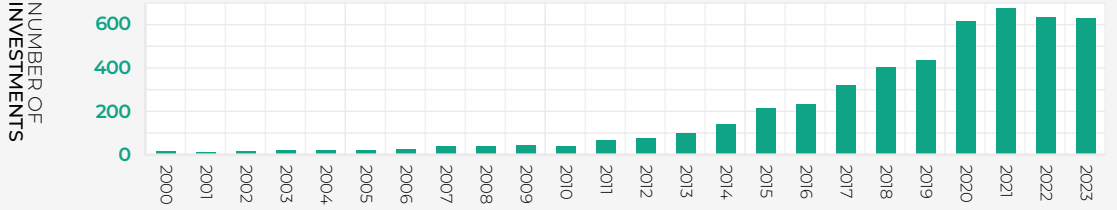
**go.gesda.global/Impact**

## MEDIA-INNOVATION MATRIX

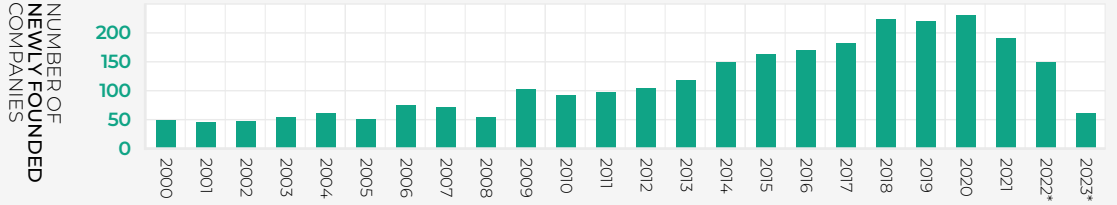
## CUMULATIVE INVESTMENT IN FUTURE FOOD SYSTEMS COMPANIES




## NUMBER OF NEW INVESTMENTS IN FUTURE FOOD SYSTEMS COMPANIES




## NUMBER OF NEWLY FOUNDED FUTURE FOOD SYSTEMS COMPANIES




IMPACT FOCUS:

# 3.3 Investment and Company Creation in Future Food Systems

Investments in the area of future food systems have increased exponentially during the last decade, propelled by a rapid acceleration during 2017. Furthermore, when compared with other science and technology-related domains in the Radar, cumulative investments in the area of future food systems are the highest over the surveyed period. Even though the rate of company creation in this area appears to be slowing, pressures from the changing climate and increased urbanisation mean that the field is likely to continue to draw large investments and interest from the private sector in the future.

Source, facing page: Deep View analysis from 1 May 2022-30 April 2024; (1) YoY media growth = YoY growth of topic mentions from May 2022/April 2023 to May 2023/April 2024; (2) YoY patent growth = YoY growth of granted topic patents from May 2022/April 2023 to May 2023/April 2024.

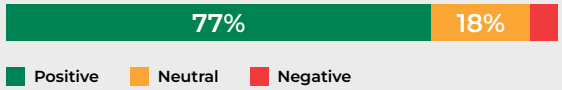
Source, this page: Pitchbook

*Data on newly-founded companies in 2023 is incomplete and will be updated once first funding is raised. Projections indicate similar levels of company creation to 2021.

## What do people say?

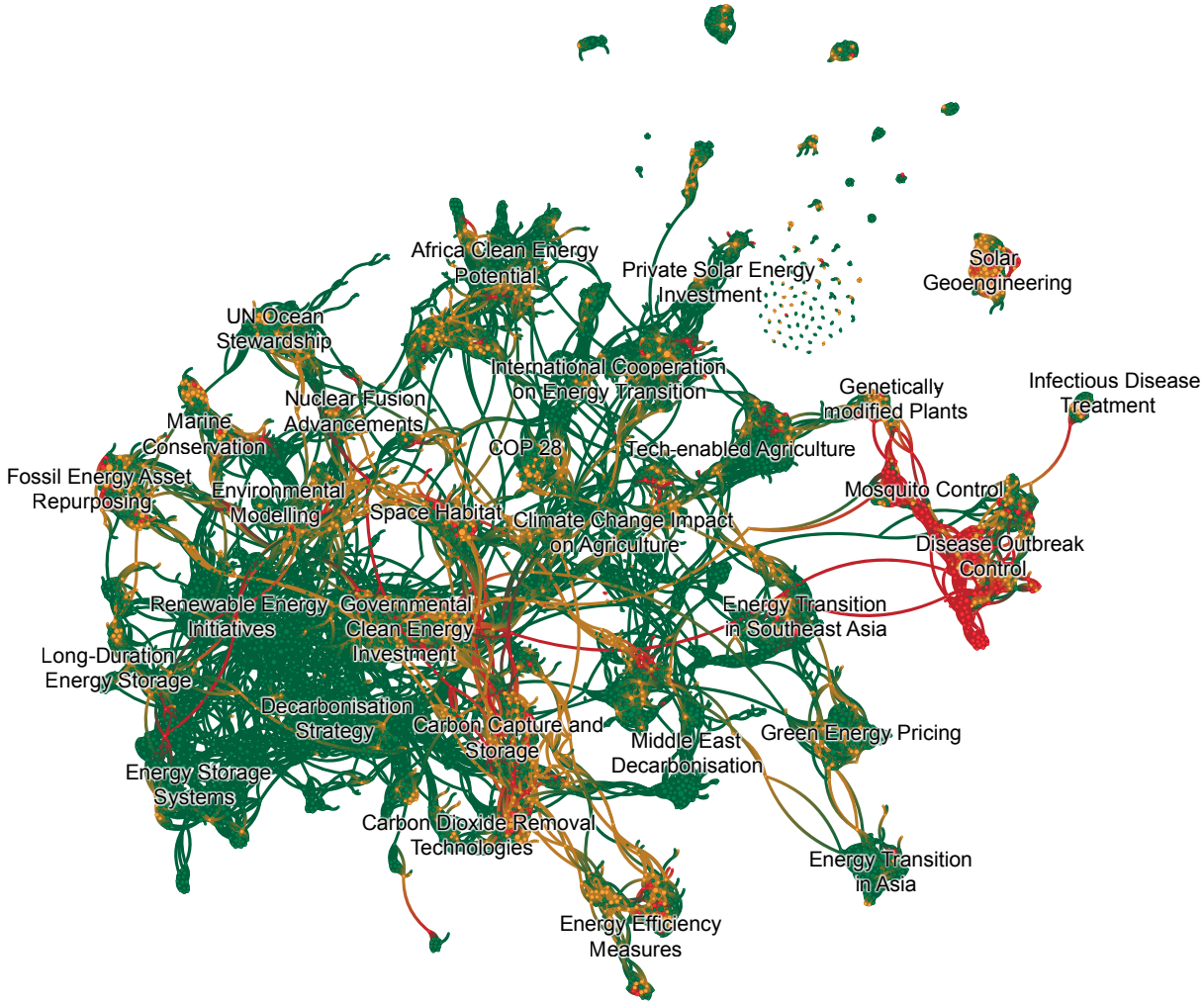
Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months shows that sentiment towards Eco-Regeneration & Geoengineering is predominantly positive, with a net sentiment of 88 per cent. This positive sentiment across all media outlets is being driven by initiatives promoting sustainable energy usage and agriculture.

MAINSTREAM MEDIA SENTIMENT

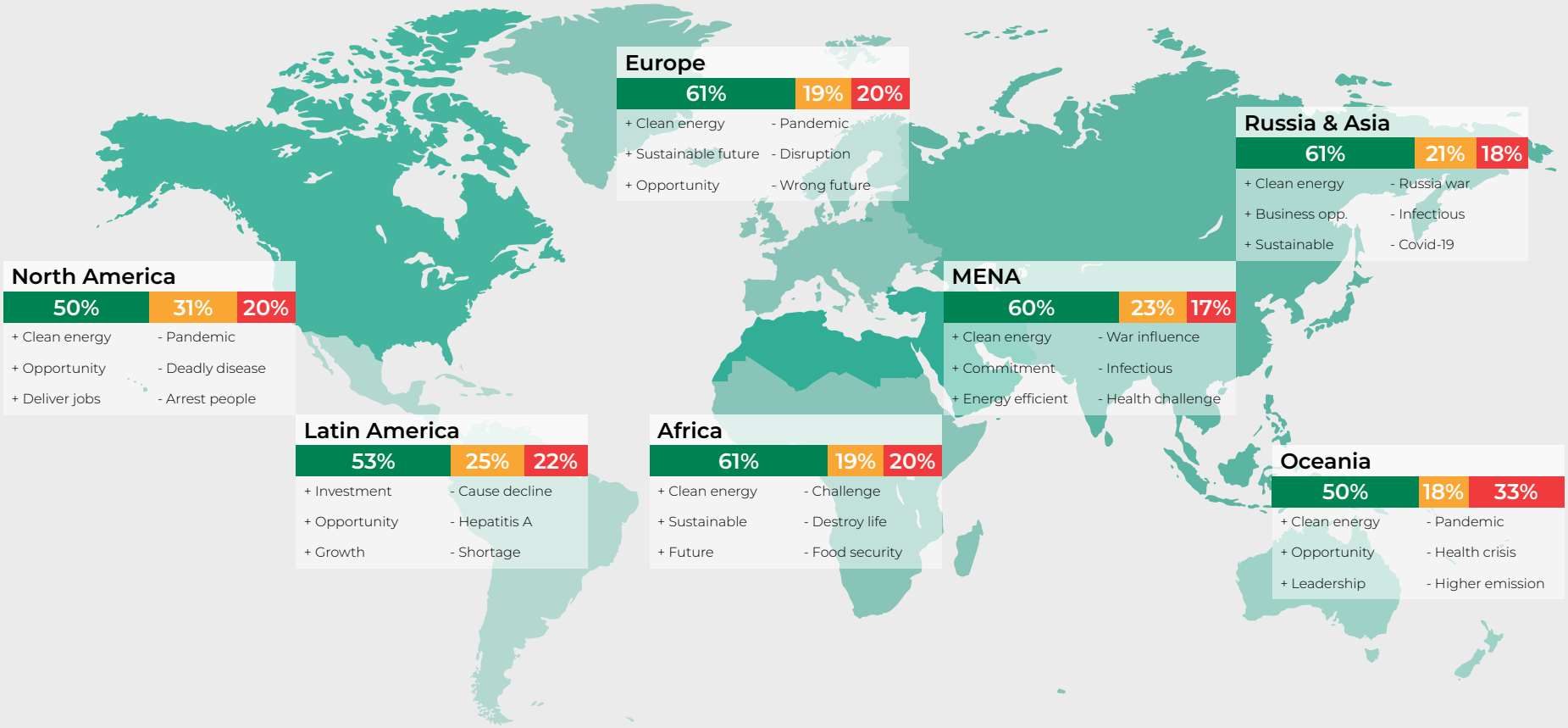



| MAINSTREAM MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| UNIQUE ARTICLES | 499k |
| VISUALISED ARTICLES | 5k |
| NET SENTIMENT | 88% |
| ARTICLE UNIQUENESS | 49% |

| SOCIAL MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| NUMBER OF POSTS | 8024k |
| VISUALISED POSTS | 10k |
| NET SENTIMENT | 31% |
| UNIQUE IMPRESSIONS | 478b |



## DEMOGRAPHICS & SENTIMENT PER REGION




## GLOBAL SENTIMENT

- The global sentiment surrounding **Eco-Regeneration & Geoengineering** is **broadly positive, particularly in Africa and the Russia & Asia regions**, where there is a strong perception of clean energy transformation as a growth lever.
- In contrast, views across **North America, Europe and MENA are more cautious**, focussing on perceived delays in the green transformation and concerns about the threat of infectious diseases, which contribute to a less optimistic outlook.
- The **discussion in North America** is largely dominated by the US, accounting for 91% of the conversation. In **Latin America and Russia & Asia**, most discourse is led by men, with notably low female involvement at 29% and 28% respectively.
- In **Europe**, the conversation primarily originates from the UK (54%), with Germany (10%) and Poland (3%) also contributing. **Africa's discussions** are led by Nigeria (34%), South Africa (20%) and Kenya (17%). In Russia & Asia, India dominates, with 59% of posts, followed by Pakistan at 5%. The **MENA region** sees Turkey (31%), the United Arab Emirates (18%) and Saudi Arabia (9%) as the primary contributors.

Source: Quid Social, containing the past 24 months of English language data from 10+ social media sources in 200+ countries.

# Media Analysis

GROWTH

The most dominantly discussed emerging topics around Eco-Regeneration & Geoengineering are Infectious Diseases and Decarbonisation, accounting for 83 per cent of all mentions, whilst Future Food Systems is growing the strongest.

DOMINANCE

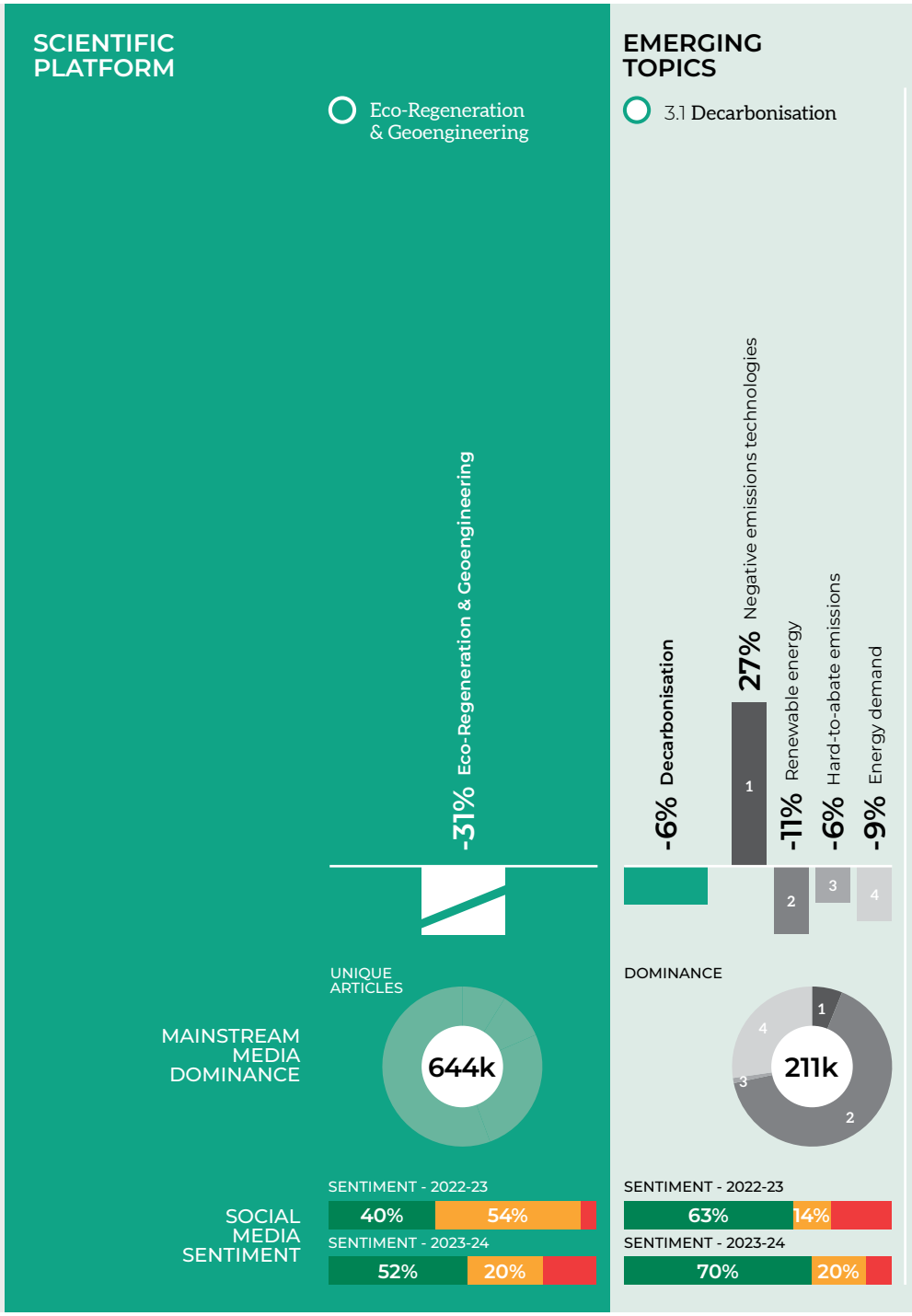
The global media landscape continues to focus on Decarbonisation, with a stable 211,000 articles, while coverage of Future Food Systems has steadily increased by 8 per cent, highlighting the ongoing relevance of the topic. Despite accounting for half of all mentions in Eco-Regeneration & Geoengineering discussions, public coverage of infectious Diseases continues to decline following the end of the spike in COVID-19 infections.

SOCIAL SENTIMENT

Comparing social media posts from 2023 with those from 2024, sentiment around Future Food Systems and Ocean Science became more positive, whereas negative perceptions regarding Infectious Diseases solidified.

MORE INFORMATION:

**go.gesda.global/Society**



## 3.2 Earth Systems Modelling




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 3.3 Future Food Systems




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 3.4 Orbital Resources




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 3.5 Ocean Science




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 3.6 Solar Radiation Modification




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 3.7 Infectious Diseases




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24

SCIENTIFIC PLATFORM

4

# Science & Diplomacy

The products of science and mathematics, such as vaccines, AI and systems for digital security and privacy, are increasingly recognised drivers of global health, engaged and active citizenship, and wealth creation. That gives science and technology a central role in multilateralism. Diplomats and policy-makers across the globe are thus ever more focused on understanding and using research breakthroughs, both to anticipate their impact on individuals, society and the planet, and to apply them in their own work. Here we provide insights into the ongoing research into key topics and capabilities in this field, including new approaches to modelling diplomacy, the future of prediction and foresight, methods to understand group behaviour, anticipated advances in digital security and an increasing impetus for futures literacy.

PULSE OF **SCIENCE** (pages 216-253)

Containing deep insights into anticipated advances in the relations between science and diplomacy over the next 5, 10 and 25 years, the GESDA Pulse of Science provides the expert opinions of leading researchers in topics such as digital security, futures literacy, group behaviour and science diplomacy.

PULSE OF **DIPLOMACY** (pages 254-257)

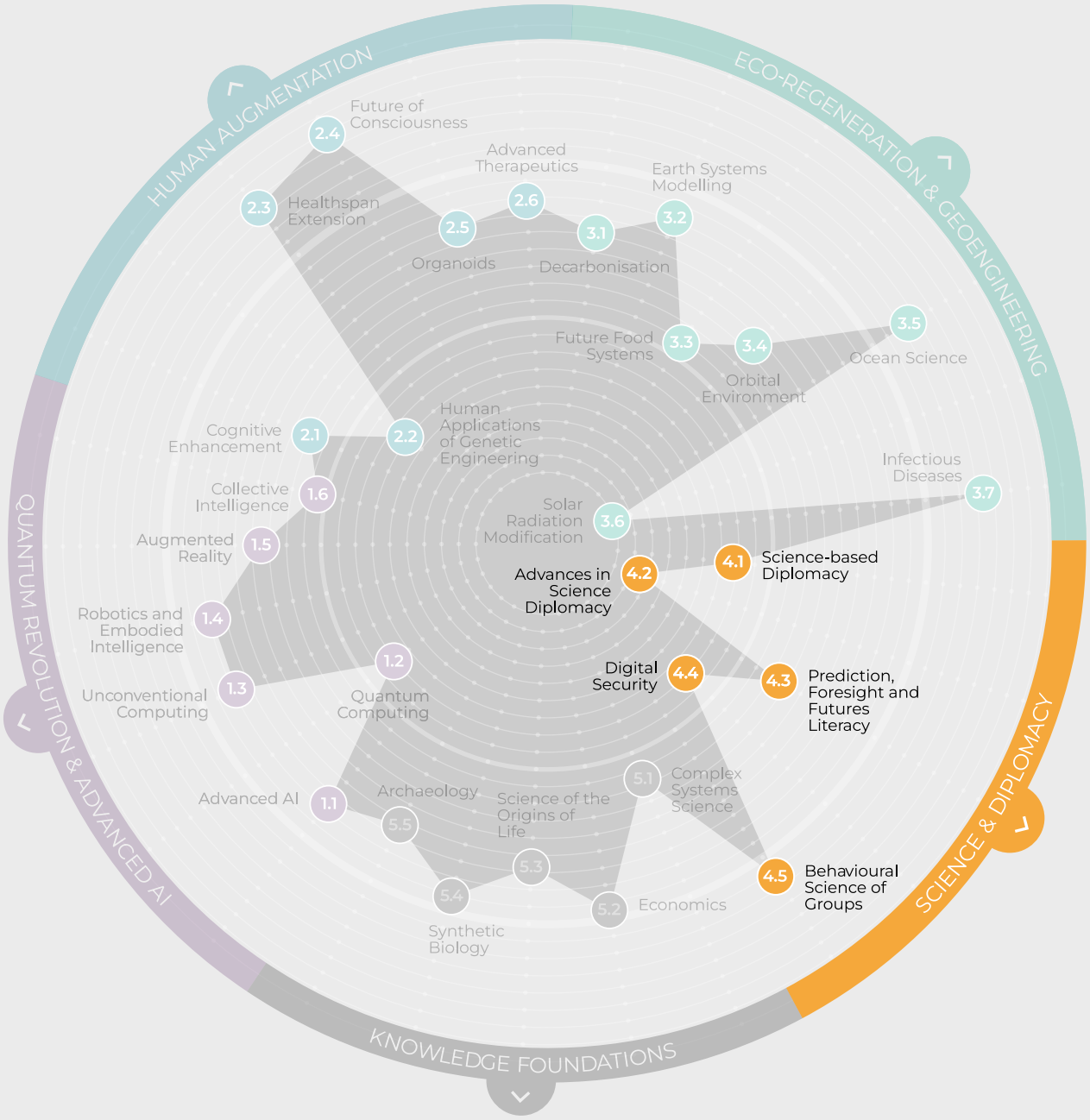
The GESDA Pulse of Diplomacy captures the latest discussions between diplomats and scientists at the 2023 GESDA Science and Anticipation Summit on topics such as predicting the onset of armed conflict, computational diplomacy and superforecasting.

PULSE OF **IMPACT** (pages 258-259)

Current investment trends and dynamics of company creation highlight digital security as an increasingly significant area. The GESDA Pulse of Impact provides data detailing private sector investment, intellectual property activity and company creation in the area of digital security since 2000.

PULSE OF **SOCIETY** (pages 260-263)

Powered by AI, the GESDA Pulse of Society's network and dynamic sentiment analysis of both mainstream and social media reveals macro and micro trends in public opinion around the world on topics relating to science and diplomacy.



4.1

# Science-based Diplomacy

CHAIR:
**Didier Wernli**
Associate Professor at the Global Studies Institute and the Department of Computer Science, University of Geneva

CONTRIBUTORS:
**Örjan Bodin, Lars-Erik Cederman, James Hollway, Rak Kim, Rafael Mesquita, Hannes Müller, Christopher Rauh**

**The "Scientification of Diplomacy" is based on interdisciplinary work between global governance, international relations, international law, computational social sciences, mathematics, optimisation theory and behavioural research. It covers different emerging fields of research, such as Computational diplomacy and Negotiation engineering.**

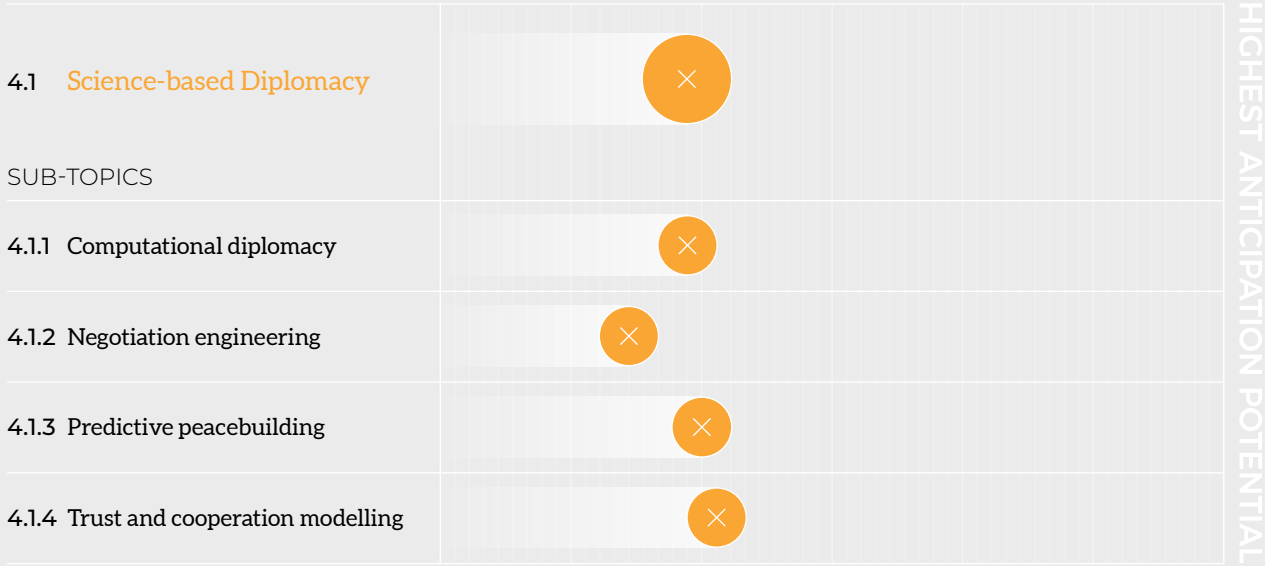
Computational diplomacy, for one, is concerned with our emerging ability to map the landscape of international relations, to gather and analyse data on unprecedented scales and to simulate potential outcomes. This has transformational potential for diplomatic activity. For instance, efforts have already begun to plot the networks of influence between actors on an international scale and to use artificial intelligence to mine the large databases of texts relating to historical negotiations and international organisations. As such, Computational diplomacy is revealing not only the complexity of modern international relations but the potential knock-on effects of future actions, giving opportunities to favour the emergence of desired outcomes. It also allows actors to better understand the history of negotiations, how changes in language reveal movements in position and to reduce uncertainty in formulating plans.

Negotiation engineering, on the other hand, is a solution-oriented approach to negotiation problems that uses quantitative methods in a heuristic way to find an adequate solution. The approach draws on breaking down and formalising the problem(s) at hand and on the heuristic application of mathematical methods such as game theory and mathematical optimisation. In this way, it can contribute to recognising feelings and better managing them during the negotiation process, as well as allowing for resolutions of more complex real-world issues.

KEY TAKEAWAYS

Researchers from a wide range of academic disciplines are collaborating to improve approaches to diplomacy through applying numerical, computational and other technical forms of understanding. **Computational diplomacy**, for instance, can exploit existing data to better understand past diplomatic achievements and the network structures that facilitated them. Also of interest is **Negotiation engineering**, which raises the possibility that future agreements will be informed by computationally derived understanding and will more successfully bring together broader groups of stakeholders in complex negotiations, while allowing progress with fewer missteps. Similarly, **Predictive peacebuilding** has potential to use machine-learning approaches to increase the chances of achieving greater international stability. **Trust and cooperation odelling** applies computational approaches to the task of establishing relationships that result in positive experiences of cooperation and collaboration while providing tools for distinguishing trustworthy from untrustworthy potential partners.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

The Anticipation Potential scores of the topics covered by Science-based Diplomacy are relatively similar. The main variable driving the scores is the uncertainty of future developments of the related fields. Predictive peacebuilding rates slightly higher because of the perceived positive impact it may have on society in the future.

MORE INFORMATION

**go.gesda.global/4-1**

## 4.1.1 Computational diplomacy

**The world of diplomacy is rich in data. The United Nations and other international forums have detailed records of debates, speeches and negotiations going back decades. Then there are databases recording demographics, trade, finance, spending and common declarations made by international organisations. Beyond these forums, important sources include records of human rights violations and other data used by international justice organisations.**

The cost of processing this data means it has not been well used to inform the process of diplomacy, to amplify cooperation and to improve outcomes. Nevertheless, organisations like the UN, the World Bank and other policy-makers are working hard to integrate quantitative methods into their organisations, which will accelerate the practice of Computational diplomacy and its use of big data, machine learning and computational thinking.

There is much low-hanging fruit here. The networks of actors on the international stage and their institutional relationships are already beginning to be mapped,[1,2,3] giving a deeper understanding of the connections that can influence negotiations. Also being mined for insight are resolutions adopted by various international organisations. Relevant examples include the UN General Assembly and Security Council resolutions histories,[4] sponsorship data[5] and debate themes, as well as the resolutions adopted by the World Health Organization.[6]

Much more can be done. Combining a data-driven approach with computational modelling can facilitate a more fundamental understanding of how multilateral governance systems work and how they can be improved, for example.[7] The growing use of AI is likely to have a significant impact here,[8] but developing the multidisciplinary expertise that can manage and exploit diplomatic processes is a significant challenge.

### 5-YEAR HORIZON

**Higher-education establishments broaden skill sets for scientists and diplomats**

Efforts to build capacity for computational diplomacy bear fruit in the form of an increased range of courses and training programmes across relevant disciplines. Predictive modelling improves at the sub-national level with AI systems providing natural-language translations of model outputs.

### 10-YEAR HORIZON

**Text-mining shows its worth on the global stage**

In helping to finalise the language in several major agreements and in helping to prevent "forum shopping" by several state actors, text-mining shows its potential and is set to become a standard tool in international negotiations. Predictive modelling becomes more fine-grained, with the potential for daily updates and a greater ability to predict the effect of policy changes.

### 25-YEAR HORIZON

**Computational diplomacy reshapes international relations as a science**

The successes with text mining and other data-driven applications allow experts to create a robust theory of diplomacy that makes testable predictions and creates useful frameworks for diplomatic interactions. Predictive forecasts become a ubiquitous tool for policy-makers, who will know in advance the effect of their actions and how they may inflame or cool tensions.

## 4.1.2 Negotiation engineering

**Negotiation engineering uses quantitative methods in a heuristic way to find an adequate solution to a set of complex negotiation problems. In doing so, it particularly draws on the decomposition and the formalisation of the problems at hand and the heuristic application of mathematical methods such as game theory and mathematical optimisation to reach agreement.[9]**

This approach could help to reveal the ingredients of success for global cooperation. Numerous non-governmental organisations in complex networks currently aim to solve complex problems such as climate change and the challenges related to Sustainable Development Goals. And yet they often achieve far less than they hope. A better understanding of the way organisations should interact to achieve specific goals could change this.

Negotiation Engineering has already achieved a number of practical successes. For instance, in the diplomatic sphere, the approach played a crucial role in the Land Transport Agreement between Switzerland and the European Union and in facilitating nuclear talks between Iran and the P5+1 group of nations.[10]

Negotiation Engineering does not intend to replace face-to-face discussion and neither does it seem likely to ever do so. It may in some cases also have limited application: not all problems are quantifiable or should be reduced to a quantitative level. However, in cases when a negotiation involves problems with a particular degree of complexity and actors with a certain level of analytical capacity open to a rational approach, Negotiation Engineering can allow for more logical accuracy in finding pragmatic solutions while building trust between mediators. To that end, significant capacity-building is required for future development.

### 5-YEAR HORIZON

**Capacity-building accelerates Negotiation Engineering**

The automated processing of text to make it machine-readable leads to more advanced models of areas of conflict. This allows stakeholders to map out and discuss potential futures before deciding on a course of action.

### 10-YEAR HORIZON

**Mathematical thinking focuses international discussions**

A new generation of scientists currently being trained in the grammar of computer science and in diplomacy become influential in the diplomatic world. That leads to an increasingly wide variety of international actors applying mathematical methods to their negotiation problems to help focus discussions and to make potential outcomes more logically accurate.

### 25-YEAR HORIZON

**Negotiating standards increase thanks to mathematical approaches**

Mathematical skills are common in positions of influence, allowing Negotiation Engineering to become a standard tool in many negotiations.

# 4.1.3 Predictive peacebuilding

**Predictive peacebuilding uses data science to better understand the roots and warning signs of conflict in order to predict where it is likely to occur and to help develop mitigation, preventative and rebuilding strategies.[11]**

The field has been bolstered by a number of successes. For example, machine-learning-based analysis of newspaper text can predict the onset of conflict, becoming particularly useful when risk in previously peaceful countries arises.[12] Analysis of food prices shows that increases beyond a threshold level are correlated with civil unrest in many parts of the world.[13] Granular, actor-based conflict data give rise to models that take these into account.[14]

Research in the field sees policies for conflict prevention — mediation, development aid, institutional reform and building state capacity, for example — as a prediction policy problem.[15] This means that the treatment effects of different policies, and the targeting of these policies in time and space, both need to be studied quantitatively. However, important limitations and potential pitfalls remain. Current conflict models have limited ability to make causal inferences and are sometimes informed by outdated data-gathering.

Even more serious is the possibility that predictive models can be self-fulfilling or self-defeating. For example, a prediction of war could cause local populations to flee, raising tensions that themselves trigger conflict. Also, care is needed in defining peace and ensuring that "peaceful" outcomes make a difference to real people's lives, such as refugees and people who have experienced trauma. Understanding these kinds of questions requires granular data gathered on a vast scale to inform decision-making and cost-effective use of resources.

## 5-YEAR HORIZON

**Computer models map potential outcomes**

Advanced models of areas of conflict allow stakeholders to map out and discuss potential futures before deciding on a course of action. Causal inference and prediction models are increasingly integrated and able to exploit new data on armed conflict, impacts and policies.

## 10-YEAR HORIZON

**Individual data-gathering creates new peacekeeping tools but raises serious issues of privacy and exclusion**

Researchers begin to use a wider range of data, such as anonymised mobile phone data, to study the potential for conflict. They lobby for accountability for social-networking companies, who can now explicitly see when activity on their sites is fuelling unrest. The real-time nature of some data-gathering exercises raises issues of privacy and exclusion of those without a digital voice, that need to be addressed. At the same time, models appear that take into account the impact of peacebuilding on people's lives.

## 25-YEAR HORIZON

**Climate change and conflict increases use of peace modelling**

As pressures from climate change increase, and civil unrest becomes common in some parts of the world, the use of predictive peacekeeping models becomes a default response.

## 4.1.4 Trust and cooperation modelling

**Political scientists, sociologists and computer scientists have begun to create systems in which autonomous agents have to find ways to cooperate by distinguishing trustworthy from untrustworthy agents. This has been applied to a wide range of problems, ranging from information-routing algorithms to online search rankings to recommendation algorithms. But there is broader sense in which trust and cooperation studies are useful — in modelling the way people behave in the groups that make up societies.**[16]

In any society, business or network, the ability to evaluate and then trust partners is a crucial component of co-operation.[17] Applying trust modelling to the networks of actors at work in the diplomatic landscape has the potential to better model potential outcomes of discussions, votes and negotiations.

This work comes at a time when the role of trust in broader society has been thrown into sharp focus by the phenomenon of fake news, manipulated images and deepfake videos. The diplomatic landscape is powerfully shaped by the information that flows through it, and false and misleading information has huge disruptive potential.

A key emerging issue is the role of artificial intelligence and how it will be used to inform cooperative decision-making. At the heart of this question is whether AI systems will become better at interpreting the complex data fed into them or worse as AI-generated data distorts their view of the world. The possibility that AI systems could create a kind of artificial truth will be an important issue for the field.

### 5-YEAR HORIZON

**Data veracity becomes a global research issue**

The increased importance of data-gathering and analysis places a greater focus on data sources and their veracity. This leads to increased research in data-verification research. Managing trust and reputation are already battlegrounds for some actors.

### 10-YEAR HORIZON

**Stakeholders battle over reputation and trust**

Reputation-building and trust further become key factors for stakeholders in a wide range of data-gathering disciplines ranging from news organisations to scientific institutions to national and multinational organisations. AI plays an increasing role in these processes.

### 25-YEAR HORIZON

**AI oversees data veracity**

Machine vision and artificial intelligence become important arbitrators of trust in data, news and images. However, a cat-and-mouse game continues between malicious actors and those attempting to shut them down.

4.2

# Advances in Science Diplomacy

CHAIR:
**Pierre-Bruno Ruffini**
Professor of Economics at the University of Le Havre, Normandy, France

CONTRIBUTORS:
**Marga Gual Soler, Derya Büyüktanir, Joy Zhang, Jean-Christophe Mauduit, Luisa Echeverría-King, Luc Van Langenhove**

**The field of science diplomacy research seeks to establish an evidence-informed foundation for supporting and empowering the increasingly diverse set of stakeholders who practise science diplomacy. These are not just nations but non-governmental actors, groups of citizens and Indigenous communities.**

The products of science are increasingly celebrated as drivers of global health, sustainable development and wealth creation. However, science and technology are also sources of tension and competition between nations or regions. The COVID-19 crisis highlighted the role of science on the international stage, how it rapidly advanced novel vaccine technologies, and how cooperation over these vaccines became a crucial part of the currency of international negotiations, diplomacy and geopolitics. But conflict also plays a role in mediating the influence of science and technology. Situations such as the war in Ukraine are revealing how careful states need to be with powerful technologies, the way they are transferred and how they are used.

Climate change is one of the many key proving grounds for this work — especially with the rapid opening of ice-free routes through the Arctic Ocean and the geopolitical tensions this is creating. “Big science” projects are also part of this diplomatic landscape, requiring long-term technical and diplomatic engagement among a broad group of stakeholders. These diverse groups must also find ways to manage traditional and emerging global commons fairly and effectively. A final challenge is to find ways to train science diplomats, build capacities and evaluate this work, to create a continual cycle of learning and improvement in the practice of science diplomacy.

The nature and complexity of reciprocal benefits in science is likely to become a more important part of the landscape for science diplomacy, particularly with regional science-diplomacy projects providing a new way to navigate rivalries between bigger global powers. New skill sets and training for science diplomats will be needed to fully explore reciprocity in science.

## KEY TAKEAWAYS

Science diplomacy plays an important role in a world that is increasingly dominated by issues of science and technology, and frequently fractured by economic and geopolitical events. Researching the use of **Science diplomacy for effective multilateralism**, for example, can establish successful means of communication and negotiation through shared interests and goals, as well as understanding how science and technology diplomacy is used to further one-sided interests and compete in global markets. The rising influence of private technology firms and local and regional concerns means that **Technology diplomacy and the role of non-state actors** is an urgent area of research, helping to establish new norms and practices. There is also a growing need to study the effects of alignment between **Science diplomacy and emerging economies**, since smaller nations are banding together in science and technology projects that increase both their effectiveness and their influence on the global stage. Research is also under way into the role of **Science diplomacy as a response to conflict- and inequality-driven tensions**; properly grounding this area of study in evidence-based discussion will be crucial to enabling science diplomacy to flourish as a means of establishing trust and cooperation.

## ANTICIPATION SURVEY RESULTS

## SURVEY OBSERVATIONS

Science diplomacy is an area that is heavily influenced by the current geopolitical situation. As a result, all issues covered by this topic will peak in the next five years. This explains the lower Anticipation Potential scores across the board. The impact of Technology diplomacy and the role of non-state actors is influential on society and thus augments the score for this sub-topic.

## MORE INFORMATION

**go.gesda.global/4-2**

# 4.2.1 Science diplomacy for effective multilateralism

**A key goal for science diplomacy is to find ways to balance strategic cooperation against competition. Science diplomacy has traditionally established itself as a way to use science as a "soft power" that can advance diplomatic objectives. The 50th anniversary of signing the Antarctic Treaty, for instance, engaged diplomatic and academic communities in the use of science diplomacy as a tool for improving multilateral relations. Commitments to science-based diplomacy have since been incorporated into national strategies and policies, opening new avenues for cooperation. This has been important in establishing positive communication and diplomacy, helping collaborative navigations of "global commons" issues such as COVID-19, climate change, exploitation of space, deep-sea mining and managing Arctic and Antarctic resources.**

At the same time, however, the reality of global politics and geo-economics means that there are increasingly areas of tension that involve science and technology.[1] In the openness vs security dilemma, the rise in tensions between certain countries is leading to move the balance towards greater security, with traditionally open and liberal countries shifting their stance. Canada, for instance, has been applying a new Policy on Sensitive Technology Research and Affiliations of Concern since the beginning of 2024.[2]

Negotiations over the location of key science projects such as the Future Circular Collider are all potential sources of conflict and competition: science diplomacy is being used to leverage national and regional power, calling into question the mainstream vision of science diplomacy as inherently at the service of peace.

### 5-YEAR HORIZON

**National bodies call for action over resources held in common**

Studies of large parts of oceans protected from exploitation — Marine Protection Areas — provide evidence that international action can bring about significant beneficial change to global commons. Tensions between the US, Russia and China over Arctic resources grow more intense, involving science diplomats in both collaborative and competitive activities.

### 10-YEAR HORIZON

**Lunar exploration and regional concerns bring challenges**

Lunar missions from a number of nations highlight the necessity and importance of science diplomacy to tackle the issues these activities raise. As nations seek to shorten supply lines and strengthen trade links, new regional interest blocs emerge. This changes balances of geopolitical power, and science-resource sharing and collaborations openly mirror economic patterns.

### 25-YEAR HORIZON

**Trained experts in science diplomacy begin to steer policy**

Decades-long training initiatives mean that science and diplomacy-savvy professionals begin to reach positions of influence in their respective careers, fields and countries. The task of balancing national interests against multilateral interests remains challenging.

## 4.2.2 Technology diplomacy and the role of non-state actors

**Transnational companies and industry associations are gaining significant diplomatic influence over policy, pushing regulation — in the cases of AI, self-driving cars and deployment of orbital resources, for example — and creating tangible effects on policy.**

The attempts at influence go both ways, however. Numerous nations (and groups of nations, such as the EU) have created "tech ambassador" roles and deployed these representatives to gather information, lobby and negotiate in Silicon Valley and other technology hubs around the world.[3]

Sometimes, technology diplomacy has to operate where the lines between nation-states and private companies are blurred, as with China's Huawei and ZTE. There are also issues with technology companies offering a country a competitive edge or working in areas that involve national security sensitivities, such as supercomputing hardware. Here, tech diplomats must tread the fine line between corporate freedoms, global balances of power and issues of national interest — often with incomplete information due to the unwillingness of all parties to fully disclose all the relevant data.

In some regions where regulatory environments are weak, lobbyists, activists and grass-roots organisations are pushing the boundaries of science with their work on anti-ageing therapies and gene editing, some of which can influence regulatory policy-making, and sometimes accelerate the pace of change. Even small-scale companies, if they are significant employers in a region, can influence local political decision-making and tech-related legislation.

All of these various initiatives demonstrate the rising importance of transnational, non-state and even individual or small-group actors to local and global governance, something that the field of science and tech diplomacy must navigate.[4,5]

### 5-YEAR HORIZON

**Science diplomacy and technology platforms shape each other**

The industrial and societal sector begins to influence science diplomacy in areas such as access to space and with respect to the lunar environment. Technology firms invest further in "ambassadors" who exist to seek ever-greater influence in transnational organisations such as the UN. Research in technology diplomacy achieves deeper elucidation of the issues where national security clashes with corporate freedoms. More embassies deploy an "attaché for innovation".

### 10-YEAR HORIZON

**Multi-stakeholder science diplomacy becomes the norm**

Science-diplomacy efforts involve actors from city, state and regional governance as well as multinational companies, global science organisations and civic groups. Training schemes for science diplomats produce a growing number of graduates to meet burgeoning need. IPCC-like organisations with transnational responsibilities and influence are significant powers in the science-diplomacy arena. Economic diplomacy is inextricably linked to science and technology diplomacy. Non-governmental actors develop greater influence on national strategies and in science diplomacy.

### 25-YEAR HORIZON

**Private-sector actors are integrated into governance**

Private-sector actors pioneer new ways of achieving governance and agreement on exploitation of deep-sea, orbital and mineral resources for manufacturing. City and regional planners and policy-makers routinely seek advice from private company representatives and researchers working outside of academia.

## 4.2.3 Science diplomacy and emerging economies

**Science diplomacy has long played a part in maintaining good relations between economic world powers.[6] In recent years, CERN has extended this to embrace partnerships with the world's emerging economies, such as Chile, India and Pakistan.[7] This has added new dimensions to diplomacy between the various nations involved.**

There are, however, significant collaborations that involve exclusively emerging economies. Intergovernmental science organisations such as the African Lightsource, the Synchrotron-Light for Experimental Science and Applications in the Middle East (SESAME) — a joint undertaking of Israel, the Palestinian Territories, Egypt, Jordan, Iran, Pakistan, Turkey and Cyprus — and the Latin American and Caribbean Space Agency are all good examples of nations with emerging economies engaging in multilateral science diplomacy on their own terms.

The value of such endeavours in establishing credentials for global engagement is clear from South Africa's success with the Square Kilometre Array (SKA), a radio-telescope project that is showcasing the nation's science and engineering talent, creating programmes to further develop its human capital and burnishing its reputation as a rising power on the world economic and intellectual stage. Although there are hurdles to overcome, there are clear reasons to encourage and pursue more such inclusive collaborations between countries of differing economic means.[8] At the same time, more and more emerging economies are taking an interest in science diplomacy as a means of moving towards greater scientific and technological development.

### 5-YEAR HORIZON

**Emerging economies invest in science diplomacy training**

Universities and institutes work with emerging-economy nations to train numerous science-diplomacy practitioners in these countries, often uniting on the basis of a shared language. Innovative immersive pairing schemes between politicians, engineers and scientists foster the mutual transfer of skill sets in a broad range of countries, establish science diplomacy as a regional endeavour and give a greater role to Indigenous peoples.

### 10-YEAR HORIZON

**Trained science diplomats are spread through relevant organisations**

Graduates from science-diplomacy-focused training courses in emerging economies become increasingly influential actors in state and non-state organisations, and amongst leaders in science. The reciprocal benefits of research between disciplines, nations and peoples becomes an increasingly important part of science, and funding becomes dependent on establishing such mutual gains.

### 25-YEAR HORIZON

**Training initiatives improve cooperation between diverse actors**

Large-scale science projects that involve cooperation between countries of different economic status are established thanks to complex, multi-layered negotiations between many state and non-state actors. Much of the progress is thanks to training initiatives where key groups of experts from a diverse range of nations are encouraged to develop skills spanning diplomacy and science.

## 4.2.4 Science diplomacy as a response to conflict- and inequality-driven tensions

**One of the significant opportunities for those in the science diplomacy sphere is the role they can play in areas of conflict and inter-group tensions. Though predominantly positive, the rising rivalries between certain powerful nations are leading to science diplomacy being used as a weapon as well as a peacebuilding tool. Nuclear diplomacy is also returning to the spotlight as these tensions escalate.**

Science is certainly affected by conflict. The war in Ukraine, for example, has hindered some collaborations between scientists of different nations: because of Russia's geographical position, these stymied collaborations are having direct effects on Arctic science and are likely to affect protections against exploitation of Arctic resources.[9]

Science has recently become part of broader policies of sanctions between nation-states, as technology has become an interestingly important element of successful economies. More positively, it may be possible for scientists — working with science-diplomacy resources — to become drivers of positive change, shaping global research to give more equitable benefit from the outcomes of science.

### 5-YEAR HORIZON

**Science diplomacy becomes a hard tool in international relations**

International scientific cooperation is increasingly weaponised as a means of participating in conflict. The majority of actors in the science diplomacy sphere nonetheless preserve inclusive and cooperative uses of science diplomacy as the most frequently deployed acts. Science diplomacy helps create projects and plans that contribute to peacekeeping efforts, inter-group negotiations and maintenance of stability.

### 10-YEAR HORIZON

**Science facilities are opened up to scientists displaced by conflict**

Researchers working in former conflict zones (particularly in developing economies) are given access to Big Science facilities, virtually and in person, as a result of science diplomacy work to re-establish countries' peacetime activities. With increased training, individual scientists become more aware of their potential role in science diplomacy.

### 25-YEAR HORIZON

**Science diplomacy improves international relations**

The dual-use aspect of science diplomacy is recognised, and efforts are made to prioritise its use in avoiding conflict and establishing peaceful, collaborative and equitable futures. Nonetheless, scientists continue to feel pressure to align with their national government's policies and ideologies.

4.3

# Prediction, Foresight and Futures Literacy

CHAIR:
**Sirkka Heinonen**
Professor Emerita, Finland Futures Research Centre, University of Turku

CONTRIBUTORS:
**Jake Sotiriadis, Jakkie Cilliers, Geci Karuri-Sebina, Patrick Noack, Peter Scoblic**

**Nobody can see what the future holds. This has been recognised as an absolute truth since at least the time of Aristotle. Modern civilisation is nonetheless built on attempts to do just that, over time scales ranging from hours (weather forecasting and traffic patterns) to decades (climate change and demographic shifts). These attempts allow us to anticipate what the future holds and to plan accordingly. The urgency of this anticipation has increased along with perceptions of the increased speed and complexity of change.**

Our attempts to see what the future holds can be grouped into two broad categories: prediction and foresight. Prediction is based on understanding of the factors that determine a system's behaviour, and how they affect each other. We can then predict how the state of that system will evolve given changes in one or more of its underlying factors and thus forecast its state at some date in the future.

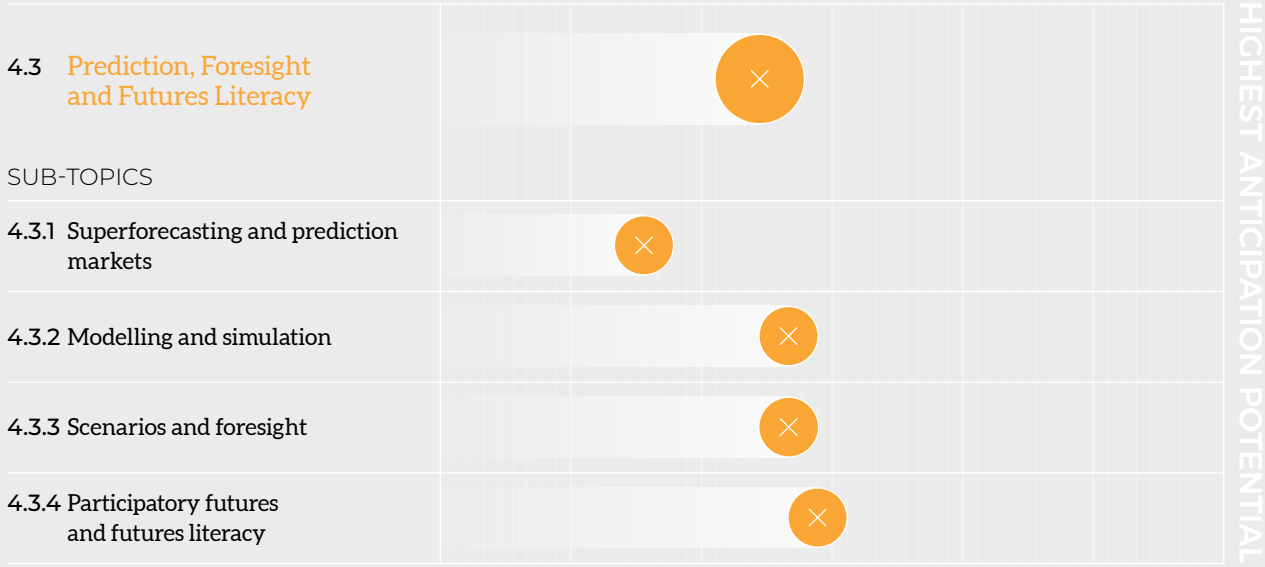
Those predictions may be precise or fuzzy, depending on the quality of the data and the tractability of the system in question: simple physical systems are generally more predictable than complex social systems. In the latter domain, brains may outperform computers, and so attempts are being made to better understand and improve human-made predictions, whether made by individual superforecasters or by many people aggregated through prediction markets. At the same time, the range of tractable systems is being expanded through increasingly sophisticated modelling and simulation.

Sometimes, we can be confident that our prediction is broadly correct and a single outcome is highly likely. However, one of the key principles in futures studies is that the future paradoxically cannot be predicted. Exact prediction of the future is always more about probabilities than sheer accuracy. There may be many distinct and plausible outcomes, and these may vary significantly. In such cases, we have to exercise foresight — a collective term for an approach and methods of gathering information relevant to these outcomes, exploring their ramifications and interconnections, as well as deliberating their preferability. In many cases, for example regarding climate change, geopolitical conflicts or lifestyle changes, the focus of foresight could be on exploring widely possible, even unexpected futures, not only probable futures. This activity can be carried out "top-down", as in strategic foresight, or "bottom-up", as in participatory futures.

KEY TAKEAWAYS

Efforts to anticipate what the future holds are fraught with difficulty but can be successful, as the growth of **Superforecasting and prediction markets** has shown. These provide a synthesis of many types of information, resulting in useful outcomes. Computational efforts in anticipation rely on high-performance **Modelling and simulation** that attempt to discern how our interconnected physical, biological and socio-economic processes, cycles and networks play out, and will be vital to tackling the grand challenges faced by humanity in the 21st century. Also important is the development of **Scenarios and foresight** methods, which use narratives and imagery to assist anticipation efforts. The impact of all of this research can be deepened through the development of **Participatory futures and futures literacy** that helps communities and organisations to understand how to think about the future and to engage with activities related to it.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

We will see significant advances in prediction, foresight and futures literacy in the coming five years, with a deep impact on science, research and society. Participatory futures and futures literacy require strong, internationally coordinated action to deploy its full potential. The scope for action and the Anticipation Potential scores are therefore higher for this topic.

MORE INFORMATION

go.gesda.global/4-3

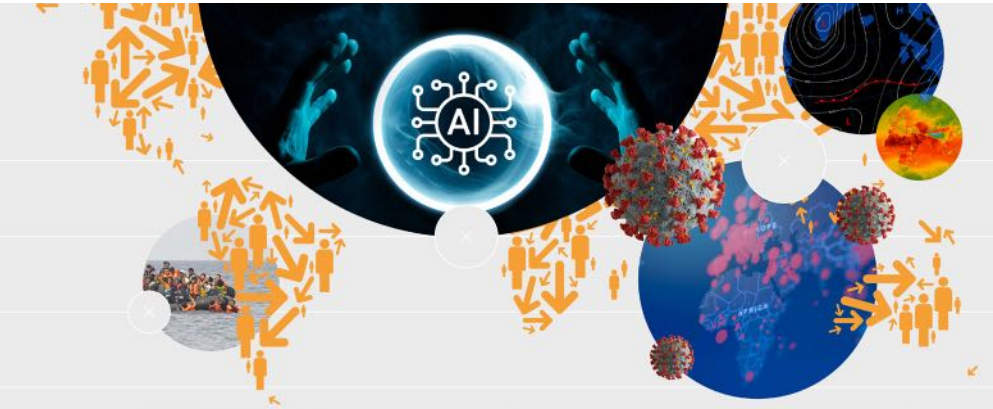
# 4.3.1 Superforecasting and prediction markets

**Some individuals are capable of reliably predicting geopolitical events with a success rate that significantly exceeds that of experts in a given field. These superforecasters' success is rooted in their skill at focusing on a few key determinants of an outcome and their exceptional willingness to update their predictions in the light of new information and arguments. It appears this can be significantly improved through training and teamwork.[1,2]**

Research is ongoing into how effectively superforecasting can be applied to domains other than geopolitics, and how it can best be integrated with expert knowledge. The ability of superforecasters to assess extreme, disruptive risks — "black swans" such as pandemics, for example — is also an area of active debate. More research and validation are needed to legitimise its use in real-world decision-making.[3]

Prediction markets also harness the human ability to synthesise many types of information, but do so by aggregating predictions made by many individuals (some of whom may be superforecasters).[4] Participants are offered financial or reputational incentives to make accurate predictions, and market mechanisms are used to establish consensus positions on political events,[5] technological developments[6] and corporate strategy.[7,8]

The optimal design of such markets is an area of active investigation.[9] One emerging model is "tournaments", in which participants first make individual forecasts before being asked to collaborate in teams, then to assess other teams' rationales and update their own predictions. One such tournament, focusing on existential risks, found that the predictions made by expert and superforecaster participants continued to be significantly different.[10]




## 5-YEAR HORIZON

**Superforecasting is better understood**

The key cognitive processes underpinning superforecasting are identified, and training people to develop their superforecasting abilities becomes routine. Standardised designs for prediction markets and tournaments emerge. Expert knowledge is productively integrated with superforecasting techniques, with artificial intelligence also becoming used.

## 10-YEAR HORIZON

**Superforecasters go mainstream**

Robust evidence emerges for the real-world accuracy of forecasters and prediction markets, and their predictions are routinely cited by journalists and policy-makers. Work continues to integrate expert evidence and incorporate predictions about extreme risks which break markedly from prevailing trends but lead to major disruption.

## 25-YEAR HORIZON

**Superforecasting is widely used at the highest levels**

Superforecasters, prediction markets and artificial intelligence work together to create forecasts for systems that cannot easily be modelled, over a range of timescales. This approach is as well-established for the political and economic domains as weather forecasting or climate modelling, and used at the highest levels of decision support.

## 4.3.2 Modelling and simulation

**Human societies are embedded in complex social-ecological systems (SESs) that are composed of interconnected physical, biological and socio-economic processes, cycles and networks. Understanding these systems and their interconnection is vital to tackling the grand challenges and "wicked problems" facing society in the 21st century, such as those related to climate change, biodiversity, human demographics and economic disruption.**

These challenges are now becoming tractable thanks to expansion of our ability to collect and analyse data about SESs through satellite imagery,[11] in situ networks of ecosystem[12,13] and urban[14] sensors, and automated aggregation of economic and social data.[15] This in turn makes it possible to build computer models that simulate processes taking place in a wide variety of systems and at a wide variety of scales.

Initially, these models were confined to physical processes, with climate modelling being by far the best-known example,[16] but as our data-gathering capabilities have expanded, we have now started to model ecosystems[17] and various dimensions of societies such as urban planning[18] and health[19] as well. Research is under way into the use of these models as decision-support tools for policy-makers.[20]

Technology vendors have put forward the idea of integrated "digital twins" that span physical, biological, social and economic dimensions from local to global scales, and particularly integrated models of cities. However, the case for these has yet to be proven, especially with regards to less wealthy communities, where the focus is more on using digital tools at more granular levels, such as buildings-information management.[21]

### 5-YEAR HORIZON

**Digital modelling achieves wider take-up**

Greater use is made of digital modelling techniques to assess individual development and infrastructure projects, as well as greater integration with decision-making processes. Research continues into how immersive models can best allow stakeholders to more intuitively yet rigorously understand the context for decision-making. Low-cost, low-risk simulation of different solutions to development and environmental challenges are developed.

### 10-YEAR HORIZON

**Better data and computational resources create better models**

High-resolution models for physical processes, initially demonstrated for select locations, become both more accurate and more widely available, thanks to increases in computational power and well-categorised and contextualised data. Integrated models of the built environment are created for some urban environments and coupled social-ecological avatars are created for especially tractable and well-studied locales, such as oceanic islands.

### 25-YEAR HORIZON

**Local and global models merge**

Local digital twins and avatars that allow predictive management and decision-making at city and island scales join up with regional and global avatars, such as physical climate models that increasingly include biological and social feedbacks. They become interconnected at nested scales, creating a global "intelligent fabric" that can be utilised in politics and diplomacy.

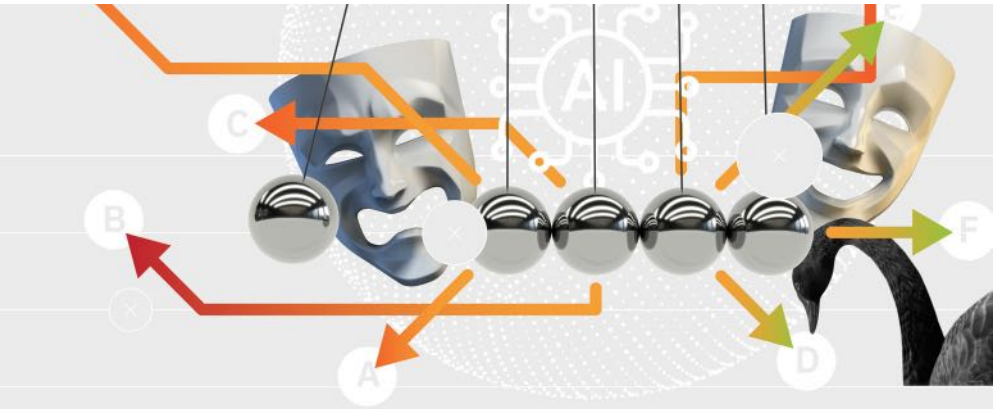
## 4.3.3 Scenarios and foresight

**Because the future is uncertain, it often holds multiple possible outcomes, presenting very different opportunities and risks. These can be assessed using approaches known collectively as foresight (or futures) methods, which are predominantly qualitative, typically focusing on developing images and narratives of alternative futures rather than numerical predictions. The most widely accepted of these techniques is scenario analysis, which has been used in corporate settings since the 1970s.**

Foresight exercises typically task a group with imagining how a situation will evolve, often using fictional prompts and props as well as real data, knowledge and expertise. This disrupts their conventional thinking, allowing them to anticipate possible outcomes that include novel and extreme possibilities. Synthetic data and machine learning are also now being used to support the creation of unorthodox narratives.[22,23]

Such techniques may help to address the current tendency of foresight work to identify positive or preferred futures. If we are to truly anticipate what the future may hold, we must also consider uncertain futures, unlikely futures and undesirable futures. This includes widely known concepts like "black swans" and "existential risks", but further work needs to be done to map and understand the space of these "unfutures".[24]

One strand of development is understanding how unknown and disruptive factors can be envisaged using scenarios or other futures methods and then integrated into the parameters or structure of a quantitative model. A second is an expansion of the application space, to address such issues as identity or the interests of transnational communities.




### 5-YEAR HORIZON

**Generation and communication of scenarios improves**

Research continues into ways to more effectively generate scenarios and communicate their implications and consequences, making greater use of insights from cognitive neuroscience and tools from interaction design.

### 10-YEAR HORIZON

**ML-generated scenarios bring surprises**

Machine learning and synthetic data are routinely used in governance contexts to create scenarios that challenge the expectations of human participants while also being grounded in real-world evidence. Foresight work remains a largely exploratory exercise.

### 25-YEAR HORIZON

**On-demand scenario creation becomes available**

Scenarios are brought to life "on demand" through the use of generative gaming engines and mixed reality, allowing participants to experience different outcomes more intuitively. Foresight work is intended to allow decision-makers to better appreciate the potential consequences of their work.

## 4.3.4 Participatory futures and futures literacy

**To date, prediction and foresight has typically been commissioned and practised by states, multinational agencies and large companies.[25] The outcomes envisaged and conclusions reached will depend on the sponsor of the work, who will deliberately or inadvertently lean towards those which suit their purposes.[26] These will not necessarily align with those considered most desirable or achievable by other stakeholders.**

As a result, there is a need for communities to understand how to think about the future and engage with participatory futures activity. This futures literacy is defined by UNESCO as an essential, universally accessible competency which allows people to better understand how they can anticipate the future and plan accordingly,[27] and the organisation has set up more than 100 "labs" aimed at fostering it.[28] Research continues to explore how the human mind envisages the future, and how this process might be duplicated or augmented by machine intelligence and immersive technologies.

Participatory futures take a variety of forms but generally aim to tackle a specific challenge, usually beginning with a briefing designed to expose participants to alternative futures, followed by structured discussion to identify and detail those that are preferable.[29] These methods are now being trialled to help rural communities define their futures after the net-zero transition, or to help city-dwellers understand how urban design can improve their quality of life.[30] The next step is futures resilience: the capacity to survive emerging challenges, obstacles, risks and crises and learn from them how to rethink existing structures, systems and practices.[31]

5-YEAR HORIZON

**Futures literacy becomes a mainstream capability**

Futures literacy becomes a core tenet of citizen empowerment, alongside the appointment of policy-makers charged with safeguarding the interests of future generations.

10-YEAR HORIZON

**Mass engagement with participatory futures is routine**

Systems are developed which allow mass engagement with participatory futures activity to be conducted routinely, rather as opinion polls are today.

25-YEAR HORIZON

**Participatory-futures events are established as part of civic responsibility**

The results of participatory-futures activity becomes legally binding in certain jurisdictions, being written into constitutional procedures for decision-making.

4.4

# Digital Security

CHAIR:
**Linus Gasser**
Lead Engineer, Center for Digital Trust (C4DT), Swiss Federal Institute of Technology in Lausanne (EPFL)

CONTRIBUTORS:
**Thomas Bourgeat, James Diggans, Jean-Pierre Hubaux, Miroslaw Kutylowski, Shujun Li, Sébastien Marcel**

**The world of the 21st century is increasingly reliant on digital technologies, creating a slew of challenges for tasks, processes, institutions and individuals that require privacy, transparency and security, in all their various forms. A number of mathematical and technical innovations, such as zero-knowledge proofs, trusted execution environments, homomorphic encryption and advances in formal verification, are improving the prospects of creating effective digital security measures.**

However, the practice of Digital Security still faces a range of theoretical and practical challenges in the face of numerous emerging forms of computing and communication. At the heart of these challenges is AI, which is dramatically increasing the capabilities of both defenders and attackers in cybersecurity. At the same time, the internet of things is extending through every aspect of human society, from transport and industry to healthcare and entertainment. By some estimates, there will be 100 billion devices connected to this network by 2050.[1] That raises a host of security issues on a scale never seen before. Next-generation telecommunications networks based on 6G technologies will also need to be secured, as will biological information. Then there is the health, financial and personal data stored in the cloud that must be processed without revealing its content. And if that were not enough, the next decade will see quantum computing coming online, with computational power to crush some existing encryption systems. Securing these systems will be a significant task and developing the mathematical foundations to guarantee this security will be even tougher.

KEY TAKEAWAYS

Thanks to increases in private, institutional and governmental activities in the digital sphere, there is a growing need for reliable and practical digital security solutions. **Privacy and security** are fundamental to democracy, economic activity, communications and healthcare delivery, but there is also a need for transparency in these activities, depending on the context. Researchers are developing a range of solutions for establishing, protecting and verifying **Digital identity**, with a growing use of biometric data offering particular challenges and opportunities. **Novel encryption technologies** are coming onto the market, although technological progress is necessarily slow here, and the prospect of emerging quantum-computing systems able to challenge some of the most widely used encryption methods is creating some legitimate concern about whether encryption can stay ahead of encryption-breaking operations. Many of these concerns might be allayed through development of better and more wide-ranging **Formal verification** protocols, which provide reliable mathematical modelling of real-world capabilities and scenarios.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Digital identity and Privacy and security are very much under the spotlight today. Research in these areas is expected to see significant developments in the coming five years. Formal verification technology breakthroughs are further away and will be less transformative. Digital identity is the area with the highest scope for action, highlighting the need for coordinated international involvement.

MORE INFORMATION

**go.gesda.global/4-4**

## 4.4.1 Privacy and security

**Issues of privacy and security now affect all citizens, as well as state-level operations. The pervasive use of digital technology means that, for an equitable society, personal data and communications have to be encrypted in ways that allow transactions and access to services such as welfare payments, healthcare and voting facilities, as well as private web-browsing, messaging and mobile-phone use. This requires a vast technological infrastructure that is not only efficient and secure but also — depending on the context — private yet transparent. At issue is the confidentiality, integrity and availability of information as well as related concerns over authenticity, accountability and reliability. There is also the inevitable trade-off between privacy and system functionality that individuals must navigate, which often brings into focus tensions between the way people think about privacy and the way they act.[2]**

New technologies are also raising security and privacy issues. Video analysis can reveal not only an individual's identity and location but also the people they meet, their mood and even certain medical conditions. The transmission and storage of biometric data requires the implementation of new protocols, and the increasing prevalence and accessibility of a wide range of biology-based data (such as genomic information, healthcare data and access protocols for laboratory samples of weaponisable pathogens) means that "cyberbiosecurity" is an emerging research topic of significant importance. Artificial intelligence is also changing this landscape,[3] not least because of its pattern-recognition capabilities and the potential it offers to automate many tracking processes.

### 5-YEAR HORIZON

**AI cybercrimes change focus of security**

AI is used to encourage people to use IT systems without employing proper security measures. A handful of spectacular cybercrimes demonstrate the role of AI in exploiting weaknesses in conventional security systems. The issue focuses the global security community on whether and how to control artificial intelligence as well as how to balance citizens' rights with public safety.

### 10-YEAR HORIZON

**Augmented reality redraws privacy boundaries**

Malicious state-level cyber-activity becomes so damaging for privacy and security that it forces an expansion of the definition of cyberwarfare. That lowers barriers to conventional war while raising the stakes for digital diplomacy. Growing activity in the metaverse focuses security research onto the challenges of privacy and safety in immersive environments. Awareness-raising about abuse of data-sharing causes individuals to take more control of their personal data, as well as protect themselves with more use of multi-factor authentication.

### 25-YEAR HORIZON

**Tension grows between the digital haves and have-nots**

Countries with secure digital infrastructures experience significant growth in their knowledge-based economies, often at the expense of digital privacy. But countries without this capability suffer economic hardship, and the division dramatically redraws the global balance of power.

## 4.4.2 Digital identity

**One of the most difficult digital security problems is to create ways for establishing digital identities that are useful in a wide range of applications but remain secure. This will mean consideration of indirect insecurities, such as LGBTQ+ people being unwillingly identified because of data-sharing leading to openly targeted advertising,[4] doxing[5] or even physical attacks. Identity security relies on data policies and software routines as well as on unlinkability[6] and secure hardware implementations such as "secure enclaves". It is likely that unlinkability will allow people to maintain several legitimate identities simultaneously, for example. Multifactor authentication is used now, but its importance is likely to grow, with distributed and independent issuers of factors making identity theft much harder than it is today.**

Reliable means of establishing identity will be key as autonomous agents begin to augment people in certain decision-making scenarios. These agents will need their own identities that are securely linked to their owners. This kind of distributed decision-making raises broader issues about the way human identity will evolve in future. What's more, establishing the identity of machines is an important issue for the Internet of Things,[7] which consists of devices with limited power, network and computational ability. Identity in this context will have to be established by methods that do not rely on strong encryption, network connections and so on. Ensuring that these mechanisms are secure and fit for purpose is an ongoing area of study.

### 5-YEAR HORIZON

**AI identity theft threatens democracy**

State-sponsored AI cybercrime combines the data from multiple security leaks to produce convincing patchworked identities for large-scale fraud. This theft occurs on such a large scale that it threatens banking systems, healthcare and even democracy. Passwords become a rarely used means of authentication, replaced by passwordless approaches. Autonomous agents trade on their owners' behalf using networks of verifiable trust that occasionally, through unpredictable herding behaviour, creates runs on certain types of goods, leading to shortages and profiteering. Encryption protocols such as PGP and SPKI flourish.

### 10-YEAR HORIZON

**The notion of personal identity mutates**

The notion of one identity per person begins to change with the legitimate use of multiple IDs. This creates diverse social landscapes, with the opportunity to segment an online existence to share different parts of each individual's life with different groups of people. A new breed of security attack via the internet of things, particularly medical devices, poses a life-threatening risk for millions of people.

### 25-YEAR HORIZON

**Establishing and protecting identity becomes routine**

Identity-authenticating technology is developed in ways that allow even young children and technology-disadvantaged individuals to establish and protect their identities.

# 4.4.3 Novel encryption technologies

**The science of hiding information by encrypting it to prevent unauthorised access faces a wide range of new challenges. Among the most significant is the advent of big data, stored in the cloud, that needs to be processed securely. This has led to much work on homomorphic encryption,[8] which allows encrypted information to be searched and processed while remaining encrypted. Applications include healthcare, banking, voting, genome encryption and beyond. Zero-knowledge proofs allow data verification without revealing anything about the data itself[9] and have applications in healthcare, electronic identity systems, arms verification and so on. Another challenge comes from quantum-computing systems, which are soon expected to become capable of breaking many public-key cryptographic systems that are in widespread use for communication, financial transactions and the like. The US National Institute of Standards and Technology is coordinating efforts to develop post-quantum cryptographic standards that will be immune to quantum attack.[10] But much work needs to be done to make sure they are safe.**

The internet of things is a network expected to connect over 40 billion devices by 2025,[11] but there are significant challenges in achieving this securely. These devices operate with lower power and with limited computational resources, which limits the data processing they can do. Ongoing research for securing the Internet of things focuses on blockchains, physically unclonable functions and post-quantum cryptography. Many of these techniques require improvements, such as error-detection routines and practical, user-friendly hardware interfaces. Device-independent cryptography, where users can test a device's security for themselves, removing any reliance on manufacturer-issued assurances, remains an important goal.

## 5-YEAR HORIZON

### Secure cloud search revolutionises healthcare research

Homomorphic encryption techniques allow researchers to process data stored in the cloud without revealing its content. That leads to significant advances in fields such as genomics, where data privacy is a key concern. However, other security weaknesses that allow malicious users to access the data via well-known shortcomings threaten to undermine the potential. Basic-level data, such as DNS traffic, is routinely encrypted.

## 10-YEAR HORIZON

### Post-quantum encryption widely adopted

A relatively small number of quantum computers become capable of breaking public-key encryption. This forces the widespread adoption of post-quantum encryption, although some of the adopted encryption methods are likely to be broken. Simple, lightweight cryptography gains in popularity, but the environments that adopt a hybrid approach, using two or more encryption systems with very different characteristics, are the most secure against attack.

## 25-YEAR HORIZON

### Genome security improves

Homomorphic techniques allow the risk posed by a given nucleic acid sequence to be assessed without the whole sequence being read, protecting IP while facilitating trade and transfer of biological materials.

# 4.4.4 Formal verification

**A crucial component of modern security systems is the task of proving their correctness with respect to a specification, a process known as formal verification. This requires accurate mathematical modelling of hardware designs along with their envisaged operations, and then an exhaustive, systematic check of all model states in a way that can offer evidence of security. While formal verification is an essential part of the development process, in practice it is often applied in retrospect, which makes the task significantly harder. Simpler user interfaces and better techniques could help to change that. This is particularly important for mobile computing and cloud computing, which have spurred the use of formal verification at earlier stages in associated platform development.**

Other new types of computing introduce their own challenges for formal verifications. The internet of things, for instance, connects a wide variety of devices together, and to the internet, using a variety of different technologies, communications protocols and security standards, rendering each one vulnerable to attack — especially since they are often installed by non-security experts.[12] 6G communications networks, which are being designed as open and programmable by multiple stakeholders, may be vulnerable to attack in ways that 5G networks are not.[13]

Because of the trend towards ever larger and more complex networks and systems, formal analysis is becoming more difficult, and AI — in particular, its pattern-identification capabilities — will play an increasingly important role in formal verification routines. However, low-end devices are likely to benefit from advances in local verifiability and public verifiability protocols, which will be of particular use in small and medium-sized countries where traditional certification is not affordable, and tools for trustworthy certification (and suitably qualified personnel) are not available.

### 5-YEAR HORIZON

**Formal verification becomes more visible**

The trend towards demanding explanations for how AI make decisions also drives wider demand for verifiable security and observation of “ceremony” in processes such as key generation. AI accelerates the testing and verification of software and hardware systems, but relatively few companies or organisations have this capacity, creating a threat of monopoly.

### 10-YEAR HORIZON

**Verification methods for biological systems spark debates**

Formal verification methods emerge for biological systems, allowing a full analysis of the capability of synthetic organisms before they are made and released into the environment.

### 25-YEAR HORIZON

**Quantum computing introduces new challenges for verification**

The challenge of verifying quantum software using quantum techniques drives new research into formal verification based on the laws of physics themselves.

4.5

# Behavioural Science of Groups

CHAIR:
**Mina Cikara**
Professor of Psychology, Director of the Intergroup Neuroscience Lab, Harvard University

CONTRIBUTORS:
**Laia Balcells, Sabina Čehajić-Clancy, Eran Halperin, Yphtach Lelkes**

**Equipped with the tools of modern research, it is becoming possible to identify, monitor and predict how individuals cohere into groups, and how those groups behave and interact with each other — to assess collective emotion as well as collective action.**

Efforts to understand conflict and cooperation have long been dominated by notions of history and geography. Attempts to avert or encourage conflict have been couched in terms of the diplomatic crafts of discussion and negotiation, staged under the aegis of (supposedly) neutral and multilateral organisations. Such efforts have had notable successes in the post-war era, but also notable failures. Great-power conflict has been avoided, but there have been numerous instances in which the established order has collapsed unexpectedly and abruptly.

The traditional tools of politics and diplomacy have proven increasingly impotent in the face of such challenges, particularly as the environment has become ever more complicated by technology, migration, climate change, polarisation and partisanship, rises in both secularism and religiosity, and geopolitical realignments. However, new tools have also emerged from the fast-developing science of group behaviour, which aims to understand the deep-seated reasons behind the formation and activity of distinct groups.

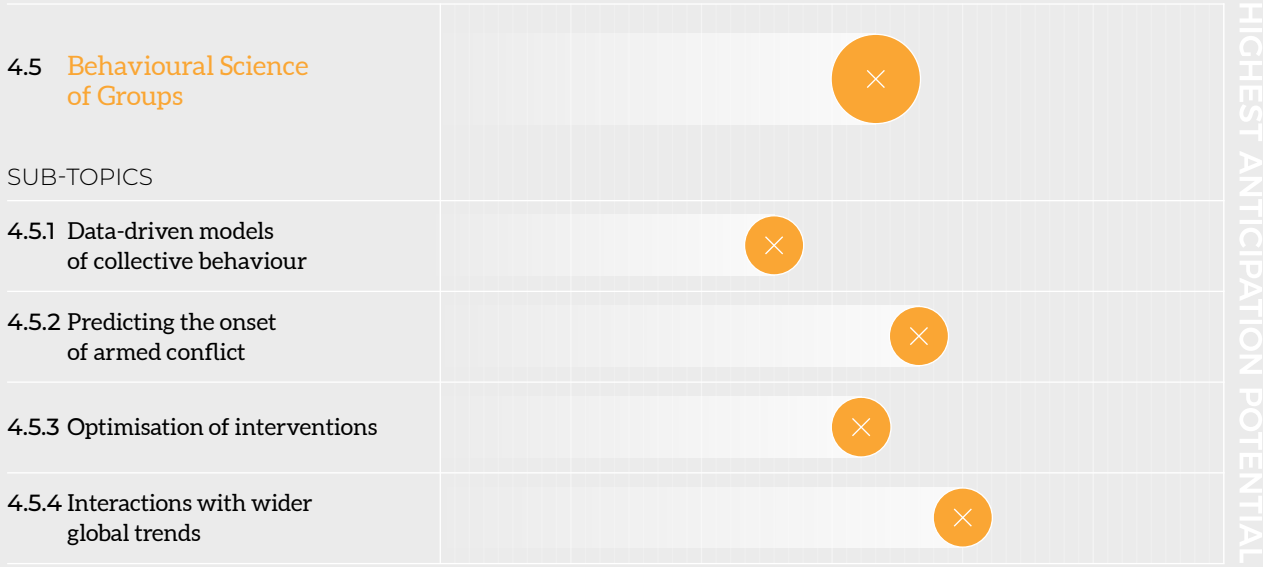
The availability of granular data is particularly significant in this respect. For example, mobile-phone data allows researchers to monitor individuals' movements, interactions and information diets. This data can then be cross-referenced with their social and political activity, and aggregated into groups of any relevant scale or scope: nations, societies or communities, demographic segments and ethnic groupings, and so on.

The point of this activity is to understand how groups interact, and particularly how they might come into conflict. Today's efforts are more often geared towards resolution — trying to stop conflict once it has already begun — rather than prevention. New methods of monitoring both top-down forces (such as messaging from elites, or economic trends) and bottom-up trends (prevailing social attitudes) are changing this, potentially allowing conflict to be anticipated. This should in turn allow interventions to be made in a more optimised fashion, suitable for the particular context of an emerging conflict, rather than applied generically. This is a young field, however, and there is still much systemisation, experimentation and validation to be done.

KEY TAKEAWAYS

Modern research tools, especially computational resources, are making it possible to analyse the various aspects of group behaviour. This holds promise for enhancing cooperation and limiting conflict, as well as understanding the basic dynamics of how groups form and behave. Particularly useful are **Data-driven models of collective behaviour**, which can achieve unprecedented insights into the hidden drivers of observed behaviours. One of the most sought-after applications is in **Predicting the onset of armed conflict**. This will, in tandem with the **Optimisation of interventions**, give governments and global organisations the tools to mitigate the harm that intergroup conflicts bring to individuals and societies. Optimising all of these actions depends on their **Interactions with wider global trends** such as climate change and access to burgeoning digital communication technologies, which affect the way group behaviours manifest and evolve.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

The Behavioural Science of Groups has a high overall Anticipation Potential score. It is an area at the convergence of disciplines that will accelerate advances and their impacts in the future. The scope for action is also high for all sub-topics considered. Predicting the onset of armed conflict and Interactions with wider global trends score highly because of higher impacts and because the fields are relatively new.

MORE INFORMATION

go.gesda.global/4-5

# 4.5.1 Data-driven models of collective behaviour

**Historically, researchers seeking to understand collective behaviour have been limited to comparatively simple models — for example, those based on correlations between the prices of basic foodstuffs and the likelihood of civic disorder.[1] But the increased availability of continuous data about movements, communication and interactions makes it possible to develop more refined models and test them against real data — a "bottom-up" approach focused on aggregated individual behaviours in addition to forces acting "top-down".**

For example, analysis of 1.2 billion mobile-phone pings in South Africa reveals that contact with a larger number of immigrants predicts more xenophobic attitudes and voting patterns. However, this effect is less pronounced if there are repeated casual interactions with the same members of the out-group.[2] Another "top-down" example is the use of artificial intelligence to categorise the way political leaders use language, thus revealing whether voters are hearing constructive debate or personal attacks.[3]

Data is not a panacea, however: there can be significant communities who are poorly represented in available data — for example, those who are not digitally connected — or hard to identify, such as those who are covertly resistant to autocratic regimes. And all the data in the world is of little use without the appropriate techniques for analysing it. These analytic approaches do not necessarily exist within the traditional social sciences and will need to be adapted and further developed in collaboration with specialists from other disciplines, such as physics and evolutionary biology.

## 5-YEAR HORIZON

### Useful datasets expand

The data sets available for analysis continue to expand — including increases in resolution (more precise records) and types of data (such as biometric data). This will require cooperation between data collectors and researchers, along with codes of conduct to ensure appropriate ethical and commercial oversight.

## 10-YEAR HORIZON

### The behavioural-science research environment matures

Integrated, cross-disciplinary teams become the norm in behavioural science, incentivised by a new wave of journals, funding opportunities and research organisations. Specialised analytical tools that draw on existing data competencies are developed, but reflect the particular concerns and idiosyncrasies of social science.

## 25-YEAR HORIZON

### Data reveals sources of collective phenomena

Widely accessible, extremely granular data becomes routinely available for analysis. This is used to understand how collective behavioural phenomena result from cascading collective dynamics at the individual, group and societal levels, and how these relate to the social, economic, ecological and political environment.

## 4.5.2 Predicting the onset of armed conflict

**The 21st century has provided ample evidence of the far-ranging effects of armed conflict. Beyond the obvious toll of immediate death and destruction, the interconnectedness of today's world means there can be significant political, economic and social repercussions far from the fighting. As such, predicting conflicts — with the aim of preventing them — is a stated objective of organisations such as the United Nations and World Bank.**

This is not simple. It is easy to identify places whose social order is fragile, or which are geopolitically exposed, but much more difficult to determine if and when this will tip into conflict, especially in countries with a long previous history of peace. Attempts are now being made to do this using machine learning, which recognises patterns in data to predict likely outcomes. However, this requires massive amounts of data. One such effort, for example, uses systems trained on millions of news articles dating back to the 1980s.[4]

Purely data-driven approaches, however, may or may not map onto prevailing theories of conflict escalation or outbreak. Nor do purely data-driven predictions offer any guidance as to the potential form of any intervention. Finally, there is also the inherent problem that any publicly disclosed prediction can itself influence the course of events by affecting public sentiment or government decision-making, or by making transparent the thresholds at which intervention becomes likely. Additionally, the use of large datasets in conflict areas raises potentially thorny questions related to surveillance and the potential misuse of data by combatants.

### 5-YEAR HORIZON

**Machine-learning models improve conflict-risk detection**

The continued development of machine-learning models and other data-driven systems helps to improve detections of increased risk of conflict. The models are validated against historical and current experience to prove that they produce accurate predictions of the effects of conflicts and any interventions made to prevent them.

### 10-YEAR HORIZON

**Explicable ML facilitates better understanding of conflict prediction**

The development of "explicable" machine-learning systems allows their predictions to be better understood. Integration with theoretical models that capture top-down forces (such as communications from political elites) help to refine predictions and shape interventions. The first real-world interventions (partially) based on such predictions occur.

### 25-YEAR HORIZON

**Conflict prediction models adopted by global organisations**

Endorsement and adoption of these approaches by global multilateral organisations spreads. The development of accompanying ethical and practical frameworks ensures that predictions instil confidence rather than hasten conflict, and that interventions are timed and designed to respect the autonomy of those affected.

# 4.5.3 Optimisation of interventions

**Many instances of conflict stem from the deterioration of intergroup relations: one community or bloc begins to mistrust another, leading to reduced cooperation and overt frustration that ultimately become outright antagonism. In response, social scientists have formulated interventions that aim to improve such relations by reducing bias, hostility or negative behaviours. This approach has had some success, as measured by improvements in key psychosocial variables such as trust and inclusivity.**

However, this has also highlighted the need to optimise interventions for particular contexts. Interventions may be categorised by what they hope to achieve, how they hope to achieve it and how they can be delivered, but this needs to be supplemented with greater consideration of precisely what attitude or behaviour they are targeting, who they are trying to reach and how effectively they can be delivered within a particular operating environment. They also need to account for the level at which they operate — of individuals (for example, education), groups (exchange programmes) or societies (anti-discrimination laws).[5]

To achieve this, there will need to be greater structure and cross-disciplinary collaboration in the design of interventions. Perhaps most important, any research efforts will need to be developed and delivered in collaboration with local community leaders and citizens. Interventions at one level can have effects at different levels (anti-bigotry museum exhibits can encourage social mixing, for example) and over different timescales. They can also interfere with each other. That means they need to be carefully implemented in a way that allows them to be compared on a more systematic basis. Evaluation will need to be comprehensive and holistic (with great sensitivity to the possibility of unintended consequences), and geared towards practical solutions rather than improvements in some relatively abstract social variables.

## 5-YEAR HORIZON

**Intervention science matures**

Continued development of intervention science aims to create repeatable, context-sensitive approaches to intergroup conflict, in collaboration with local community members and with an emphasis on demonstrable real-world effectiveness, backed up by new sources of funding.

## 10-YEAR HORIZON

**Careful deployment of interventions begins**

Interventions are deployed after careful assessment of particular actors (leaders who may exploit them, for example) and contexts (which may affect delivery and efficacy), while also recognising their mutual interactions to ensure net benefit. Researchers will move even more toward collaborating with cultural institutions (museums, for example) and municipal leaders to inform the broader community about conflict narratives and opportunities for community investment.

## 25-YEAR HORIZON

**Refined, customisable interventions improve intergroup relations**

A full taxonomy of highly refined interventions can be deployed to improve intergroup relations, customised to particular circumstances and with full understanding of the appropriate timing and targeting for maximum effect.

## 4.5.4 Interaction with wider global trends

**Several megatrends are changing how intergroup conflict plays out. The changing climate, for instance, alters the viability of some lifestyles while opening up new ones — pastoralism versus mining in the Arctic, for example.[6] The superpower face-off of the late 20th century has given way to a new, more multipolar environment in which nations may simultaneously collaborate and compete, or enter into new alliances and alignments. These factors are causing significant changes in global mobility and thus leading to novel intergroup interactions.**

Combined with greater interconnection, this allows people to find and build common cause with others with whom they might previously have shared little affinity or even mutual awareness. This creates new groups, which may span geographies: for example, climate activists engaging in stochastic disruption, or the formation of new political blocs. Conversely, it can lead to competition for resources, whether real or perceived, and friction over cultural norms. These consequences might arise equally from forced migration away from poorer countries as from lifestyle tourism into them. State actors may also exploit these trends, for example through online propaganda or proxy conflicts.

Overlaid on all these factors are the effects of digital communication, particularly those mediated by opaque algorithms. This can lead to distorted perceptions about both social opportunities and social threats, including the motivations and intentions of others. Across contexts and cultures, overly negative "meta-perceptions" make people believe the worst of the other side and encourage support for hostile actions against them. Dramatic increases in polarisation suggest this is an increasing problem. Corrective information can de-escalate hostility, however, and engender a positive shift in attitude.

### 5-YEAR HORIZON

**Research develops solutions to disinformation**

Techniques to "inoculate" people against disinformation and malign online activity designed to foment conflict are developed and delivered through both formal and informal education programmes. These techniques must be developed simultaneously with a push for greater support of publicly funded media and sources of information.

### 10-YEAR HORIZON

**Migration creates novel interactions**

Climate change becomes a major driver of migration, leading to more novel interactions. Rather than impoverished migrants seeking to improve their economic fortunes, wealthier emigrants move away from fragile geographies.

### 25-YEAR HORIZON

**Research facilitates addressing global challenges as they arise**

The megatrends described above have become entrenched, as have their mitigants and other responses. Further challenges are arising as environmental, economic and geopolitical drivers continue to evolve. But half a century of group behavioural science means that they can be addressed far more systematically and effectively.

INVITED CONTRIBUTION:

# The Future of Multilateralism

**Thomas Biersteker**
Honorary Professor, International Relations/ Political Science, Honorary Curt Gasteyger Chair, Geneva Graduate Institute

MORE INFORMATION:

go.gesda.global/4-IC-1

**The decade following World War Two saw the beginnings of a profound change in global governance, with the founding of the United Nations (UN) in 1945 and the creation of many other new treaty-based, formal intergovernmental organisations (FIGOs), such as the International Monetary Fund, the World Bank and the World Health Organization. Much of our current understanding of international organisations, global governance and rules-based international order is based on analyses of the operations of these organisations.**[1]

Since the mid-1990s, however, there has been a significant increase in the number of informal governance arrangements and institutional forms. These include informal intergovernmental organisations (such as the G7, the G20, and BRICS) and trans-governmental initiatives (such as the Kimberly Process, which certifies conflict-free diamonds). At the same time, governance actors increasingly rely on informal practices. This is true even within FIGOs, with unspoken but implicit rules around, for example, the nationalities of those who hold key positions such as Director General or President. Lastly, informal transnational policy networks have emerged, consisting of a collection of individuals who share expertise and a common language for discussion of certain topics: this shared knowledge defines the community or network, to the exclusion of those who do not possess it. Such networks can set agendas and shape policy around both formal and informal organisations.[2]

The phenomenon of increasing numbers of informal intergovernmental organisations should be watched closely by those who hope to anticipate the future of multilateralism. Given the unique institutional characteristics of the UN, it is likely to remain a critical actor in multilateral global governance. Although it is a profoundly state-centric organisation — particularly around international security — its near-universal membership gives it legitimacy unrivalled by informal institutions. It is both inclusive and broadly representative, even in the Security Council, whose elected members are drawn from different regional groupings. However, the trend towards informality has several implications for its role over the next 5, 10 and 25 years.

On the one hand, informal arrangements create opportunities for more effective governance. The UN as a whole, its specialised agencies and other UN bodies increasingly address complex problems through multi-stakeholder partnerships that incorporate the expertise, operational capacity, material resources and societal connections of diverse actors. An important recent example is the Access to COVID-19 Tools Accelerator (ACT-A), in which the World Health Organization joined with diverse non-state actors such as the Bill & Melinda Gates Foundation and the Wellcome Trust to promote vaccines, treatments and other responses to the COVID-19 pandemic.

On the other hand, the proliferation of informal organisations in global governance leads to competition for authoritative influence, creating particular challenges for the UN. While it remains the first among equals in some domains (such as the protection of global intellectual property rights at the World Trade Organisation), in many others (such as cyber-governance), it is merely one actor among many.

To understand the implications of the interplay between both formal and informal multilateral actors more fully, some scholars in the discipline of International Relations have made both an ontological and epistemological move away from conventional teaching and training. One new approach is termed "Quantum International Relations", which fosters a multi-perspectivist and open dialectical approach to multilateralism. In this approach, concepts from quantum physics — such as entanglement, superposition, uncertainty and complementarity — are used to form new understandings of International Relations.

The quantum concepts of entanglement, superposition and complementarity have implications for how we think about the world. For example, quantum entanglement suggests that the quantum state of any particle or group of particles cannot be described independently of the state of the others, even if they are widely separated. Similarly, international relations should incorporate ideas of constitutive relationships, that parts and wholes are intrinsically interrelated, and that they could be mutually constitutive. Centre-periphery relationships in the world system should be viewed as co-constitutive and parts of a larger whole.

Further, the principle of quantum superposition asserts that an individual particle can be in one of several different locations at any given moment, and that the most general state of existence is a combination of these different possibilities. The location of a particle can be comprehended via the concepts and theoretical formulations of wave theory or in terms of particles. The idea that one of these theoretical approaches has to be correct and the other incorrect forces an unnecessary choice they can both be right at the same time and should be interpreted as different ways of conceptualising the same phenomenon. It might be that different formulations are equally valid simultaneously, depending on one's vantage point.[3]

Complementarity, introduced by Niels Bohr, describes the coexistence and duality of wave and particle theories, and is another metaphor that can be brought into International Relations. For instance, internationally shared histories are difficult to write and full of tensions, disputes and contradictions, but it is important to make the effort. Taken together, different, seemingly incommensurable understandings compose our world. This has important implications for how scholars from different parts of the world think about contemporary multilateralism.

A more open-ended, multidisciplinary approach can accommodate a multiplicity of contending, overlapping, incommensurable and interpenetrating world-order views, and one that leaves room for perspectives with different units, levels, ontologies and epistemologies characteristic of different approaches to inquiry.[4] This shift in orientation will be critical for the future understanding of global governance and the developing field of Global International Relations, as it enables one to recognise that actions taken to balance power can be simultaneously viewed by others as acts of imperialism. This does not mean that every perspective is equally valid, but that we need to make a concerted effort to understand them on their own terms, because they may be fundamentally incommensurable. In International Relations now and in the future, it will be essential to take an empathetic understanding of the positions of others, even if you strongly disagree with them,

so as to be able to engage in discourse with them "in their own language". The point is not to legitimise such perspectives, but rather to understand them and their contradictions.

There is significant resistance to dialectical approaches within the mainstream academic community. The methods and approaches that form the core of mainstream International Relations theory remain largely (and unreflectively) Newtonian, and training programmes are structured and designed accordingly. The introduction of open-ended dialectical thinking is not only timely, but essential for advancing the study and practice of International Relations, addressing the dynamic and multifaceted nature of global governance. This unconventional understanding of International Relations should not be considered as anti-scientific, separate from largely rational and analytical-empirical social science. Instead, it recognises human affairs as a highly complicated, contingent, reflective and fallible enterprise.

INVITED CONTRIBUTION:

# The Future of Trade

**Richard Baldwin**
Professor of International Economics
at IMD Business School, Lausanne, Switzerland;
Founder and Editor-inChielf, VoxEU

MORE INFORMATION:

go.gesda.global/4-IC-2

**Digital technology has had a profound impact on modern society, permeating nearly every aspect of our lives and economies. One aspect that is not as widely recognised as it should be is the transformation it is bringing about in world trade.**

Global trade is becoming "weightless", as trade in goods — things that you can drop on your foot — has plateaued, while trade in services — which are largely weightless, consisting of electronic transmissions and documents — has not. Service exports worldwide have grown 15-fold since 1998; goods exports grew by only 9 times during the same period. Services trade will most likely continue to grow faster than goods trade for the foreseeable future.

Why? There are essentially no taxes on imported services. And while services sold directly to consumers tend to be restricted by regulations, services that support the operations of companies — such as accounting, human-resource management, IT support, legal services, research and development, marketing and the like — are generally less constrained. So the barriers to trade in such "intermediate services" are not due to government policies but are simply due to the difficulty of using foreign teleworkers — and digital technology is lowering these barriers at an exponential pace.

The changes that came with telework during COVID accelerated this trend by 5 to 10 years. The use of artificial intelligence is rapidly making domestic and foreign workers better substitutes than they were in the past. Simultaneous speech translation, for example, will mean that most emerging-economy workers will be able to speak (via an app) good enough English to deliver services to clients anywhere.

Generative AI will accelerate this by distilling the experience of rich-nation service workers into an app which can be given to emerging-economy service workers in order to "level up" their skills.

Putting these factors together, it is clear that the future of trade lies in services. Barriers are radically higher for services than goods, but falling radically faster, and, unlike farm and factory goods, there is no capacity constraint in emerging economies when it comes to intermediate services. The demand for intermediate services is huge in rich nations and the supply of appropriate workers is huge in emerging economies, since they are already providing these services in their local economies. The growth of service exports from emerging markets has been remarkable: since 2016, emerging economies have seen their service exports grow far faster than those from high-wage nations.

This trend is now reshaping the economic development pathways of these countries, offering new opportunities for growth and job creation. Just as Bengaluru thrived on service exports, I believe that cities ranging from Nairobi and Cape Town to Bogotá and Buenos Aires are poised to become centres of service exports and thus drivers of their nations' economic prosperity and growth.

This new development path will require a shift in mindsets, since services have hitherto played almost no role in development thinking. Services were viewed as incapable of sparking a growth take-off in the way manufacturing could. This is strange, since most of the growth in today's rich nations is driven by the expansion of service sectors in cities, not factories in the countryside. Overall, national-development strategists in the digital era may do well to look to urban economics rather than development economics for inspiration and guidance.

Companies should adapt their strategies to leverage the benefits of digital technologies and global labour markets. This change in world trade will release a tidal wave of low-cost, highly skilled workers who have so far been forced to work for low wages in their local economy. Investing in digital infrastructure, enhancing workforce skills and fostering innovation in service delivery will be crucial for businesses to remain competitive in the evolving global trade landscape.

Policy-makers, on the other hand, need to create supportive regulatory frameworks that facilitate the seamless exchange of services across borders while ensuring fair competition and protecting domestic labor markets. This may include addressing issues related to data privacy, cybersecurity and the taxation of digital services. Moreover, policies that support workforce retraining and upskilling will be essential to help workers transition to new roles in the digital economy.

The transformative shift towards service-oriented globalisation presents both challenges and opportunities for businesses and policy-makers. Companies should adapt their strategies to leverage the benefits of digital technologies and global labor markets. Investing in digital infrastructure, enhancing workforce skills and fostering innovation in service delivery will be crucial for maintaining competitiveness in the evolving global trade landscape. Policy-makers, meanwhile, need to create supportive regulatory frameworks that facilitate the seamless exchange of services across borders while ensuring fair competition and protecting domestic labor markets. This includes addressing issues related to data privacy, cybersecurity, and the taxation of digital services. Policies that support workforce retraining and upskilling will be essential to help workers transition to new roles in the digital economy.

To conclude, the future of globalisation lies in services, not goods. Embracing this transformation is key to harnessing the full potential of the new era of globalisation and ensuring inclusive growth and development. The “emerging market miracle” will continue, driven by services rather than industry and commodities. The future is arriving faster than most believe, driven by exponential advances in digital technology and AI. Now is the time to decide what the future will hold and make the most of the opportunities that unfold.

CONFERENCE PROCEEDINGS

# Science Diplomacy at Scale

## 4.1 Science-based Diplomacy

Transboundary challenges such as COVID-19 or the climate crises can only be addressed through global collaboration. However, geopolitical tensions point in the opposite direction as nations retreat from multilateralism and erect barriers to international collaboration and challenges to evidence-informed policy-making. Join this session to learn how a globally recognised science diplomacy curriculum and capacity-building framework dedicated to effective multilateralism will equip future leaders and their institutions to tackle emerging global challenges.

MORE INFORMATION:

go.gesda.global/4-1-Diplomacy

PARTICIPANTS
Moderated by:

**Annika Brack**
CEO, International Center for Future Generations, Belgium

Opening remarks by:

**Martin Chungong**
Secretary-General, Inter-Parliamentary Union

With:

**Stephanie Balme**
Research Professor, Center for International Studies and Paris School of International Affairs, Sciences Po

**Jan Marco Müller**
Coordinator, Science Diplomacy and Multilateral Relations, European Commission

**Marcella Ohira**
Deputy Executive Director, Inter-American Institute for Global Change Research

**Daan du Toit**
Deputy Director-General, International Cooperation and Resources, Department of Science and Innovation

Closing remarks by:

**Martin Smith**
Head of Policy Lab, Wellcome Trust, London

TAKEAWAY MESSAGES:

*"Science diplomacy, involving nations, NGOs, citizens and Indigenous communities, is considered a modern tool for addressing transboundary challenges such as pandemics and climate change. Switzerland, Japan, the UK and the US, among others, include science diplomacy in their policy-making, supported by agreements like the 2019 Madrid Declaration and 2021 Vienna Statement."*

*"GESDA is working on creating a Global Curriculum for Science and Diplomacy, aiming to provide anticipatory science and diplomacy training to current and future leaders across sectors. The curriculum aims to foster a 'multilingual' mindset, encouraging collaboration across STEM [science, technology, engineering and mathematics] fields, governments, multilateral institutions and the private sector."*

*"Science diplomacy faces challenges in fragmented academic approaches and the need for a future-oriented, inclusive and multidisciplinary approach. Geneva, with its international organisations and diplomatic presence, is seen as a promising hub for training in science diplomacy and promoting global collaboration."*

*"As well as anticipating scientific breakthroughs, it is important to invest in building up the cadre of people who can interact at the interface between science and diplomacy to address global challenges."*

# From the Atomic Bomb to AI: Lessons from Oppenheimer

4.2 Advances in Science Diplomacy

Whether it be artificial intelligence or the climate crisis, all global challenges require international cooperation in science and engagement with society. In the face of rapid scientific and technological development, what lessons can be learned from the past and ensure that we responsibly anticipate the next breakthrough and its impact at large?

MORE INFORMATION:

go.gesda.global/4-2-Diplomacy

PARTICIPANTS
Moderated by:

**Adrian Monck**
Editor-in-Chief, *Seven Things*

With:

**Patrick Aebischer**
Vice-Chairman, GESDA; President Emeritus, Swiss Federal Institute of Technology Lausanne

**Paolo Benanti**
Theologian and Academic, Third Order Regular of St Francis; Professor, Pontifical Gregorian University; Advisor to Pope Francis on AI and Technology Ethics

**Doreen Bogdan-Martin**
Secretary-General, International Telecommunications Union

**Charles Oppenheimer**
Founding Member, Oppenheimer Project

**Kate Oppenheimer**
Founding Member, Oppenheimer Project

TAKEAWAY MESSAGES:

*"J. Robert Oppenheimer, known as 'the father of the atomic bomb', is viewed as a model of leadership for handling major scientific and technological crises. His role in the Manhattan Project, leading a team of Nobel-prizewinning scientists, is seen as particularly relevant to today's challenges in artificial intelligence."*

*"Developments in artificial intelligence are prompting fear because, unlike the atomic bomb, there is not necessarily any human in the loop to make a decision."*

*"Anticipating the latest developments in science and technology — as GESDA does — so that society has sufficient time to assess their impact and act could help to prevent mistakes of the past."*

CONFERENCE PROCEEDINGS

# Investing in Emerging Science

4.3 Prediction, Foresight and Futures Literacy

The emergence and impact of scientific breakthroughs are not only steered by academic or political interests but also follow the economic logic of market forces. Join this interactive session to learn which emerging topics mapped in the GESDA Science Breakthrough Radar® are likely going to be driven by an investment perspective — and which ones are not.

MORE INFORMATION:

go.gesda.global/4-3-Diplomacy

PARTICIPANTS
Moderated by:

**Meret Gaugler**
Healthcare Investor and Advisor, Switzerland

With:

**Julia Angeles**
Investment Manager and Partner, Baillie Gifford, UK

**William Egbe**
Managing Partner, Vibranium Capital Group, Cameroon

**Henrietta Fore**
Former Executive Director, UNICEF; Chairperson and CEO, Holsman International, US; GESDA Board Member

**Nicolas Roelofs**
Investment Director, Summa Equity, Sweden

**Ian Walmsley**
Provost, Imperial College London, UK

TAKEAWAY MESSAGES:

*"The world pledged to substantially raise investment in R&D and bolster research capacity as part of the UN's 17 Sustainable Development Goals (SDGs) for 2030 yet only 15 per cent of them are on track for completion."*

*"Both global spending on R&D and research capacity vary wildly between countries, with some such as Germany and Japan investing over 3 per cent of their GDP in R&D and having more than 4400 and 5000 researchers per million inhabitants respectively."*

TAKEAWAY MESSAGES:

*"The emerging topics mapped out in the GESDA 2023 Science Breakthrough Radar® that are most likely to be driven by an investment perspective are in sectors that are heavily focused on using technology in commodities or consumer goods."*

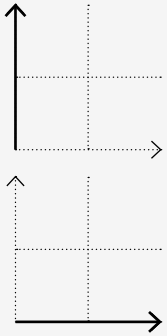
*"Science and diplomacy is another area where expected advances could help build more robust democracies in Africa and in Latin America, which in turn could transform lives very quickly and accelerate the reduction of poverty or indeed loss of life through scaling up the healthcare system."*

*"Geneva's financial hub could facilitate more public-private support for emerging science so that breakthroughs can move out of the lab and into the market. Challenges to funding for emerging science remain, including what is provided for redundant projects or those without a real-world use case. Understanding the potential output and value as well as intellectual property potential are paramount for good investment."*

# Media-Innovation Analysis

While the media coverage grown for Science-Diplomacy is lower than that for other Scientific Platforms, this topic is gaining significant momentum in terms of granted patents. However, patents issued relating to Digital Security are more stagnant, correlating with the lower increase in media coverage for this topic.

LEGEND:



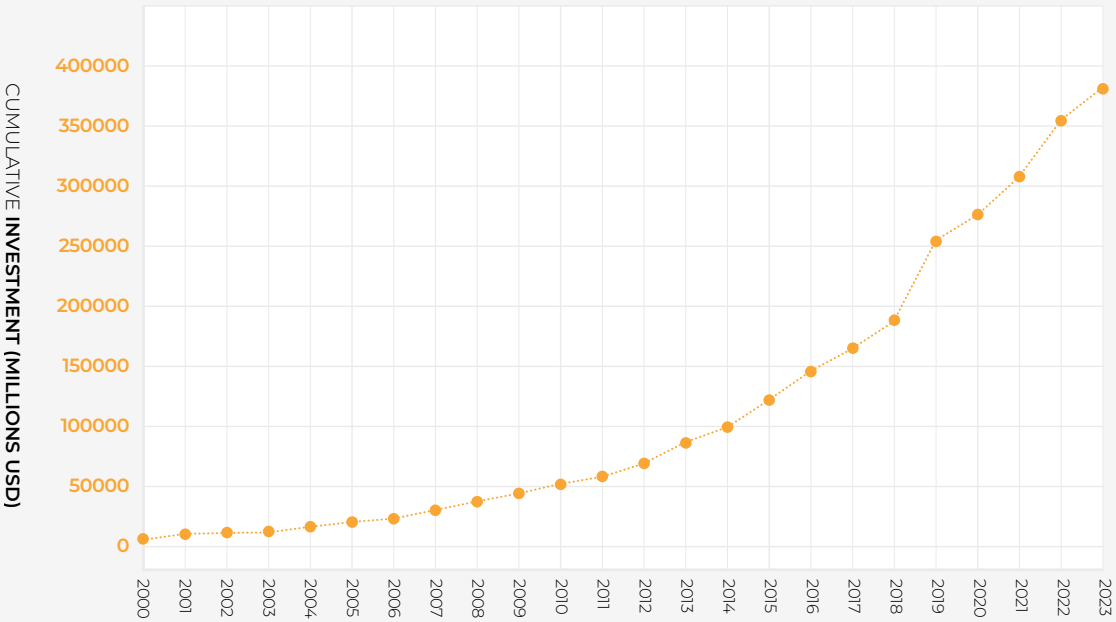
**YoY PATENT GROWTH**
YoY (year-on-year) growth of granted topic patents[1] from May 2022/Apr 2023 to May 2023/April 2024

**YoY MEDIA GROWTH**
YoY (year-on-year) growth of topic mentions in news and blogs from May 2022/Apr 2023 to May 2023/April 2024

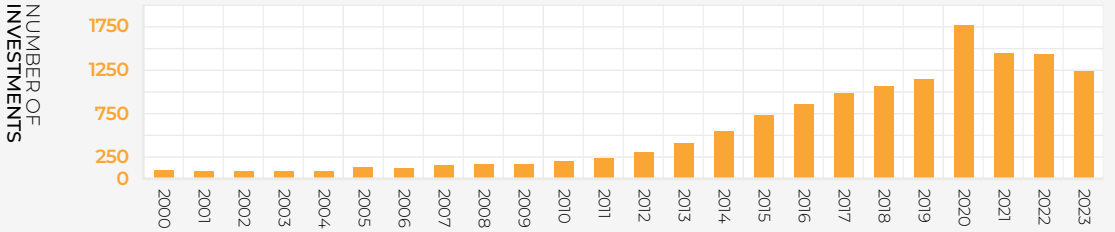
MORE INFORMATION:

go.gesda.global/Impact

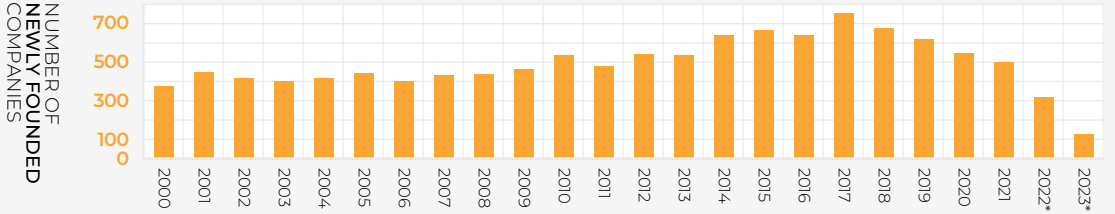
## CUMULATIVE INVESTMENT IN DIGITAL SECURITY COMPANIES




## NUMBER OF NEW INVESTMENTS IN DIGITAL SECURITY COMPANIES




## NUMBER OF NEWLY-FOUNDED DIGITAL SECURITY COMPANIES




IMPACT FOCUS:

# 4.4 Investment and Company Creation in Digital Security

Year-on-year investments in Digital Security have grown exponentially since 2000. The total and yearly value of investments are large compared with other science and technology-related investments surveyed in the Radar, coherent with the established nature of the Digital Security field. This can be observed in the large number of new companies coming into existence each year since 2000. The large jump in investments in 2020 may be a result of the increased reliance on digital infrastructure for remote work during the pandemic and increasing geopolitical tensions and resulting cyberattacks.

Source facing page: Deep View analysis from 1 May 2022 to 30 April 2024; (1) YoY media growth = YoY growth of topic mentions from May 2022/April 2023 to May 2023/April 2024; (2) YoY patent growth = YoY growth of granted topic patents from May 2022/April 2023 to May 2023/April 2024: (*) No patents identified for this topic.

Source, this page: Pitchbook
*Data on newly-founded companies in 2023 is incomplete and will be updated once first funding is raised. Projections indicate similar levels of company creation to 2021.

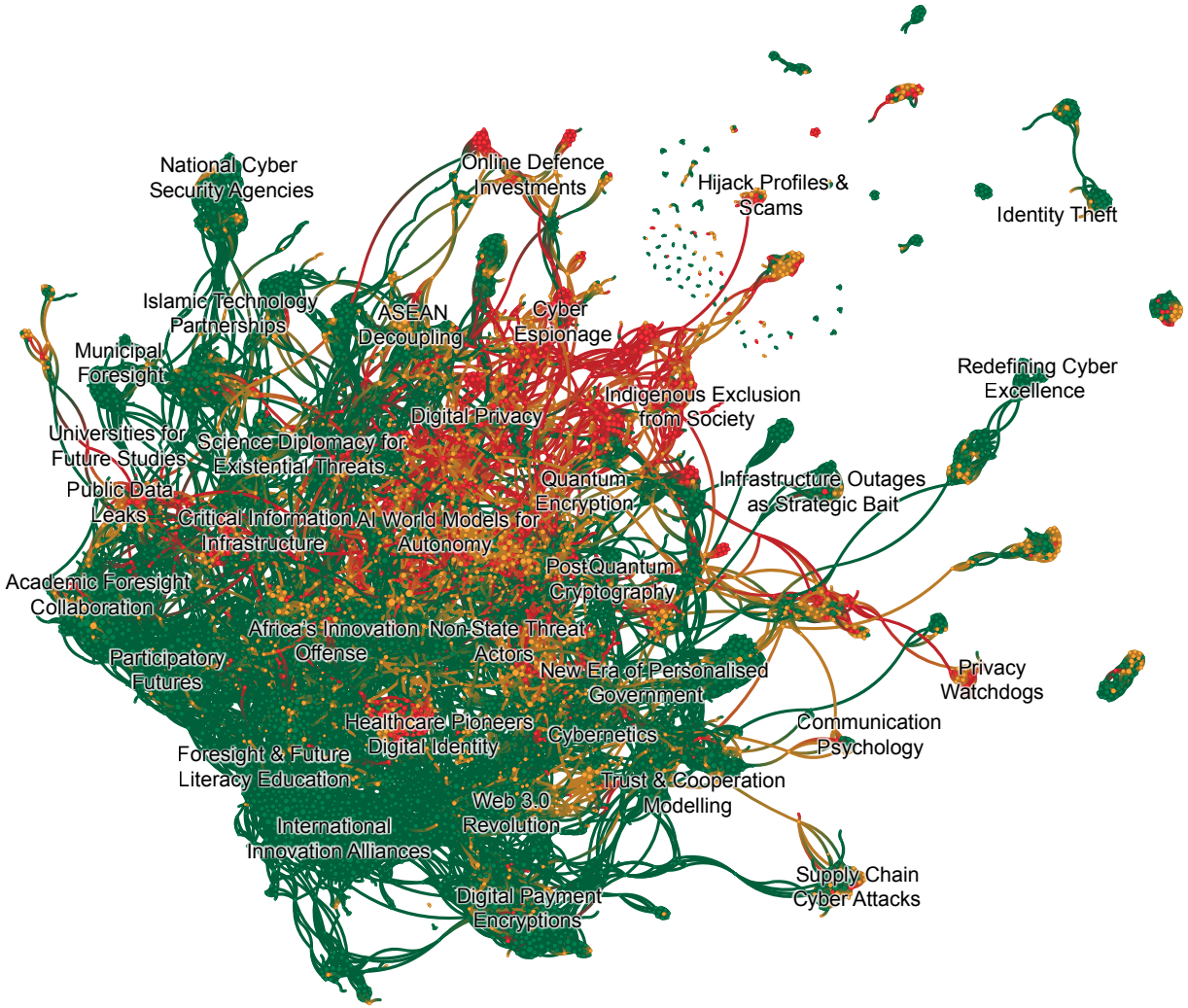
## What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months shows that the discourse around Science & Diplomacy is less optimistic than the other conversations around Scientific Platforms in the Radar, with predominant concerns including the fear that future diplomatic efforts and processes will be unsuited to addressing diverse global perspectives, and fears of increased state surveillance via a transition to digital identity. Science & Diplomacy has a 67 per cent net positive sentiment in mainstream media.

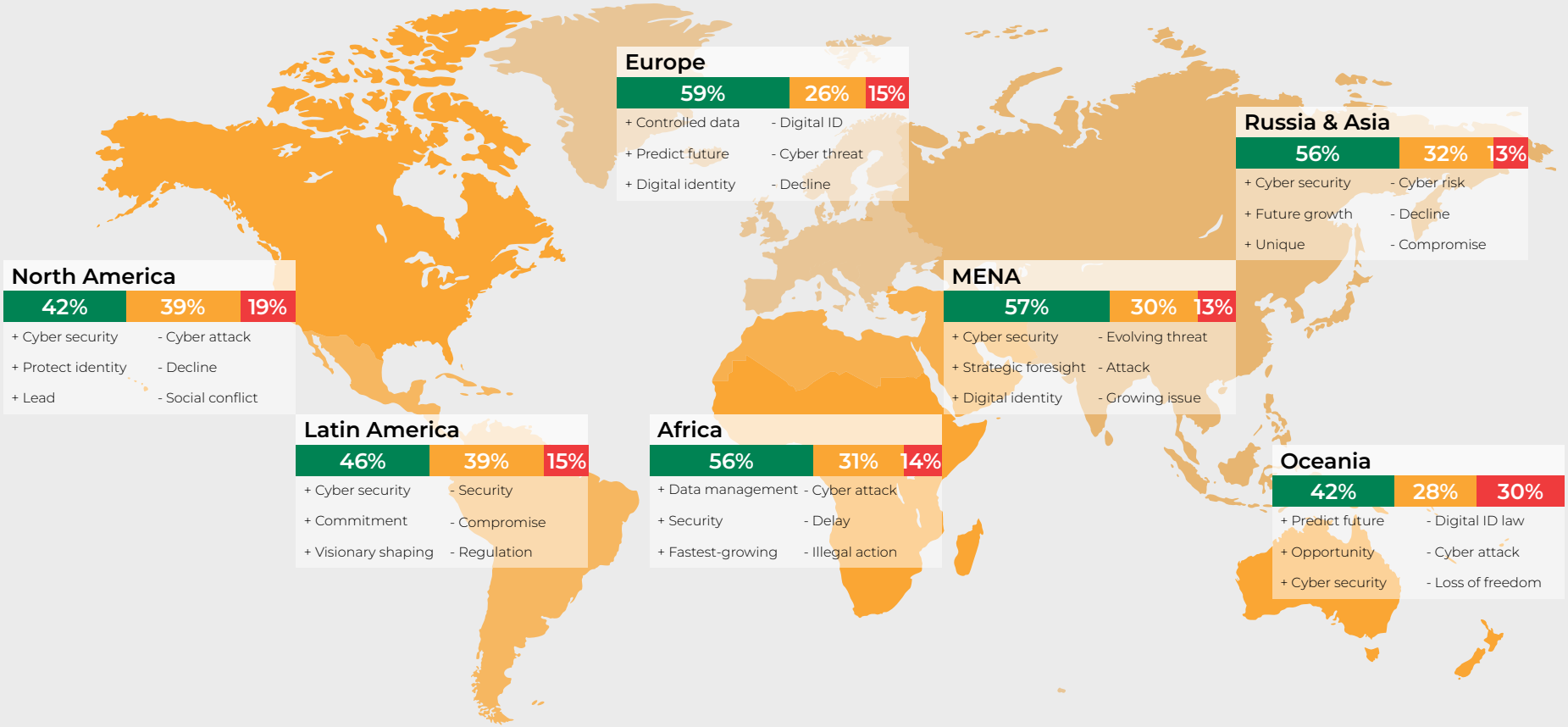
MAINSTREAM MEDIA SENTIMENT

| MAINSTREAM MEDIA | 1 May 2023 to 30 April 2024 |
|---|---|
| UNIQUE ARTICLES | 548k |
| VISUALISED ARTICLES | 6k |
| NET SENTIMENT | 67% |
| ARTICLE UNIQUENESS | 13% |

| SOCIAL MEDIA | 1 May 2023 to 30 April 2024 |
|---|---|
| NUMBER OF POSTS | 1430k |
| VISUALISED POSTS | 10k |
| NET SENTIMENT | 55% |
| UNIQUE IMPRESSIONS | 61b |



## DEMOGRAPHICS & SENTIMENT PER REGION




## GLOBAL SENTIMENT

- Sentiment regarding **Science & Diplomacy varies significantly across the globe. Europe, Russia & Asia and MENA regions** are associated with **more positive sentiments**, whereas **North America, South America and Oceania display less positive sentiments**. In **Oceania**, the discourse around **Science & Diplomacy** is associated positively with leadership, but the relatively high level of negative sentiment is centred around health concerns — pandemics in particular.

- The discourse is predominantly led by the **US** in North America (93%), while in **Europe**, the UK (35%) and Montenegro (38%) are the top contributors the forefront. **Latin America** shows a spread of involvement, including Brazil (23%), Chile (12%) and Mexico (13%). In **Africa**, Nigeria (57%) and Kenya (16%) lead the conversation. **Russia and Asia** see major contributions from India (51%) and Indonesia (11%). In the **MENA region**, Turkey (34%) and the United Arab Emirates (13%) are prominent contributors.

Source: Quid Social, containing the past 24 months of English language data from 10+ social media sources in 200+ countries.

# Media Analysis

## GROWTH

The discourse on Prediction, Foresight and Futures Literacy is witnessing an explosive growth, whereas Digital Security, despite its comparatively lower growth rate of just 13 per cent, remains predominant, accounting for over 50 per cent of all mentions.

## DOMINANCE

In the dominant topic of Prediction, Foresight & Futures Literacy, the science and art of strategic foresight has seen a near doubling of mentions in public discourse. Compared with other topics, Digital Security and Behavioural Science of Groups saw moderate growth rates of 13 per cent and 14 per cent respectively, fuelled by the expansion of concerns around privacy and security.

## SOCIAL SENTIMENT

Discussions around Science & Diplomacy are highly emotionally charged, as indicated by fewer neutral-sentiment posts. Significant changes in net sentiment could indicate a strong influence of political developments on public perspectives regarding topics in this Scientific Platform.

MORE INFORMATION:

**go.gesda.global/Society**

## 4.2 Advances in Science Diplomacy




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 4.3 Prediction, Foresight & Futures Literacy




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 4.4 Digital Security




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 4.5 Behavioural Science of Groups




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24

SCIENTIFIC PLATFORM

4

# Science & Diplomacy

The products of science and mathematics, such as vaccines, AI and systems for digital security and privacy, are increasingly recognised drivers of global health, engaged and active citizenship, and wealth creation. That gives science and technology a central role in multilateralism. Diplomats and policy-makers across the globe are thus ever more focused on understanding and using research breakthroughs, both to anticipate their impact on individuals, society and the planet, and to apply them in their own work. Here we provide insights into the ongoing research into key topics and capabilities in this field, including new approaches to modelling diplomacy, the future of prediction and foresight, methods to understand group behaviour, anticipated advances in digital security and an increasing impetus for futures literacy.

PULSE OF **SCIENCE** (pages 216-253)

Containing deep insights into anticipated advances in the relations between science and diplomacy over the next 5, 10 and 25 years, the GESDA Pulse of Science provides the expert opinions of leading researchers in topics such as digital security, futures literacy, group behaviour and science diplomacy.

PULSE OF **DIPLOMACY** (pages 254-257)

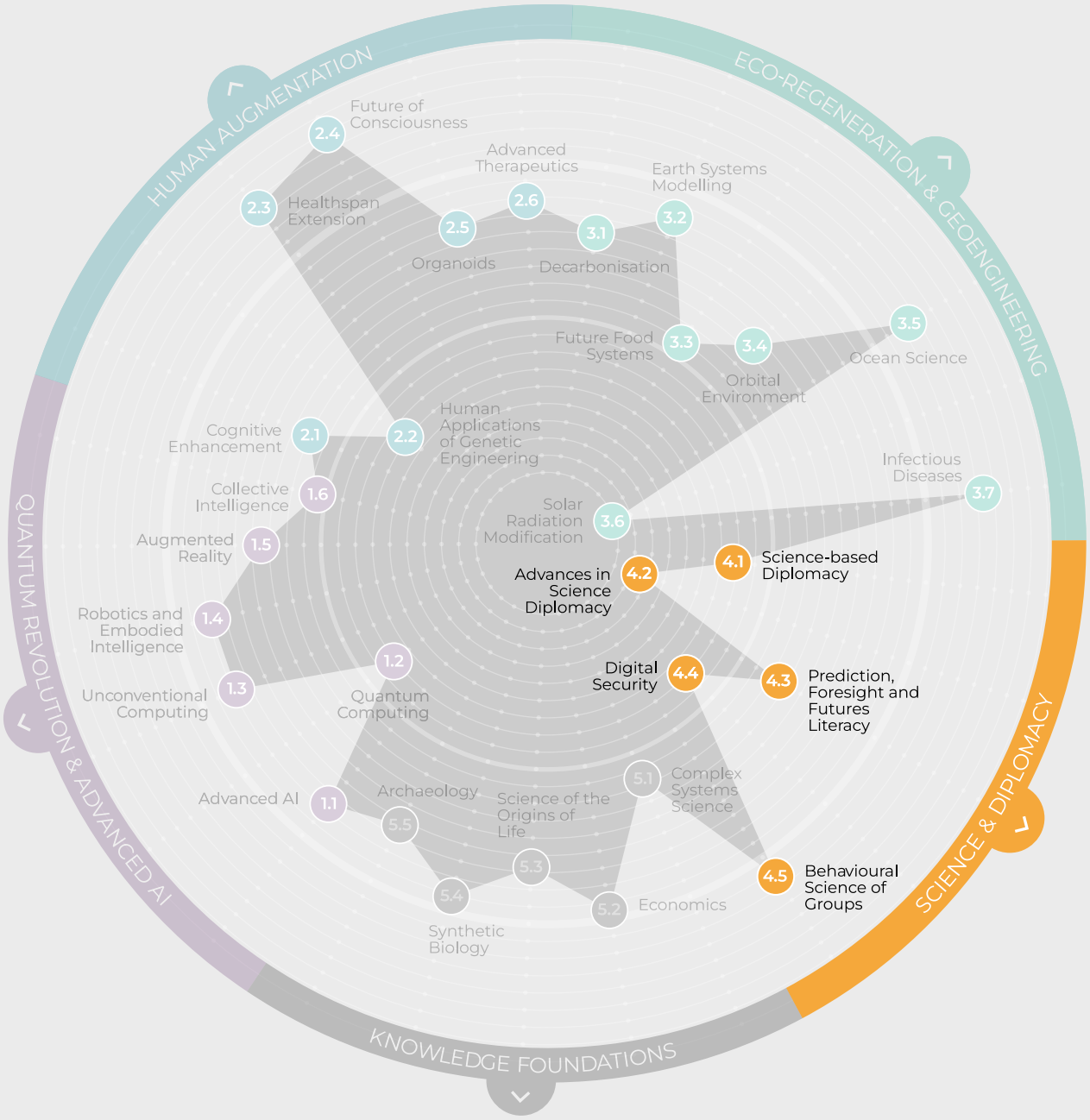
The GESDA Pulse of Diplomacy captures the latest discussions between diplomats and scientists at the 2023 GESDA Science and Anticipation Summit on topics such as predicting the onset of armed conflict, computational diplomacy and superforecasting.

PULSE OF **IMPACT** (pages 258-259)

Current investment trends and dynamics of company creation highlight digital security as an increasingly significant area. The GESDA Pulse of Impact provides data detailing private sector investment, intellectual property activity and company creation in the area of digital security since 2000.

PULSE OF **SOCIETY** (pages 260-263)

Powered by AI, the GESDA Pulse of Society's network and dynamic sentiment analysis of both mainstream and social media reveals macro and micro trends in public opinion around the world on topics relating to science and diplomacy.



4.1

# Science-based Diplomacy

CHAIR:
**Didier Wernli**
Associate Professor at the Global Studies Institute and the Department of Computer Science, University of Geneva

CONTRIBUTORS:
**Örjan Bodin, Lars-Erik Cederman, James Hollway, Rak Kim, Rafael Mesquita, Hannes Müller, Christopher Rauh**

**The "Scientification of Diplomacy" is based on interdisciplinary work between global governance, international relations, international law, computational social sciences, mathematics, optimisation theory and behavioural research. It covers different emerging fields of research, such as Computational diplomacy and Negotiation engineering.**

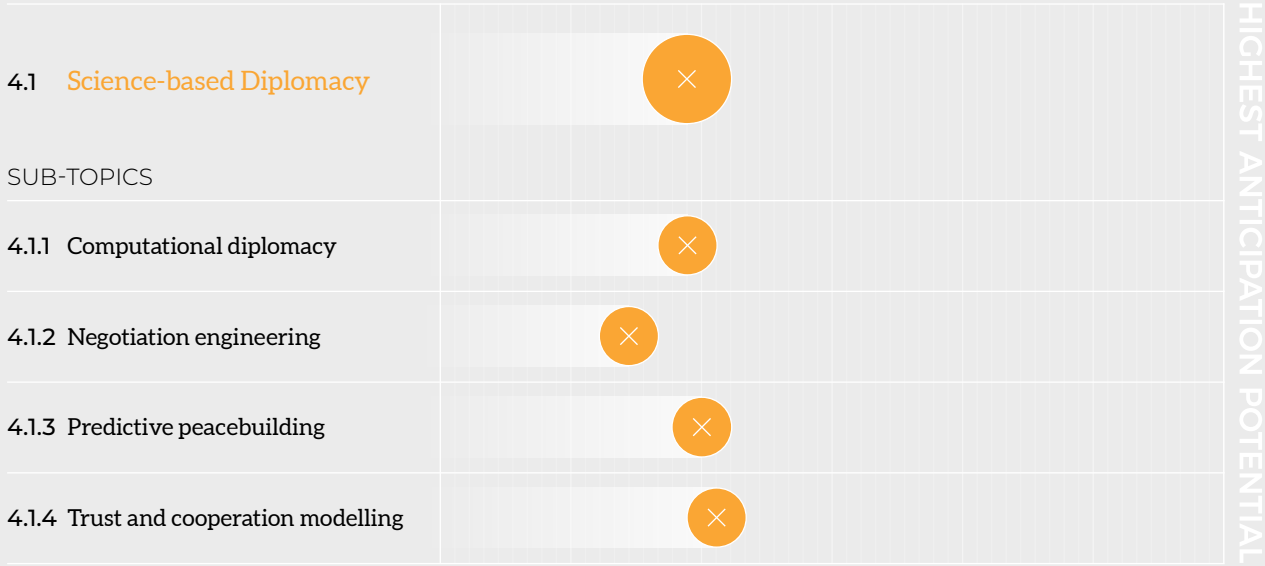
Computational diplomacy, for one, is concerned with our emerging ability to map the landscape of international relations, to gather and analyse data on unprecedented scales and to simulate potential outcomes. This has transformational potential for diplomatic activity. For instance, efforts have already begun to plot the networks of influence between actors on an international scale and to use artificial intelligence to mine the large databases of texts relating to historical negotiations and international organisations. As such, Computational diplomacy is revealing not only the complexity of modern international relations but the potential knock-on effects of future actions, giving opportunities to favour the emergence of desired outcomes. It also allows actors to better understand the history of negotiations, how changes in language reveal movements in position and to reduce uncertainty in formulating plans.

Negotiation engineering, on the other hand, is a solution-oriented approach to negotiation problems that uses quantitative methods in a heuristic way to find an adequate solution. The approach draws on breaking down and formalising the problem(s) at hand and on the heuristic application of mathematical methods such as game theory and mathematical optimisation. In this way, it can contribute to recognising feelings and better managing them during the negotiation process, as well as allowing for resolutions of more complex real-world issues.

KEY TAKEAWAYS

Researchers from a wide range of academic disciplines are collaborating to improve approaches to diplomacy through applying numerical, computational and other technical forms of understanding. **Computational diplomacy**, for instance, can exploit existing data to better understand past diplomatic achievements and the network structures that facilitated them. Also of interest is **Negotiation engineering**, which raises the possibility that future agreements will be informed by computationally derived understanding and will more successfully bring together broader groups of stakeholders in complex negotiations, while allowing progress with fewer missteps. Similarly, **Predictive peacebuilding** has potential to use machine-learning approaches to increase the chances of achieving greater international stability. **Trust and cooperation odelling** applies computational approaches to the task of establishing relationships that result in positive experiences of cooperation and collaboration while providing tools for distinguishing trustworthy from untrustworthy potential partners.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

The Anticipation Potential scores of the topics covered by Science-based Diplomacy are relatively similar. The main variable driving the scores is the uncertainty of future developments of the related fields. Predictive peacebuilding rates slightly higher because of the perceived positive impact it may have on society in the future.

MORE INFORMATION

**go.gesda.global/4-1**

## 4.1.1 Computational diplomacy

**The world of diplomacy is rich in data. The United Nations and other international forums have detailed records of debates, speeches and negotiations going back decades. Then there are databases recording demographics, trade, finance, spending and common declarations made by international organisations. Beyond these forums, important sources include records of human rights violations and other data used by international justice organisations.**

The cost of processing this data means it has not been well used to inform the process of diplomacy, to amplify cooperation and to improve outcomes. Nevertheless, organisations like the UN, the World Bank and other policy-makers are working hard to integrate quantitative methods into their organisations, which will accelerate the practice of Computational diplomacy and its use of big data, machine learning and computational thinking.

There is much low-hanging fruit here. The networks of actors on the international stage and their institutional relationships are already beginning to be mapped,[1,2,3] giving a deeper understanding of the connections that can influence negotiations. Also being mined for insight are resolutions adopted by various international organisations. Relevant examples include the UN General Assembly and Security Council resolutions histories,[4] sponsorship data[5] and debate themes, as well as the resolutions adopted by the World Health Organization.[6]

Much more can be done. Combining a data-driven approach with computational modelling can facilitate a more fundamental understanding of how multilateral governance systems work and how they can be improved, for example.[7] The growing use of AI is likely to have a significant impact here,[8] but developing the multidisciplinary expertise that can manage and exploit diplomatic processes is a significant challenge.

### 5-YEAR HORIZON

**Higher-education establishments broaden skill sets for scientists and diplomats**

Efforts to build capacity for computational diplomacy bear fruit in the form of an increased range of courses and training programmes across relevant disciplines. Predictive modelling improves at the sub-national level with AI systems providing natural-language translations of model outputs.

### 10-YEAR HORIZON

**Text-mining shows its worth on the global stage**

In helping to finalise the language in several major agreements and in helping to prevent "forum shopping" by several state actors, text-mining shows its potential and is set to become a standard tool in international negotiations. Predictive modelling becomes more fine-grained, with the potential for daily updates and a greater ability to predict the effect of policy changes.

### 25-YEAR HORIZON

**Computational diplomacy reshapes international relations as a science**

The successes with text mining and other data-driven applications allow experts to create a robust theory of diplomacy that makes testable predictions and creates useful frameworks for diplomatic interactions. Predictive forecasts become a ubiquitous tool for policy-makers, who will know in advance the effect of their actions and how they may inflame or cool tensions.

## 4.1.2 Negotiation engineering

**Negotiation engineering uses quantitative methods in a heuristic way to find an adequate solution to a set of complex negotiation problems. In doing so, it particularly draws on the decomposition and the formalisation of the problems at hand and the heuristic application of mathematical methods such as game theory and mathematical optimisation to reach agreement.[9]**

This approach could help to reveal the ingredients of success for global cooperation. Numerous non-governmental organisations in complex networks currently aim to solve complex problems such as climate change and the challenges related to Sustainable Development Goals. And yet they often achieve far less than they hope. A better understanding of the way organisations should interact to achieve specific goals could change this.

Negotiation Engineering has already achieved a number of practical successes. For instance, in the diplomatic sphere, the approach played a crucial role in the Land Transport Agreement between Switzerland and the European Union and in facilitating nuclear talks between Iran and the P5+1 group of nations.[10]

Negotiation Engineering does not intend to replace face-to-face discussion and neither does it seem likely to ever do so. It may in some cases also have limited application: not all problems are quantifiable or should be reduced to a quantitative level. However, in cases when a negotiation involves problems with a particular degree of complexity and actors with a certain level of analytical capacity open to a rational approach, Negotiation Engineering can allow for more logical accuracy in finding pragmatic solutions while building trust between mediators. To that end, significant capacity-building is required for future development.

### 5-YEAR HORIZON

**Capacity-building accelerates Negotiation Engineering**

The automated processing of text to make it machine-readable leads to more advanced models of areas of conflict. This allows stakeholders to map out and discuss potential futures before deciding on a course of action.

### 10-YEAR HORIZON

**Mathematical thinking focuses international discussions**

A new generation of scientists currently being trained in the grammar of computer science and in diplomacy become influential in the diplomatic world. That leads to an increasingly wide variety of international actors applying mathematical methods to their negotiation problems to help focus discussions and to make potential outcomes more logically accurate.

### 25-YEAR HORIZON

**Negotiating standards increase thanks to mathematical approaches**

Mathematical skills are common in positions of influence, allowing Negotiation Engineering to become a standard tool in many negotiations.

# 4.1.3 Predictive peacebuilding

**Predictive peacebuilding uses data science to better understand the roots and warning signs of conflict in order to predict where it is likely to occur and to help develop mitigation, preventative and rebuilding strategies.[11]**

The field has been bolstered by a number of successes. For example, machine-learning-based analysis of newspaper text can predict the onset of conflict, becoming particularly useful when risk in previously peaceful countries arises.[12] Analysis of food prices shows that increases beyond a threshold level are correlated with civil unrest in many parts of the world.[13] Granular, actor-based conflict data give rise to models that take these into account.[14]

Research in the field sees policies for conflict prevention — mediation, development aid, institutional reform and building state capacity, for example — as a prediction policy problem.[15] This means that the treatment effects of different policies, and the targeting of these policies in time and space, both need to be studied quantitatively. However, important limitations and potential pitfalls remain. Current conflict models have limited ability to make causal inferences and are sometimes informed by outdated data-gathering.

Even more serious is the possibility that predictive models can be self-fulfilling or self-defeating. For example, a prediction of war could cause local populations to flee, raising tensions that themselves trigger conflict. Also, care is needed in defining peace and ensuring that "peaceful" outcomes make a difference to real people's lives, such as refugees and people who have experienced trauma. Understanding these kinds of questions requires granular data gathered on a vast scale to inform decision-making and cost-effective use of resources.

## 5-YEAR HORIZON

**Computer models map potential outcomes**

Advanced models of areas of conflict allow stakeholders to map out and discuss potential futures before deciding on a course of action. Causal inference and prediction models are increasingly integrated and able to exploit new data on armed conflict, impacts and policies.

## 10-YEAR HORIZON

**Individual data-gathering creates new peacekeeping tools but raises serious issues of privacy and exclusion**

Researchers begin to use a wider range of data, such as anonymised mobile phone data, to study the potential for conflict. They lobby for accountability for social-networking companies, who can now explicitly see when activity on their sites is fuelling unrest. The real-time nature of some data-gathering exercises raises issues of privacy and exclusion of those without a digital voice, that need to be addressed. At the same time, models appear that take into account the impact of peacebuilding on people's lives.

## 25-YEAR HORIZON

**Climate change and conflict increases use of peace modelling**

As pressures from climate change increase, and civil unrest becomes common in some parts of the world, the use of predictive peacekeeping models becomes a default response.

## 4.1.4 Trust and cooperation modelling

**Political scientists, sociologists and computer scientists have begun to create systems in which autonomous agents have to find ways to cooperate by distinguishing trustworthy from untrustworthy agents. This has been applied to a wide range of problems, ranging from information-routing algorithms to online search rankings to recommendation algorithms. But there is broader sense in which trust and cooperation studies are useful — in modelling the way people behave in the groups that make up societies.**[16]

In any society, business or network, the ability to evaluate and then trust partners is a crucial component of co-operation.[17] Applying trust modelling to the networks of actors at work in the diplomatic landscape has the potential to better model potential outcomes of discussions, votes and negotiations.

This work comes at a time when the role of trust in broader society has been thrown into sharp focus by the phenomenon of fake news, manipulated images and deepfake videos. The diplomatic landscape is powerfully shaped by the information that flows through it, and false and misleading information has huge disruptive potential.

A key emerging issue is the role of artificial intelligence and how it will be used to inform cooperative decision-making. At the heart of this question is whether AI systems will become better at interpreting the complex data fed into them or worse as AI-generated data distorts their view of the world. The possibility that AI systems could create a kind of artificial truth will be an important issue for the field.

### 5-YEAR HORIZON

**Data veracity becomes a global research issue**

The increased importance of data-gathering and analysis places a greater focus on data sources and their veracity. This leads to increased research in data-verification research. Managing trust and reputation are already battlegrounds for some actors.

### 10-YEAR HORIZON

**Stakeholders battle over reputation and trust**

Reputation-building and trust further become key factors for stakeholders in a wide range of data-gathering disciplines ranging from news organisations to scientific institutions to national and multinational organisations. AI plays an increasing role in these processes.

### 25-YEAR HORIZON

**AI oversees data veracity**

Machine vision and artificial intelligence become important arbitrators of trust in data, news and images. However, a cat-and-mouse game continues between malicious actors and those attempting to shut them down.

4.2

# Advances in Science Diplomacy

CHAIR:
**Pierre-Bruno Ruffini**
Professor of Economics at the University of Le Havre, Normandy, France

CONTRIBUTORS:
**Marga Gual Soler, Derya Büyüktanir, Joy Zhang, Jean-Christophe Mauduit, Luisa Echeverría-King, Luc Van Langenhove**

**The field of science diplomacy research seeks to establish an evidence-informed foundation for supporting and empowering the increasingly diverse set of stakeholders who practise science diplomacy. These are not just nations but non-governmental actors, groups of citizens and Indigenous communities.**

The products of science are increasingly celebrated as drivers of global health, sustainable development and wealth creation. However, science and technology are also sources of tension and competition between nations or regions. The COVID-19 crisis highlighted the role of science on the international stage, how it rapidly advanced novel vaccine technologies, and how cooperation over these vaccines became a crucial part of the currency of international negotiations, diplomacy and geopolitics. But conflict also plays a role in mediating the influence of science and technology. Situations such as the war in Ukraine are revealing how careful states need to be with powerful technologies, the way they are transferred and how they are used.

Climate change is one of the many key proving grounds for this work — especially with the rapid opening of ice-free routes through the Arctic Ocean and the geopolitical tensions this is creating. “Big science” projects are also part of this diplomatic landscape, requiring long-term technical and diplomatic engagement among a broad group of stakeholders. These diverse groups must also find ways to manage traditional and emerging global commons fairly and effectively. A final challenge is to find ways to train science diplomats, build capacities and evaluate this work, to create a continual cycle of learning and improvement in the practice of science diplomacy.

The nature and complexity of reciprocal benefits in science is likely to become a more important part of the landscape for science diplomacy, particularly with regional science-diplomacy projects providing a new way to navigate rivalries between bigger global powers. New skill sets and training for science diplomats will be needed to fully explore reciprocity in science.

## KEY TAKEAWAYS

Science diplomacy plays an important role in a world that is increasingly dominated by issues of science and technology, and frequently fractured by economic and geopolitical events. Researching the use of **Science diplomacy for effective multilateralism**, for example, can establish successful means of communication and negotiation through shared interests and goals, as well as understanding how science and technology diplomacy is used to further one-sided interests and compete in global markets. The rising influence of private technology firms and local and regional concerns means that **Technology diplomacy and the role of non-state actors** is an urgent area of research, helping to establish new norms and practices. There is also a growing need to study the effects of alignment between **Science diplomacy and emerging economies**, since smaller nations are banding together in science and technology projects that increase both their effectiveness and their influence on the global stage. Research is also under way into the role of **Science diplomacy as a response to conflict- and inequality-driven tensions**; properly grounding this area of study in evidence-based discussion will be crucial to enabling science diplomacy to flourish as a means of establishing trust and cooperation.

## ANTICIPATION SURVEY RESULTS

## SURVEY OBSERVATIONS

Science diplomacy is an area that is heavily influenced by the current geopolitical situation. As a result, all issues covered by this topic will peak in the next five years. This explains the lower Anticipation Potential scores across the board. The impact of Technology diplomacy and the role of non-state actors is influential on society and thus augments the score for this sub-topic.

## MORE INFORMATION

**go.gesda.global/4-2**

# 4.2.1 Science diplomacy for effective multilateralism

**A key goal for science diplomacy is to find ways to balance strategic cooperation against competition. Science diplomacy has traditionally established itself as a way to use science as a "soft power" that can advance diplomatic objectives. The 50th anniversary of signing the Antarctic Treaty, for instance, engaged diplomatic and academic communities in the use of science diplomacy as a tool for improving multilateral relations. Commitments to science-based diplomacy have since been incorporated into national strategies and policies, opening new avenues for cooperation. This has been important in establishing positive communication and diplomacy, helping collaborative navigations of "global commons" issues such as COVID-19, climate change, exploitation of space, deep-sea mining and managing Arctic and Antarctic resources.**

At the same time, however, the reality of global politics and geo-economics means that there are increasingly areas of tension that involve science and technology.[1] In the openness vs security dilemma, the rise in tensions between certain countries is leading to move the balance towards greater security, with traditionally open and liberal countries shifting their stance. Canada, for instance, has been applying a new Policy on Sensitive Technology Research and Affiliations of Concern since the beginning of 2024.[2]

Negotiations over the location of key science projects such as the Future Circular Collider are all potential sources of conflict and competition: science diplomacy is being used to leverage national and regional power, calling into question the mainstream vision of science diplomacy as inherently at the service of peace.

### 5-YEAR HORIZON

**National bodies call for action over resources held in common**

Studies of large parts of oceans protected from exploitation — Marine Protection Areas — provide evidence that international action can bring about significant beneficial change to global commons. Tensions between the US, Russia and China over Arctic resources grow more intense, involving science diplomats in both collaborative and competitive activities.

### 10-YEAR HORIZON

**Lunar exploration and regional concerns bring challenges**

Lunar missions from a number of nations highlight the necessity and importance of science diplomacy to tackle the issues these activities raise. As nations seek to shorten supply lines and strengthen trade links, new regional interest blocs emerge. This changes balances of geopolitical power, and science-resource sharing and collaborations openly mirror economic patterns.

### 25-YEAR HORIZON

**Trained experts in science diplomacy begin to steer policy**

Decades-long training initiatives mean that science and diplomacy-savvy professionals begin to reach positions of influence in their respective careers, fields and countries. The task of balancing national interests against multilateral interests remains challenging.

## 4.2.2 Technology diplomacy and the role of non-state actors

**Transnational companies and industry associations are gaining significant diplomatic influence over policy, pushing regulation — in the cases of AI, self-driving cars and deployment of orbital resources, for example — and creating tangible effects on policy.**

The attempts at influence go both ways, however. Numerous nations (and groups of nations, such as the EU) have created "tech ambassador" roles and deployed these representatives to gather information, lobby and negotiate in Silicon Valley and other technology hubs around the world.[3]

Sometimes, technology diplomacy has to operate where the lines between nation-states and private companies are blurred, as with China's Huawei and ZTE. There are also issues with technology companies offering a country a competitive edge or working in areas that involve national security sensitivities, such as supercomputing hardware. Here, tech diplomats must tread the fine line between corporate freedoms, global balances of power and issues of national interest — often with incomplete information due to the unwillingness of all parties to fully disclose all the relevant data.

In some regions where regulatory environments are weak, lobbyists, activists and grass-roots organisations are pushing the boundaries of science with their work on anti-ageing therapies and gene editing, some of which can influence regulatory policy-making, and sometimes accelerate the pace of change. Even small-scale companies, if they are significant employers in a region, can influence local political decision-making and tech-related legislation.

All of these various initiatives demonstrate the rising importance of transnational, non-state and even individual or small-group actors to local and global governance, something that the field of science and tech diplomacy must navigate.[4,5]

### 5-YEAR HORIZON

**Science diplomacy and technology platforms shape each other**

The industrial and societal sector begins to influence science diplomacy in areas such as access to space and with respect to the lunar environment. Technology firms invest further in "ambassadors" who exist to seek ever-greater influence in transnational organisations such as the UN. Research in technology diplomacy achieves deeper elucidation of the issues where national security clashes with corporate freedoms. More embassies deploy an "attaché for innovation".

### 10-YEAR HORIZON

**Multi-stakeholder science diplomacy becomes the norm**

Science-diplomacy efforts involve actors from city, state and regional governance as well as multinational companies, global science organisations and civic groups. Training schemes for science diplomats produce a growing number of graduates to meet burgeoning need. IPCC-like organisations with transnational responsibilities and influence are significant powers in the science-diplomacy arena. Economic diplomacy is inextricably linked to science and technology diplomacy. Non-governmental actors develop greater influence on national strategies and in science diplomacy.

### 25-YEAR HORIZON

**Private-sector actors are integrated into governance**

Private-sector actors pioneer new ways of achieving governance and agreement on exploitation of deep-sea, orbital and mineral resources for manufacturing. City and regional planners and policy-makers routinely seek advice from private company representatives and researchers working outside of academia.

## 4.2.3 Science diplomacy and emerging economies

**Science diplomacy has long played a part in maintaining good relations between economic world powers.[6] In recent years, CERN has extended this to embrace partnerships with the world's emerging economies, such as Chile, India and Pakistan.[7] This has added new dimensions to diplomacy between the various nations involved.**

There are, however, significant collaborations that involve exclusively emerging economies. Intergovernmental science organisations such as the African Lightsource, the Synchrotron-Light for Experimental Science and Applications in the Middle East (SESAME) — a joint undertaking of Israel, the Palestinian Territories, Egypt, Jordan, Iran, Pakistan, Turkey and Cyprus — and the Latin American and Caribbean Space Agency are all good examples of nations with emerging economies engaging in multilateral science diplomacy on their own terms.

The value of such endeavours in establishing credentials for global engagement is clear from South Africa's success with the Square Kilometre Array (SKA), a radio-telescope project that is showcasing the nation's science and engineering talent, creating programmes to further develop its human capital and burnishing its reputation as a rising power on the world economic and intellectual stage. Although there are hurdles to overcome, there are clear reasons to encourage and pursue more such inclusive collaborations between countries of differing economic means.[8] At the same time, more and more emerging economies are taking an interest in science diplomacy as a means of moving towards greater scientific and technological development.

### 5-YEAR HORIZON

**Emerging economies invest in science diplomacy training**

Universities and institutes work with emerging-economy nations to train numerous science-diplomacy practitioners in these countries, often uniting on the basis of a shared language. Innovative immersive pairing schemes between politicians, engineers and scientists foster the mutual transfer of skill sets in a broad range of countries, establish science diplomacy as a regional endeavour and give a greater role to Indigenous peoples.

### 10-YEAR HORIZON

**Trained science diplomats are spread through relevant organisations**

Graduates from science-diplomacy-focused training courses in emerging economies become increasingly influential actors in state and non-state organisations, and amongst leaders in science. The reciprocal benefits of research between disciplines, nations and peoples becomes an increasingly important part of science, and funding becomes dependent on establishing such mutual gains.

### 25-YEAR HORIZON

**Training initiatives improve cooperation between diverse actors**

Large-scale science projects that involve cooperation between countries of different economic status are established thanks to complex, multi-layered negotiations between many state and non-state actors. Much of the progress is thanks to training initiatives where key groups of experts from a diverse range of nations are encouraged to develop skills spanning diplomacy and science.

## 4.2.4 Science diplomacy as a response to conflict- and inequality-driven tensions

**One of the significant opportunities for those in the science diplomacy sphere is the role they can play in areas of conflict and inter-group tensions. Though predominantly positive, the rising rivalries between certain powerful nations are leading to science diplomacy being used as a weapon as well as a peacebuilding tool. Nuclear diplomacy is also returning to the spotlight as these tensions escalate.**

Science is certainly affected by conflict. The war in Ukraine, for example, has hindered some collaborations between scientists of different nations: because of Russia's geographical position, these stymied collaborations are having direct effects on Arctic science and are likely to affect protections against exploitation of Arctic resources.[9]

Science has recently become part of broader policies of sanctions between nation-states, as technology has become an interestingly important element of successful economies. More positively, it may be possible for scientists — working with science-diplomacy resources — to become drivers of positive change, shaping global research to give more equitable benefit from the outcomes of science.

### 5-YEAR HORIZON

**Science diplomacy becomes a hard tool in international relations**

International scientific cooperation is increasingly weaponised as a means of participating in conflict. The majority of actors in the science diplomacy sphere nonetheless preserve inclusive and cooperative uses of science diplomacy as the most frequently deployed acts. Science diplomacy helps create projects and plans that contribute to peacekeeping efforts, inter-group negotiations and maintenance of stability.

### 10-YEAR HORIZON

**Science facilities are opened up to scientists displaced by conflict**

Researchers working in former conflict zones (particularly in developing economies) are given access to Big Science facilities, virtually and in person, as a result of science diplomacy work to re-establish countries' peacetime activities. With increased training, individual scientists become more aware of their potential role in science diplomacy.

### 25-YEAR HORIZON

**Science diplomacy improves international relations**

The dual-use aspect of science diplomacy is recognised, and efforts are made to prioritise its use in avoiding conflict and establishing peaceful, collaborative and equitable futures. Nonetheless, scientists continue to feel pressure to align with their national government's policies and ideologies.

4.3

# Prediction, Foresight and Futures Literacy

CHAIR:
**Sirkka Heinonen**
Professor Emerita, Finland Futures Research Centre, University of Turku

CONTRIBUTORS:
**Jake Sotiriadis, Jakkie Cilliers, Geci Karuri-Sebina, Patrick Noack, Peter Scoblic**

**Nobody can see what the future holds. This has been recognised as an absolute truth since at least the time of Aristotle. Modern civilisation is nonetheless built on attempts to do just that, over time scales ranging from hours (weather forecasting and traffic patterns) to decades (climate change and demographic shifts). These attempts allow us to anticipate what the future holds and to plan accordingly. The urgency of this anticipation has increased along with perceptions of the increased speed and complexity of change.**

Our attempts to see what the future holds can be grouped into two broad categories: prediction and foresight. Prediction is based on understanding of the factors that determine a system's behaviour, and how they affect each other. We can then predict how the state of that system will evolve given changes in one or more of its underlying factors and thus forecast its state at some date in the future.

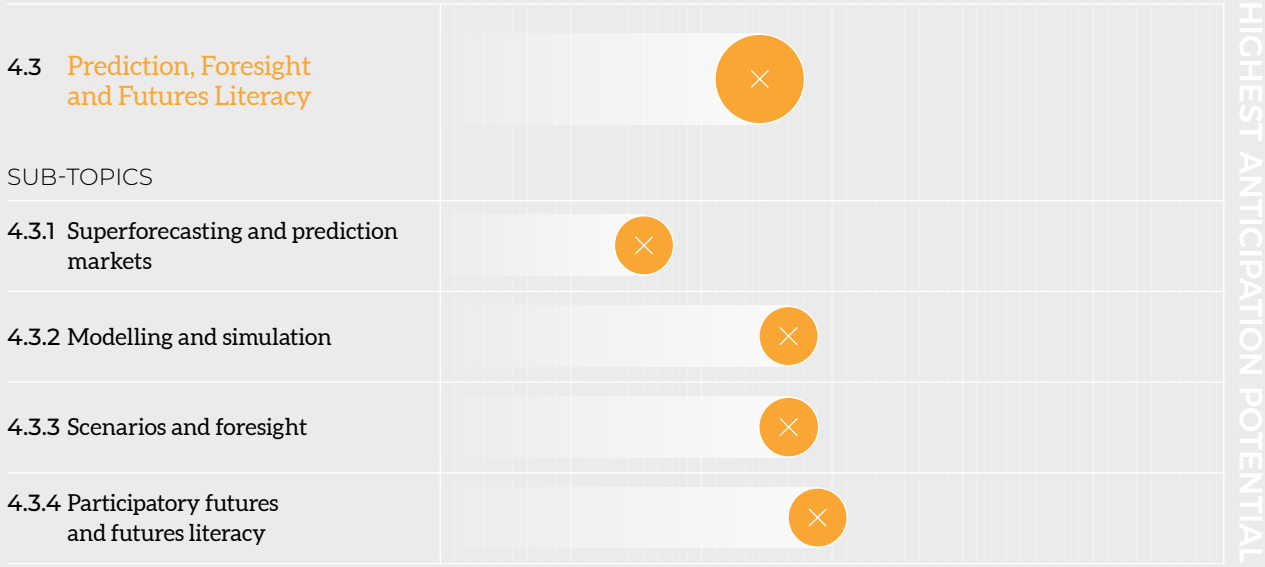
Those predictions may be precise or fuzzy, depending on the quality of the data and the tractability of the system in question: simple physical systems are generally more predictable than complex social systems. In the latter domain, brains may outperform computers, and so attempts are being made to better understand and improve human-made predictions, whether made by individual superforecasters or by many people aggregated through prediction markets. At the same time, the range of tractable systems is being expanded through increasingly sophisticated modelling and simulation.

Sometimes, we can be confident that our prediction is broadly correct and a single outcome is highly likely. However, one of the key principles in futures studies is that the future paradoxically cannot be predicted. Exact prediction of the future is always more about probabilities than sheer accuracy. There may be many distinct and plausible outcomes, and these may vary significantly. In such cases, we have to exercise foresight — a collective term for an approach and methods of gathering information relevant to these outcomes, exploring their ramifications and interconnections, as well as deliberating their preferability. In many cases, for example regarding climate change, geopolitical conflicts or lifestyle changes, the focus of foresight could be on exploring widely possible, even unexpected futures, not only probable futures. This activity can be carried out "top-down", as in strategic foresight, or "bottom-up", as in participatory futures.

KEY TAKEAWAYS

Efforts to anticipate what the future holds are fraught with difficulty but can be successful, as the growth of **Superforecasting and prediction markets** has shown. These provide a synthesis of many types of information, resulting in useful outcomes. Computational efforts in anticipation rely on high-performance **Modelling and simulation** that attempt to discern how our interconnected physical, biological and socio-economic processes, cycles and networks play out, and will be vital to tackling the grand challenges faced by humanity in the 21st century. Also important is the development of **Scenarios and foresight** methods, which use narratives and imagery to assist anticipation efforts. The impact of all of this research can be deepened through the development of **Participatory futures and futures literacy** that helps communities and organisations to understand how to think about the future and to engage with activities related to it.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

We will see significant advances in prediction, foresight and futures literacy in the coming five years, with a deep impact on science, research and society. Participatory futures and futures literacy require strong, internationally coordinated action to deploy its full potential. The scope for action and the Anticipation Potential scores are therefore higher for this topic.

MORE INFORMATION

go.gesda.global/4-3

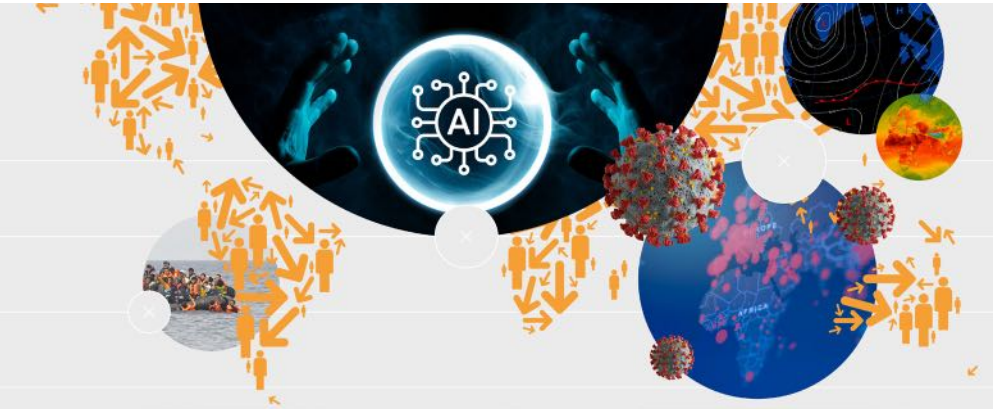
# 4.3.1 Superforecasting and prediction markets

**Some individuals are capable of reliably predicting geopolitical events with a success rate that significantly exceeds that of experts in a given field. These superforecasters' success is rooted in their skill at focusing on a few key determinants of an outcome and their exceptional willingness to update their predictions in the light of new information and arguments. It appears this can be significantly improved through training and teamwork.[1,2]**

Research is ongoing into how effectively superforecasting can be applied to domains other than geopolitics, and how it can best be integrated with expert knowledge. The ability of superforecasters to assess extreme, disruptive risks — "black swans" such as pandemics, for example — is also an area of active debate. More research and validation are needed to legitimise its use in real-world decision-making.[3]

Prediction markets also harness the human ability to synthesise many types of information, but do so by aggregating predictions made by many individuals (some of whom may be superforecasters).[4] Participants are offered financial or reputational incentives to make accurate predictions, and market mechanisms are used to establish consensus positions on political events,[5] technological developments[6] and corporate strategy.[7,8]

The optimal design of such markets is an area of active investigation.[9] One emerging model is "tournaments", in which participants first make individual forecasts before being asked to collaborate in teams, then to assess other teams' rationales and update their own predictions. One such tournament, focusing on existential risks, found that the predictions made by expert and superforecaster participants continued to be significantly different.[10]




## 5-YEAR HORIZON

**Superforecasting is better understood**

The key cognitive processes underpinning superforecasting are identified, and training people to develop their superforecasting abilities becomes routine. Standardised designs for prediction markets and tournaments emerge. Expert knowledge is productively integrated with superforecasting techniques, with artificial intelligence also becoming used.

## 10-YEAR HORIZON

**Superforecasters go mainstream**

Robust evidence emerges for the real-world accuracy of forecasters and prediction markets, and their predictions are routinely cited by journalists and policy-makers. Work continues to integrate expert evidence and incorporate predictions about extreme risks which break markedly from prevailing trends but lead to major disruption.

## 25-YEAR HORIZON

**Superforecasting is widely used at the highest levels**

Superforecasters, prediction markets and artificial intelligence work together to create forecasts for systems that cannot easily be modelled, over a range of timescales. This approach is as well-established for the political and economic domains as weather forecasting or climate modelling, and used at the highest levels of decision support.

## 4.3.2 Modelling and simulation

**Human societies are embedded in complex social-ecological systems (SESs) that are composed of interconnected physical, biological and socio-economic processes, cycles and networks. Understanding these systems and their interconnection is vital to tackling the grand challenges and "wicked problems" facing society in the 21st century, such as those related to climate change, biodiversity, human demographics and economic disruption.**

These challenges are now becoming tractable thanks to expansion of our ability to collect and analyse data about SESs through satellite imagery,[11] in situ networks of ecosystem[12,13] and urban[14] sensors, and automated aggregation of economic and social data.[15] This in turn makes it possible to build computer models that simulate processes taking place in a wide variety of systems and at a wide variety of scales.

Initially, these models were confined to physical processes, with climate modelling being by far the best-known example,[16] but as our data-gathering capabilities have expanded, we have now started to model ecosystems[17] and various dimensions of societies such as urban planning[18] and health[19] as well. Research is under way into the use of these models as decision-support tools for policy-makers.[20]

Technology vendors have put forward the idea of integrated "digital twins" that span physical, biological, social and economic dimensions from local to global scales, and particularly integrated models of cities. However, the case for these has yet to be proven, especially with regards to less wealthy communities, where the focus is more on using digital tools at more granular levels, such as buildings-information management.[21]

### 5-YEAR HORIZON

**Digital modelling achieves wider take-up**

Greater use is made of digital modelling techniques to assess individual development and infrastructure projects, as well as greater integration with decision-making processes. Research continues into how immersive models can best allow stakeholders to more intuitively yet rigorously understand the context for decision-making. Low-cost, low-risk simulation of different solutions to development and environmental challenges are developed.

### 10-YEAR HORIZON

**Better data and computational resources create better models**

High-resolution models for physical processes, initially demonstrated for select locations, become both more accurate and more widely available, thanks to increases in computational power and well-categorised and contextualised data. Integrated models of the built environment are created for some urban environments and coupled social-ecological avatars are created for especially tractable and well-studied locales, such as oceanic islands.

### 25-YEAR HORIZON

**Local and global models merge**

Local digital twins and avatars that allow predictive management and decision-making at city and island scales join up with regional and global avatars, such as physical climate models that increasingly include biological and social feedbacks. They become interconnected at nested scales, creating a global "intelligent fabric" that can be utilised in politics and diplomacy.

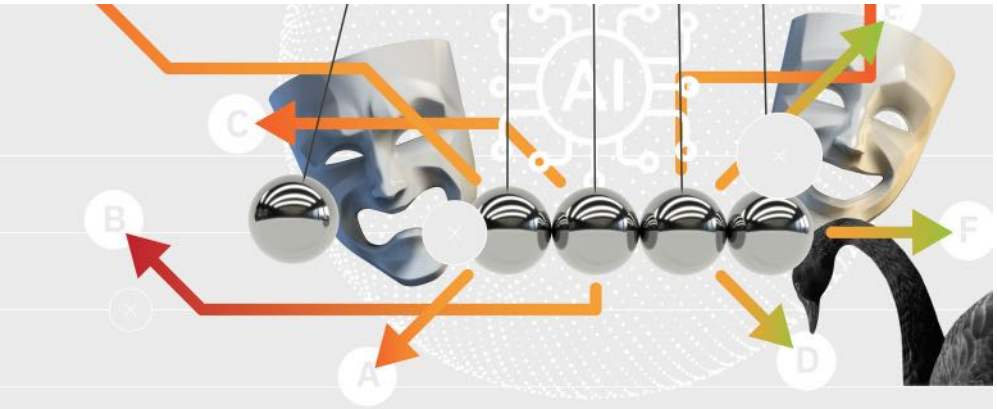
## 4.3.3 Scenarios and foresight

**Because the future is uncertain, it often holds multiple possible outcomes, presenting very different opportunities and risks. These can be assessed using approaches known collectively as foresight (or futures) methods, which are predominantly qualitative, typically focusing on developing images and narratives of alternative futures rather than numerical predictions. The most widely accepted of these techniques is scenario analysis, which has been used in corporate settings since the 1970s.**

Foresight exercises typically task a group with imagining how a situation will evolve, often using fictional prompts and props as well as real data, knowledge and expertise. This disrupts their conventional thinking, allowing them to anticipate possible outcomes that include novel and extreme possibilities. Synthetic data and machine learning are also now being used to support the creation of unorthodox narratives.[22,23]

Such techniques may help to address the current tendency of foresight work to identify positive or preferred futures. If we are to truly anticipate what the future may hold, we must also consider uncertain futures, unlikely futures and undesirable futures. This includes widely known concepts like "black swans" and "existential risks", but further work needs to be done to map and understand the space of these "unfutures".[24]

One strand of development is understanding how unknown and disruptive factors can be envisaged using scenarios or other futures methods and then integrated into the parameters or structure of a quantitative model. A second is an expansion of the application space, to address such issues as identity or the interests of transnational communities.




### 5-YEAR HORIZON

**Generation and communication of scenarios improves**

Research continues into ways to more effectively generate scenarios and communicate their implications and consequences, making greater use of insights from cognitive neuroscience and tools from interaction design.

### 10-YEAR HORIZON

**ML-generated scenarios bring surprises**

Machine learning and synthetic data are routinely used in governance contexts to create scenarios that challenge the expectations of human participants while also being grounded in real-world evidence. Foresight work remains a largely exploratory exercise.

### 25-YEAR HORIZON

**On-demand scenario creation becomes available**

Scenarios are brought to life "on demand" through the use of generative gaming engines and mixed reality, allowing participants to experience different outcomes more intuitively. Foresight work is intended to allow decision-makers to better appreciate the potential consequences of their work.

## 4.3.4 Participatory futures and futures literacy

**To date, prediction and foresight has typically been commissioned and practised by states, multinational agencies and large companies.[25] The outcomes envisaged and conclusions reached will depend on the sponsor of the work, who will deliberately or inadvertently lean towards those which suit their purposes.[26] These will not necessarily align with those considered most desirable or achievable by other stakeholders.**

As a result, there is a need for communities to understand how to think about the future and engage with participatory futures activity. This futures literacy is defined by UNESCO as an essential, universally accessible competency which allows people to better understand how they can anticipate the future and plan accordingly,[27] and the organisation has set up more than 100 "labs" aimed at fostering it.[28] Research continues to explore how the human mind envisages the future, and how this process might be duplicated or augmented by machine intelligence and immersive technologies.

Participatory futures take a variety of forms but generally aim to tackle a specific challenge, usually beginning with a briefing designed to expose participants to alternative futures, followed by structured discussion to identify and detail those that are preferable.[29] These methods are now being trialled to help rural communities define their futures after the net-zero transition, or to help city-dwellers understand how urban design can improve their quality of life.[30] The next step is futures resilience: the capacity to survive emerging challenges, obstacles, risks and crises and learn from them how to rethink existing structures, systems and practices.[31]

5-YEAR HORIZON

**Futures literacy becomes a mainstream capability**

Futures literacy becomes a core tenet of citizen empowerment, alongside the appointment of policy-makers charged with safeguarding the interests of future generations.

10-YEAR HORIZON

**Mass engagement with participatory futures is routine**

Systems are developed which allow mass engagement with participatory futures activity to be conducted routinely, rather as opinion polls are today.

25-YEAR HORIZON

**Participatory-futures events are established as part of civic responsibility**

The results of participatory-futures activity becomes legally binding in certain jurisdictions, being written into constitutional procedures for decision-making.

4.4

# Digital Security

CHAIR:
**Linus Gasser**
Lead Engineer, Center for Digital Trust (C4DT), Swiss Federal Institute of Technology in Lausanne (EPFL)

CONTRIBUTORS:
**Thomas Bourgeat, James Diggans, Jean-Pierre Hubaux, Miroslaw Kutylowski, Shujun Li, Sébastien Marcel**

**The world of the 21st century is increasingly reliant on digital technologies, creating a slew of challenges for tasks, processes, institutions and individuals that require privacy, transparency and security, in all their various forms. A number of mathematical and technical innovations, such as zero-knowledge proofs, trusted execution environments, homomorphic encryption and advances in formal verification, are improving the prospects of creating effective digital security measures.**

However, the practice of Digital Security still faces a range of theoretical and practical challenges in the face of numerous emerging forms of computing and communication. At the heart of these challenges is AI, which is dramatically increasing the capabilities of both defenders and attackers in cybersecurity. At the same time, the internet of things is extending through every aspect of human society, from transport and industry to healthcare and entertainment. By some estimates, there will be 100 billion devices connected to this network by 2050.[1] That raises a host of security issues on a scale never seen before. Next-generation telecommunications networks based on 6G technologies will also need to be secured, as will biological information. Then there is the health, financial and personal data stored in the cloud that must be processed without revealing its content. And if that were not enough, the next decade will see quantum computing coming online, with computational power to crush some existing encryption systems. Securing these systems will be a significant task and developing the mathematical foundations to guarantee this security will be even tougher.

KEY TAKEAWAYS

Thanks to increases in private, institutional and governmental activities in the digital sphere, there is a growing need for reliable and practical digital security solutions. **Privacy and security** are fundamental to democracy, economic activity, communications and healthcare delivery, but there is also a need for transparency in these activities, depending on the context. Researchers are developing a range of solutions for establishing, protecting and verifying **Digital identity**, with a growing use of biometric data offering particular challenges and opportunities. **Novel encryption technologies** are coming onto the market, although technological progress is necessarily slow here, and the prospect of emerging quantum-computing systems able to challenge some of the most widely used encryption methods is creating some legitimate concern about whether encryption can stay ahead of encryption-breaking operations. Many of these concerns might be allayed through development of better and more wide-ranging **Formal verification** protocols, which provide reliable mathematical modelling of real-world capabilities and scenarios.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Digital identity and Privacy and security are very much under the spotlight today. Research in these areas is expected to see significant developments in the coming five years. Formal verification technology breakthroughs are further away and will be less transformative. Digital identity is the area with the highest scope for action, highlighting the need for coordinated international involvement.

MORE INFORMATION

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## 4.4.1 Privacy and security

**Issues of privacy and security now affect all citizens, as well as state-level operations. The pervasive use of digital technology means that, for an equitable society, personal data and communications have to be encrypted in ways that allow transactions and access to services such as welfare payments, healthcare and voting facilities, as well as private web-browsing, messaging and mobile-phone use. This requires a vast technological infrastructure that is not only efficient and secure but also — depending on the context — private yet transparent. At issue is the confidentiality, integrity and availability of information as well as related concerns over authenticity, accountability and reliability. There is also the inevitable trade-off between privacy and system functionality that individuals must navigate, which often brings into focus tensions between the way people think about privacy and the way they act.[2]**

New technologies are also raising security and privacy issues. Video analysis can reveal not only an individual's identity and location but also the people they meet, their mood and even certain medical conditions. The transmission and storage of biometric data requires the implementation of new protocols, and the increasing prevalence and accessibility of a wide range of biology-based data (such as genomic information, healthcare data and access protocols for laboratory samples of weaponisable pathogens) means that "cyberbiosecurity" is an emerging research topic of significant importance. Artificial intelligence is also changing this landscape,[3] not least because of its pattern-recognition capabilities and the potential it offers to automate many tracking processes.

### 5-YEAR HORIZON

**AI cybercrimes change focus of security**

AI is used to encourage people to use IT systems without employing proper security measures. A handful of spectacular cybercrimes demonstrate the role of AI in exploiting weaknesses in conventional security systems. The issue focuses the global security community on whether and how to control artificial intelligence as well as how to balance citizens' rights with public safety.

### 10-YEAR HORIZON

**Augmented reality redraws privacy boundaries**

Malicious state-level cyber-activity becomes so damaging for privacy and security that it forces an expansion of the definition of cyberwarfare. That lowers barriers to conventional war while raising the stakes for digital diplomacy. Growing activity in the metaverse focuses security research onto the challenges of privacy and safety in immersive environments. Awareness-raising about abuse of data-sharing causes individuals to take more control of their personal data, as well as protect themselves with more use of multi-factor authentication.

### 25-YEAR HORIZON

**Tension grows between the digital haves and have-nots**

Countries with secure digital infrastructures experience significant growth in their knowledge-based economies, often at the expense of digital privacy. But countries without this capability suffer economic hardship, and the division dramatically redraws the global balance of power.

## 4.4.2 Digital identity

**One of the most difficult digital security problems is to create ways for establishing digital identities that are useful in a wide range of applications but remain secure. This will mean consideration of indirect insecurities, such as LGBTQ+ people being unwillingly identified because of data-sharing leading to openly targeted advertising,[4] doxing[5] or even physical attacks. Identity security relies on data policies and software routines as well as on unlinkability[6] and secure hardware implementations such as "secure enclaves". It is likely that unlinkability will allow people to maintain several legitimate identities simultaneously, for example. Multifactor authentication is used now, but its importance is likely to grow, with distributed and independent issuers of factors making identity theft much harder than it is today.**

Reliable means of establishing identity will be key as autonomous agents begin to augment people in certain decision-making scenarios. These agents will need their own identities that are securely linked to their owners. This kind of distributed decision-making raises broader issues about the way human identity will evolve in future. What's more, establishing the identity of machines is an important issue for the Internet of Things,[7] which consists of devices with limited power, network and computational ability. Identity in this context will have to be established by methods that do not rely on strong encryption, network connections and so on. Ensuring that these mechanisms are secure and fit for purpose is an ongoing area of study.

### 5-YEAR HORIZON

**AI identity theft threatens democracy**

State-sponsored AI cybercrime combines the data from multiple security leaks to produce convincing patchworked identities for large-scale fraud. This theft occurs on such a large scale that it threatens banking systems, healthcare and even democracy. Passwords become a rarely used means of authentication, replaced by passwordless approaches. Autonomous agents trade on their owners' behalf using networks of verifiable trust that occasionally, through unpredictable herding behaviour, creates runs on certain types of goods, leading to shortages and profiteering. Encryption protocols such as PGP and SPKI flourish.

### 10-YEAR HORIZON

**The notion of personal identity mutates**

The notion of one identity per person begins to change with the legitimate use of multiple IDs. This creates diverse social landscapes, with the opportunity to segment an online existence to share different parts of each individual's life with different groups of people. A new breed of security attack via the internet of things, particularly medical devices, poses a life-threatening risk for millions of people.

### 25-YEAR HORIZON

**Establishing and protecting identity becomes routine**

Identity-authenticating technology is developed in ways that allow even young children and technology-disadvantaged individuals to establish and protect their identities.

# 4.4.3 Novel encryption technologies

**The science of hiding information by encrypting it to prevent unauthorised access faces a wide range of new challenges. Among the most significant is the advent of big data, stored in the cloud, that needs to be processed securely. This has led to much work on homomorphic encryption,[8] which allows encrypted information to be searched and processed while remaining encrypted. Applications include healthcare, banking, voting, genome encryption and beyond. Zero-knowledge proofs allow data verification without revealing anything about the data itself[9] and have applications in healthcare, electronic identity systems, arms verification and so on. Another challenge comes from quantum-computing systems, which are soon expected to become capable of breaking many public-key cryptographic systems that are in widespread use for communication, financial transactions and the like. The US National Institute of Standards and Technology is coordinating efforts to develop post-quantum cryptographic standards that will be immune to quantum attack.[10] But much work needs to be done to make sure they are safe.**

The internet of things is a network expected to connect over 40 billion devices by 2025,[11] but there are significant challenges in achieving this securely. These devices operate with lower power and with limited computational resources, which limits the data processing they can do. Ongoing research for securing the Internet of things focuses on blockchains, physically unclonable functions and post-quantum cryptography. Many of these techniques require improvements, such as error-detection routines and practical, user-friendly hardware interfaces. Device-independent cryptography, where users can test a device's security for themselves, removing any reliance on manufacturer-issued assurances, remains an important goal.

## 5-YEAR HORIZON

### Secure cloud search revolutionises healthcare research

Homomorphic encryption techniques allow researchers to process data stored in the cloud without revealing its content. That leads to significant advances in fields such as genomics, where data privacy is a key concern. However, other security weaknesses that allow malicious users to access the data via well-known shortcomings threaten to undermine the potential. Basic-level data, such as DNS traffic, is routinely encrypted.

## 10-YEAR HORIZON

### Post-quantum encryption widely adopted

A relatively small number of quantum computers become capable of breaking public-key encryption. This forces the widespread adoption of post-quantum encryption, although some of the adopted encryption methods are likely to be broken. Simple, lightweight cryptography gains in popularity, but the environments that adopt a hybrid approach, using two or more encryption systems with very different characteristics, are the most secure against attack.

## 25-YEAR HORIZON

### Genome security improves

Homomorphic techniques allow the risk posed by a given nucleic acid sequence to be assessed without the whole sequence being read, protecting IP while facilitating trade and transfer of biological materials.

# 4.4.4 Formal verification

**A crucial component of modern security systems is the task of proving their correctness with respect to a specification, a process known as formal verification. This requires accurate mathematical modelling of hardware designs along with their envisaged operations, and then an exhaustive, systematic check of all model states in a way that can offer evidence of security. While formal verification is an essential part of the development process, in practice it is often applied in retrospect, which makes the task significantly harder. Simpler user interfaces and better techniques could help to change that. This is particularly important for mobile computing and cloud computing, which have spurred the use of formal verification at earlier stages in associated platform development.**

Other new types of computing introduce their own challenges for formal verifications. The internet of things, for instance, connects a wide variety of devices together, and to the internet, using a variety of different technologies, communications protocols and security standards, rendering each one vulnerable to attack — especially since they are often installed by non-security experts.[12] 6G communications networks, which are being designed as open and programmable by multiple stakeholders, may be vulnerable to attack in ways that 5G networks are not.[13]

Because of the trend towards ever larger and more complex networks and systems, formal analysis is becoming more difficult, and AI — in particular, its pattern-identification capabilities — will play an increasingly important role in formal verification routines. However, low-end devices are likely to benefit from advances in local verifiability and public verifiability protocols, which will be of particular use in small and medium-sized countries where traditional certification is not affordable, and tools for trustworthy certification (and suitably qualified personnel) are not available.

### 5-YEAR HORIZON

**Formal verification becomes more visible**

The trend towards demanding explanations for how AI make decisions also drives wider demand for verifiable security and observation of “ceremony” in processes such as key generation. AI accelerates the testing and verification of software and hardware systems, but relatively few companies or organisations have this capacity, creating a threat of monopoly.

### 10-YEAR HORIZON

**Verification methods for biological systems spark debates**

Formal verification methods emerge for biological systems, allowing a full analysis of the capability of synthetic organisms before they are made and released into the environment.

### 25-YEAR HORIZON

**Quantum computing introduces new challenges for verification**

The challenge of verifying quantum software using quantum techniques drives new research into formal verification based on the laws of physics themselves.

4.5

# Behavioural Science of Groups

CHAIR:
**Mina Cikara**
Professor of Psychology, Director of the Intergroup Neuroscience Lab, Harvard University

CONTRIBUTORS:
**Laia Balcells, Sabina Čehajić-Clancy, Eran Halperin, Yphtach Lelkes**

**Equipped with the tools of modern research, it is becoming possible to identify, monitor and predict how individuals cohere into groups, and how those groups behave and interact with each other — to assess collective emotion as well as collective action.**

Efforts to understand conflict and cooperation have long been dominated by notions of history and geography. Attempts to avert or encourage conflict have been couched in terms of the diplomatic crafts of discussion and negotiation, staged under the aegis of (supposedly) neutral and multilateral organisations. Such efforts have had notable successes in the post-war era, but also notable failures. Great-power conflict has been avoided, but there have been numerous instances in which the established order has collapsed unexpectedly and abruptly.

The traditional tools of politics and diplomacy have proven increasingly impotent in the face of such challenges, particularly as the environment has become ever more complicated by technology, migration, climate change, polarisation and partisanship, rises in both secularism and religiosity, and geopolitical realignments. However, new tools have also emerged from the fast-developing science of group behaviour, which aims to understand the deep-seated reasons behind the formation and activity of distinct groups.

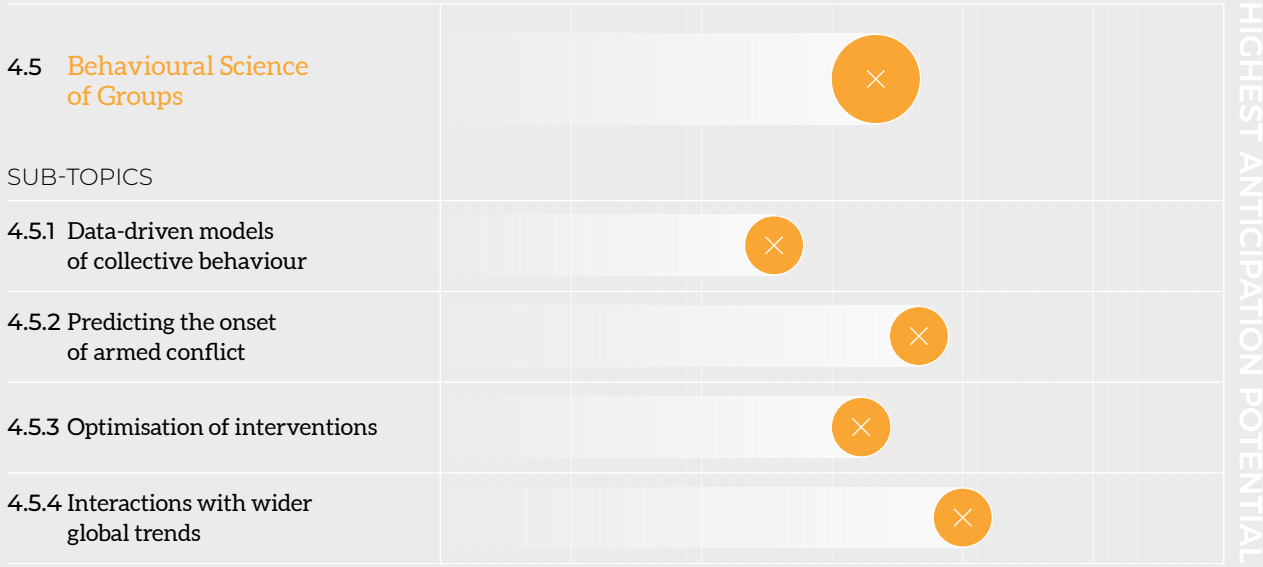
The availability of granular data is particularly significant in this respect. For example, mobile-phone data allows researchers to monitor individuals' movements, interactions and information diets. This data can then be cross-referenced with their social and political activity, and aggregated into groups of any relevant scale or scope: nations, societies or communities, demographic segments and ethnic groupings, and so on.

The point of this activity is to understand how groups interact, and particularly how they might come into conflict. Today's efforts are more often geared towards resolution — trying to stop conflict once it has already begun — rather than prevention. New methods of monitoring both top-down forces (such as messaging from elites, or economic trends) and bottom-up trends (prevailing social attitudes) are changing this, potentially allowing conflict to be anticipated. This should in turn allow interventions to be made in a more optimised fashion, suitable for the particular context of an emerging conflict, rather than applied generically. This is a young field, however, and there is still much systemisation, experimentation and validation to be done.

KEY TAKEAWAYS

Modern research tools, especially computational resources, are making it possible to analyse the various aspects of group behaviour. This holds promise for enhancing cooperation and limiting conflict, as well as understanding the basic dynamics of how groups form and behave. Particularly useful are **Data-driven models of collective behaviour**, which can achieve unprecedented insights into the hidden drivers of observed behaviours. One of the most sought-after applications is in **Predicting the onset of armed conflict**. This will, in tandem with the **Optimisation of interventions**, give governments and global organisations the tools to mitigate the harm that intergroup conflicts bring to individuals and societies. Optimising all of these actions depends on their **Interactions with wider global trends** such as climate change and access to burgeoning digital communication technologies, which affect the way group behaviours manifest and evolve.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

The Behavioural Science of Groups has a high overall Anticipation Potential score. It is an area at the convergence of disciplines that will accelerate advances and their impacts in the future. The scope for action is also high for all sub-topics considered. Predicting the onset of armed conflict and Interactions with wider global trends score highly because of higher impacts and because the fields are relatively new.

MORE INFORMATION

go.gesda.global/4-5

# 4.5.1 Data-driven models of collective behaviour

**Historically, researchers seeking to understand collective behaviour have been limited to comparatively simple models — for example, those based on correlations between the prices of basic foodstuffs and the likelihood of civic disorder.[1] But the increased availability of continuous data about movements, communication and interactions makes it possible to develop more refined models and test them against real data — a "bottom-up" approach focused on aggregated individual behaviours in addition to forces acting "top-down".**

For example, analysis of 1.2 billion mobile-phone pings in South Africa reveals that contact with a larger number of immigrants predicts more xenophobic attitudes and voting patterns. However, this effect is less pronounced if there are repeated casual interactions with the same members of the out-group.[2] Another "top-down" example is the use of artificial intelligence to categorise the way political leaders use language, thus revealing whether voters are hearing constructive debate or personal attacks.[3]

Data is not a panacea, however: there can be significant communities who are poorly represented in available data — for example, those who are not digitally connected — or hard to identify, such as those who are covertly resistant to autocratic regimes. And all the data in the world is of little use without the appropriate techniques for analysing it. These analytic approaches do not necessarily exist within the traditional social sciences and will need to be adapted and further developed in collaboration with specialists from other disciplines, such as physics and evolutionary biology.

## 5-YEAR HORIZON

### Useful datasets expand

The data sets available for analysis continue to expand — including increases in resolution (more precise records) and types of data (such as biometric data). This will require cooperation between data collectors and researchers, along with codes of conduct to ensure appropriate ethical and commercial oversight.

## 10-YEAR HORIZON

### The behavioural-science research environment matures

Integrated, cross-disciplinary teams become the norm in behavioural science, incentivised by a new wave of journals, funding opportunities and research organisations. Specialised analytical tools that draw on existing data competencies are developed, but reflect the particular concerns and idiosyncrasies of social science.

## 25-YEAR HORIZON

### Data reveals sources of collective phenomena

Widely accessible, extremely granular data becomes routinely available for analysis. This is used to understand how collective behavioural phenomena result from cascading collective dynamics at the individual, group and societal levels, and how these relate to the social, economic, ecological and political environment.

## 4.5.2 Predicting the onset of armed conflict

**The 21st century has provided ample evidence of the far-ranging effects of armed conflict. Beyond the obvious toll of immediate death and destruction, the interconnectedness of today's world means there can be significant political, economic and social repercussions far from the fighting. As such, predicting conflicts — with the aim of preventing them — is a stated objective of organisations such as the United Nations and World Bank.**

This is not simple. It is easy to identify places whose social order is fragile, or which are geopolitically exposed, but much more difficult to determine if and when this will tip into conflict, especially in countries with a long previous history of peace. Attempts are now being made to do this using machine learning, which recognises patterns in data to predict likely outcomes. However, this requires massive amounts of data. One such effort, for example, uses systems trained on millions of news articles dating back to the 1980s.[4]

Purely data-driven approaches, however, may or may not map onto prevailing theories of conflict escalation or outbreak. Nor do purely data-driven predictions offer any guidance as to the potential form of any intervention. Finally, there is also the inherent problem that any publicly disclosed prediction can itself influence the course of events by affecting public sentiment or government decision-making, or by making transparent the thresholds at which intervention becomes likely. Additionally, the use of large datasets in conflict areas raises potentially thorny questions related to surveillance and the potential misuse of data by combatants.

### 5-YEAR HORIZON

**Machine-learning models improve conflict-risk detection**

The continued development of machine-learning models and other data-driven systems helps to improve detections of increased risk of conflict. The models are validated against historical and current experience to prove that they produce accurate predictions of the effects of conflicts and any interventions made to prevent them.

### 10-YEAR HORIZON

**Explicable ML facilitates better understanding of conflict prediction**

The development of "explicable" machine-learning systems allows their predictions to be better understood. Integration with theoretical models that capture top-down forces (such as communications from political elites) help to refine predictions and shape interventions. The first real-world interventions (partially) based on such predictions occur.

### 25-YEAR HORIZON

**Conflict prediction models adopted by global organisations**

Endorsement and adoption of these approaches by global multilateral organisations spreads. The development of accompanying ethical and practical frameworks ensures that predictions instil confidence rather than hasten conflict, and that interventions are timed and designed to respect the autonomy of those affected.

# 4.5.3 Optimisation of interventions

**Many instances of conflict stem from the deterioration of intergroup relations: one community or bloc begins to mistrust another, leading to reduced cooperation and overt frustration that ultimately become outright antagonism. In response, social scientists have formulated interventions that aim to improve such relations by reducing bias, hostility or negative behaviours. This approach has had some success, as measured by improvements in key psychosocial variables such as trust and inclusivity.**

However, this has also highlighted the need to optimise interventions for particular contexts. Interventions may be categorised by what they hope to achieve, how they hope to achieve it and how they can be delivered, but this needs to be supplemented with greater consideration of precisely what attitude or behaviour they are targeting, who they are trying to reach and how effectively they can be delivered within a particular operating environment. They also need to account for the level at which they operate — of individuals (for example, education), groups (exchange programmes) or societies (anti-discrimination laws).[5]

To achieve this, there will need to be greater structure and cross-disciplinary collaboration in the design of interventions. Perhaps most important, any research efforts will need to be developed and delivered in collaboration with local community leaders and citizens. Interventions at one level can have effects at different levels (anti-bigotry museum exhibits can encourage social mixing, for example) and over different timescales. They can also interfere with each other. That means they need to be carefully implemented in a way that allows them to be compared on a more systematic basis. Evaluation will need to be comprehensive and holistic (with great sensitivity to the possibility of unintended consequences), and geared towards practical solutions rather than improvements in some relatively abstract social variables.

## 5-YEAR HORIZON

**Intervention science matures**

Continued development of intervention science aims to create repeatable, context-sensitive approaches to intergroup conflict, in collaboration with local community members and with an emphasis on demonstrable real-world effectiveness, backed up by new sources of funding.

## 10-YEAR HORIZON

**Careful deployment of interventions begins**

Interventions are deployed after careful assessment of particular actors (leaders who may exploit them, for example) and contexts (which may affect delivery and efficacy), while also recognising their mutual interactions to ensure net benefit. Researchers will move even more toward collaborating with cultural institutions (museums, for example) and municipal leaders to inform the broader community about conflict narratives and opportunities for community investment.

## 25-YEAR HORIZON

**Refined, customisable interventions improve intergroup relations**

A full taxonomy of highly refined interventions can be deployed to improve intergroup relations, customised to particular circumstances and with full understanding of the appropriate timing and targeting for maximum effect.

## 4.5.4 Interaction with wider global trends

**Several megatrends are changing how intergroup conflict plays out. The changing climate, for instance, alters the viability of some lifestyles while opening up new ones — pastoralism versus mining in the Arctic, for example.[6] The superpower face-off of the late 20th century has given way to a new, more multipolar environment in which nations may simultaneously collaborate and compete, or enter into new alliances and alignments. These factors are causing significant changes in global mobility and thus leading to novel intergroup interactions.**

Combined with greater interconnection, this allows people to find and build common cause with others with whom they might previously have shared little affinity or even mutual awareness. This creates new groups, which may span geographies: for example, climate activists engaging in stochastic disruption, or the formation of new political blocs. Conversely, it can lead to competition for resources, whether real or perceived, and friction over cultural norms. These consequences might arise equally from forced migration away from poorer countries as from lifestyle tourism into them. State actors may also exploit these trends, for example through online propaganda or proxy conflicts.

Overlaid on all these factors are the effects of digital communication, particularly those mediated by opaque algorithms. This can lead to distorted perceptions about both social opportunities and social threats, including the motivations and intentions of others. Across contexts and cultures, overly negative "meta-perceptions" make people believe the worst of the other side and encourage support for hostile actions against them. Dramatic increases in polarisation suggest this is an increasing problem. Corrective information can de-escalate hostility, however, and engender a positive shift in attitude.

### 5-YEAR HORIZON

**Research develops solutions to disinformation**

Techniques to "inoculate" people against disinformation and malign online activity designed to foment conflict are developed and delivered through both formal and informal education programmes. These techniques must be developed simultaneously with a push for greater support of publicly funded media and sources of information.

### 10-YEAR HORIZON

**Migration creates novel interactions**

Climate change becomes a major driver of migration, leading to more novel interactions. Rather than impoverished migrants seeking to improve their economic fortunes, wealthier emigrants move away from fragile geographies.

### 25-YEAR HORIZON

**Research facilitates addressing global challenges as they arise**

The megatrends described above have become entrenched, as have their mitigants and other responses. Further challenges are arising as environmental, economic and geopolitical drivers continue to evolve. But half a century of group behavioural science means that they can be addressed far more systematically and effectively.

INVITED CONTRIBUTION:

# The Future of Multilateralism

**Thomas Biersteker**
Honorary Professor, International Relations/ Political Science, Honorary Curt Gasteyger Chair, Geneva Graduate Institute

MORE INFORMATION:

go.gesda.global/4-IC-1

**The decade following World War Two saw the beginnings of a profound change in global governance, with the founding of the United Nations (UN) in 1945 and the creation of many other new treaty-based, formal intergovernmental organisations (FIGOs), such as the International Monetary Fund, the World Bank and the World Health Organization. Much of our current understanding of international organisations, global governance and rules-based international order is based on analyses of the operations of these organisations.**[1]

Since the mid-1990s, however, there has been a significant increase in the number of informal governance arrangements and institutional forms. These include informal intergovernmental organisations (such as the G7, the G20, and BRICS) and trans-governmental initiatives (such as the Kimberly Process, which certifies conflict-free diamonds). At the same time, governance actors increasingly rely on informal practices. This is true even within FIGOs, with unspoken but implicit rules around, for example, the nationalities of those who hold key positions such as Director General or President. Lastly, informal transnational policy networks have emerged, consisting of a collection of individuals who share expertise and a common language for discussion of certain topics: this shared knowledge defines the community or network, to the exclusion of those who do not possess it. Such networks can set agendas and shape policy around both formal and informal organisations.[2]

The phenomenon of increasing numbers of informal intergovernmental organisations should be watched closely by those who hope to anticipate the future of multilateralism. Given the unique institutional characteristics of the UN, it is likely to remain a critical actor in multilateral global governance. Although it is a profoundly state-centric organisation — particularly around international security — its near-universal membership gives it legitimacy unrivalled by informal institutions. It is both inclusive and broadly representative, even in the Security Council, whose elected members are drawn from different regional groupings. However, the trend towards informality has several implications for its role over the next 5, 10 and 25 years.

On the one hand, informal arrangements create opportunities for more effective governance. The UN as a whole, its specialised agencies and other UN bodies increasingly address complex problems through multi-stakeholder partnerships that incorporate the expertise, operational capacity, material resources and societal connections of diverse actors. An important recent example is the Access to COVID-19 Tools Accelerator (ACT-A), in which the World Health Organization joined with diverse non-state actors such as the Bill & Melinda Gates Foundation and the Wellcome Trust to promote vaccines, treatments and other responses to the COVID-19 pandemic.

On the other hand, the proliferation of informal organisations in global governance leads to competition for authoritative influence, creating particular challenges for the UN. While it remains the first among equals in some domains (such as the protection of global intellectual property rights at the World Trade Organisation), in many others (such as cyber-governance), it is merely one actor among many.

To understand the implications of the interplay between both formal and informal multilateral actors more fully, some scholars in the discipline of International Relations have made both an ontological and epistemological move away from conventional teaching and training. One new approach is termed "Quantum International Relations", which fosters a multi-perspectivist and open dialectical approach to multilateralism. In this approach, concepts from quantum physics — such as entanglement, superposition, uncertainty and complementarity — are used to form new understandings of International Relations.

The quantum concepts of entanglement, superposition and complementarity have implications for how we think about the world. For example, quantum entanglement suggests that the quantum state of any particle or group of particles cannot be described independently of the state of the others, even if they are widely separated. Similarly, international relations should incorporate ideas of constitutive relationships, that parts and wholes are intrinsically interrelated, and that they could be mutually constitutive. Centre-periphery relationships in the world system should be viewed as co-constitutive and parts of a larger whole.

Further, the principle of quantum superposition asserts that an individual particle can be in one of several different locations at any given moment, and that the most general state of existence is a combination of these different possibilities. The location of a particle can be comprehended via the concepts and theoretical formulations of wave theory or in terms of particles. The idea that one of these theoretical approaches has to be correct and the other incorrect forces an unnecessary choice they can both be right at the same time and should be interpreted as different ways of conceptualising the same phenomenon. It might be that different formulations are equally valid simultaneously, depending on one's vantage point.[3]

Complementarity, introduced by Niels Bohr, describes the coexistence and duality of wave and particle theories, and is another metaphor that can be brought into International Relations. For instance, internationally shared histories are difficult to write and full of tensions, disputes and contradictions, but it is important to make the effort. Taken together, different, seemingly incommensurable understandings compose our world. This has important implications for how scholars from different parts of the world think about contemporary multilateralism.

A more open-ended, multidisciplinary approach can accommodate a multiplicity of contending, overlapping, incommensurable and interpenetrating world-order views, and one that leaves room for perspectives with different units, levels, ontologies and epistemologies characteristic of different approaches to inquiry.[4] This shift in orientation will be critical for the future understanding of global governance and the developing field of Global International Relations, as it enables one to recognise that actions taken to balance power can be simultaneously viewed by others as acts of imperialism. This does not mean that every perspective is equally valid, but that we need to make a concerted effort to understand them on their own terms, because they may be fundamentally incommensurable. In International Relations now and in the future, it will be essential to take an empathetic understanding of the positions of others, even if you strongly disagree with them,

so as to be able to engage in discourse with them "in their own language". The point is not to legitimise such perspectives, but rather to understand them and their contradictions.

There is significant resistance to dialectical approaches within the mainstream academic community. The methods and approaches that form the core of mainstream International Relations theory remain largely (and unreflectively) Newtonian, and training programmes are structured and designed accordingly. The introduction of open-ended dialectical thinking is not only timely, but essential for advancing the study and practice of International Relations, addressing the dynamic and multifaceted nature of global governance. This unconventional understanding of International Relations should not be considered as anti-scientific, separate from largely rational and analytical-empirical social science. Instead, it recognises human affairs as a highly complicated, contingent, reflective and fallible enterprise.

INVITED CONTRIBUTION:

# The Future of Trade

**Richard Baldwin**
Professor of International Economics
at IMD Business School, Lausanne, Switzerland;
Founder and Editor-inChielf, VoxEU

MORE INFORMATION:

go.gesda.global/4-IC-2

**Digital technology has had a profound impact on modern society, permeating nearly every aspect of our lives and economies. One aspect that is not as widely recognised as it should be is the transformation it is bringing about in world trade.**

Global trade is becoming "weightless", as trade in goods — things that you can drop on your foot — has plateaued, while trade in services — which are largely weightless, consisting of electronic transmissions and documents — has not. Service exports worldwide have grown 15-fold since 1998; goods exports grew by only 9 times during the same period. Services trade will most likely continue to grow faster than goods trade for the foreseeable future.

Why? There are essentially no taxes on imported services. And while services sold directly to consumers tend to be restricted by regulations, services that support the operations of companies — such as accounting, human-resource management, IT support, legal services, research and development, marketing and the like — are generally less constrained. So the barriers to trade in such "intermediate services" are not due to government policies but are simply due to the difficulty of using foreign teleworkers — and digital technology is lowering these barriers at an exponential pace.

The changes that came with telework during COVID accelerated this trend by 5 to 10 years. The use of artificial intelligence is rapidly making domestic and foreign workers better substitutes than they were in the past. Simultaneous speech translation, for example, will mean that most emerging-economy workers will be able to speak (via an app) good enough English to deliver services to clients anywhere.

Generative AI will accelerate this by distilling the experience of rich-nation service workers into an app which can be given to emerging-economy service workers in order to "level up" their skills.

Putting these factors together, it is clear that the future of trade lies in services. Barriers are radically higher for services than goods, but falling radically faster, and, unlike farm and factory goods, there is no capacity constraint in emerging economies when it comes to intermediate services. The demand for intermediate services is huge in rich nations and the supply of appropriate workers is huge in emerging economies, since they are already providing these services in their local economies. The growth of service exports from emerging markets has been remarkable: since 2016, emerging economies have seen their service exports grow far faster than those from high-wage nations.

This trend is now reshaping the economic development pathways of these countries, offering new opportunities for growth and job creation. Just as Bengaluru thrived on service exports, I believe that cities ranging from Nairobi and Cape Town to Bogotá and Buenos Aires are poised to become centres of service exports and thus drivers of their nations' economic prosperity and growth.

This new development path will require a shift in mindsets, since services have hitherto played almost no role in development thinking. Services were viewed as incapable of sparking a growth take-off in the way manufacturing could. This is strange, since most of the growth in today's rich nations is driven by the expansion of service sectors in cities, not factories in the countryside. Overall, national-development strategists in the digital era may do well to look to urban economics rather than development economics for inspiration and guidance.

Companies should adapt their strategies to leverage the benefits of digital technologies and global labour markets. This change in world trade will release a tidal wave of low-cost, highly skilled workers who have so far been forced to work for low wages in their local economy. Investing in digital infrastructure, enhancing workforce skills and fostering innovation in service delivery will be crucial for businesses to remain competitive in the evolving global trade landscape.

Policy-makers, on the other hand, need to create supportive regulatory frameworks that facilitate the seamless exchange of services across borders while ensuring fair competition and protecting domestic labor markets. This may include addressing issues related to data privacy, cybersecurity and the taxation of digital services. Moreover, policies that support workforce retraining and upskilling will be essential to help workers transition to new roles in the digital economy.

The transformative shift towards service-oriented globalisation presents both challenges and opportunities for businesses and policy-makers. Companies should adapt their strategies to leverage the benefits of digital technologies and global labor markets. Investing in digital infrastructure, enhancing workforce skills and fostering innovation in service delivery will be crucial for maintaining competitiveness in the evolving global trade landscape. Policy-makers, meanwhile, need to create supportive regulatory frameworks that facilitate the seamless exchange of services across borders while ensuring fair competition and protecting domestic labor markets. This includes addressing issues related to data privacy, cybersecurity, and the taxation of digital services. Policies that support workforce retraining and upskilling will be essential to help workers transition to new roles in the digital economy.

To conclude, the future of globalisation lies in services, not goods. Embracing this transformation is key to harnessing the full potential of the new era of globalisation and ensuring inclusive growth and development. The “emerging market miracle” will continue, driven by services rather than industry and commodities. The future is arriving faster than most believe, driven by exponential advances in digital technology and AI. Now is the time to decide what the future will hold and make the most of the opportunities that unfold.

CONFERENCE PROCEEDINGS

# Science Diplomacy at Scale

## 4.1 Science-based Diplomacy

Transboundary challenges such as COVID-19 or the climate crises can only be addressed through global collaboration. However, geopolitical tensions point in the opposite direction as nations retreat from multilateralism and erect barriers to international collaboration and challenges to evidence-informed policy-making. Join this session to learn how a globally recognised science diplomacy curriculum and capacity-building framework dedicated to effective multilateralism will equip future leaders and their institutions to tackle emerging global challenges.

MORE INFORMATION:

go.gesda.global/4-1-Diplomacy

PARTICIPANTS
Moderated by:

**Annika Brack**
CEO, International Center for Future Generations, Belgium

Opening remarks by:

**Martin Chungong**
Secretary-General, Inter-Parliamentary Union

With:

**Stephanie Balme**
Research Professor, Center for International Studies and Paris School of International Affairs, Sciences Po

**Jan Marco Müller**
Coordinator, Science Diplomacy and Multilateral Relations, European Commission

**Marcella Ohira**
Deputy Executive Director, Inter-American Institute for Global Change Research

**Daan du Toit**
Deputy Director-General, International Cooperation and Resources, Department of Science and Innovation

Closing remarks by:

**Martin Smith**
Head of Policy Lab, Wellcome Trust, London

TAKEAWAY MESSAGES:

*"Science diplomacy, involving nations, NGOs, citizens and Indigenous communities, is considered a modern tool for addressing transboundary challenges such as pandemics and climate change. Switzerland, Japan, the UK and the US, among others, include science diplomacy in their policy-making, supported by agreements like the 2019 Madrid Declaration and 2021 Vienna Statement."*

*"GESDA is working on creating a Global Curriculum for Science and Diplomacy, aiming to provide anticipatory science and diplomacy training to current and future leaders across sectors. The curriculum aims to foster a 'multilingual' mindset, encouraging collaboration across STEM [science, technology, engineering and mathematics] fields, governments, multilateral institutions and the private sector."*

*"Science diplomacy faces challenges in fragmented academic approaches and the need for a future-oriented, inclusive and multidisciplinary approach. Geneva, with its international organisations and diplomatic presence, is seen as a promising hub for training in science diplomacy and promoting global collaboration."*

*"As well as anticipating scientific breakthroughs, it is important to invest in building up the cadre of people who can interact at the interface between science and diplomacy to address global challenges."*

# From the Atomic Bomb to AI: Lessons from Oppenheimer

4.2 Advances in Science Diplomacy

Whether it be artificial intelligence or the climate crisis, all global challenges require international cooperation in science and engagement with society. In the face of rapid scientific and technological development, what lessons can be learned from the past and ensure that we responsibly anticipate the next breakthrough and its impact at large?

MORE INFORMATION:

go.gesda.global/4-2-Diplomacy

PARTICIPANTS
Moderated by:

**Adrian Monck**
Editor-in-Chief, *Seven Things*

With:

**Patrick Aebischer**
Vice-Chairman, GESDA; President Emeritus, Swiss Federal Institute of Technology Lausanne

**Paolo Benanti**
Theologian and Academic, Third Order Regular of St Francis; Professor, Pontifical Gregorian University; Advisor to Pope Francis on AI and Technology Ethics

**Doreen Bogdan-Martin**
Secretary-General, International Telecommunications Union

**Charles Oppenheimer**
Founding Member, Oppenheimer Project

**Kate Oppenheimer**
Founding Member, Oppenheimer Project

TAKEAWAY MESSAGES:

*"J. Robert Oppenheimer, known as 'the father of the atomic bomb', is viewed as a model of leadership for handling major scientific and technological crises. His role in the Manhattan Project, leading a team of Nobel-prizewinning scientists, is seen as particularly relevant to today's challenges in artificial intelligence."*

*"Developments in artificial intelligence are prompting fear because, unlike the atomic bomb, there is not necessarily any human in the loop to make a decision."*

*"Anticipating the latest developments in science and technology — as GESDA does — so that society has sufficient time to assess their impact and act could help to prevent mistakes of the past."*

CONFERENCE PROCEEDINGS

# Investing in Emerging Science

4.3 Prediction, Foresight and Futures Literacy

The emergence and impact of scientific breakthroughs are not only steered by academic or political interests but also follow the economic logic of market forces. Join this interactive session to learn which emerging topics mapped in the GESDA Science Breakthrough Radar® are likely going to be driven by an investment perspective — and which ones are not.

MORE INFORMATION:

go.gesda.global/4-3-Diplomacy

PARTICIPANTS
Moderated by:

**Meret Gaugler**
Healthcare Investor and Advisor, Switzerland

With:

**Julia Angeles**
Investment Manager and Partner, Baillie Gifford, UK

**William Egbe**
Managing Partner, Vibranium Capital Group, Cameroon

**Henrietta Fore**
Former Executive Director, UNICEF; Chairperson and CEO, Holsman International, US; GESDA Board Member

**Nicolas Roelofs**
Investment Director, Summa Equity, Sweden

**Ian Walmsley**
Provost, Imperial College London, UK

TAKEAWAY MESSAGES:

*"The world pledged to substantially raise investment in R&D and bolster research capacity as part of the UN's 17 Sustainable Development Goals (SDGs) for 2030 yet only 15 per cent of them are on track for completion."*

*"Both global spending on R&D and research capacity vary wildly between countries, with some such as Germany and Japan investing over 3 per cent of their GDP in R&D and having more than 4400 and 5000 researchers per million inhabitants respectively."*

TAKEAWAY MESSAGES:

*"The emerging topics mapped out in the GESDA 2023 Science Breakthrough Radar® that are most likely to be driven by an investment perspective are in sectors that are heavily focused on using technology in commodities or consumer goods."*

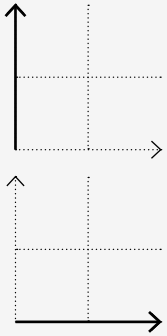
*"Science and diplomacy is another area where expected advances could help build more robust democracies in Africa and in Latin America, which in turn could transform lives very quickly and accelerate the reduction of poverty or indeed loss of life through scaling up the healthcare system."*

*"Geneva's financial hub could facilitate more public-private support for emerging science so that breakthroughs can move out of the lab and into the market. Challenges to funding for emerging science remain, including what is provided for redundant projects or those without a real-world use case. Understanding the potential output and value as well as intellectual property potential are paramount for good investment."*

# Media-Innovation Analysis

While the media coverage grown for Science-Diplomacy is lower than that for other Scientific Platforms, this topic is gaining significant momentum in terms of granted patents. However, patents issued relating to Digital Security are more stagnant, correlating with the lower increase in media coverage for this topic.

LEGEND:



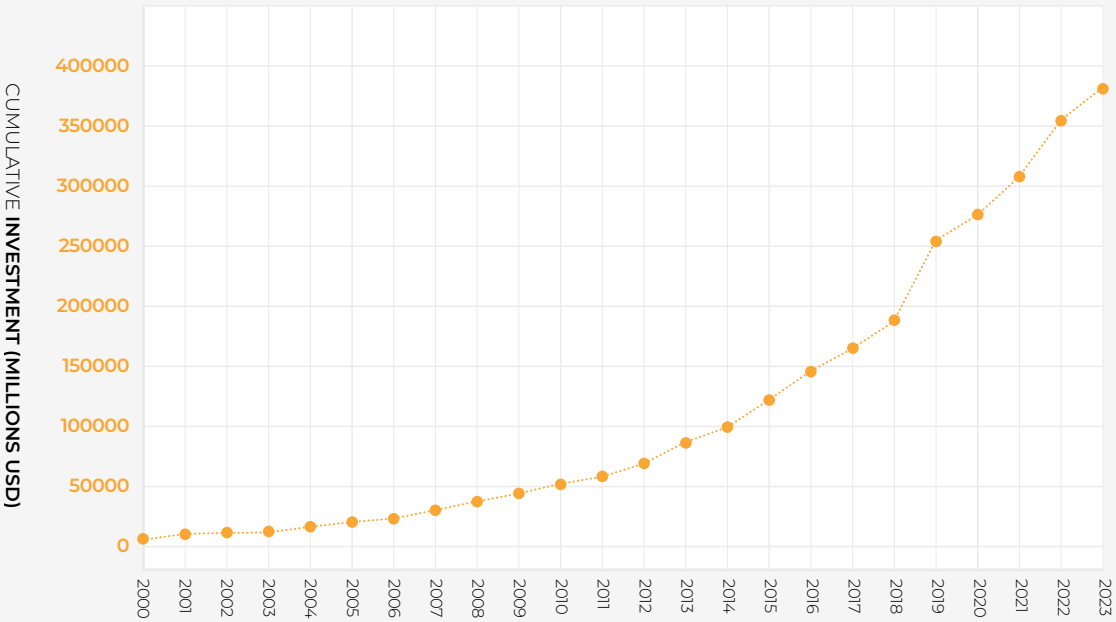
**YoY PATENT GROWTH**
YoY (year-on-year) growth of granted topic patents[1] from May 2022/Apr 2023 to May 2023/April 2024

**YoY MEDIA GROWTH**
YoY (year-on-year) growth of topic mentions in news and blogs from May 2022/Apr 2023 to May 2023/April 2024

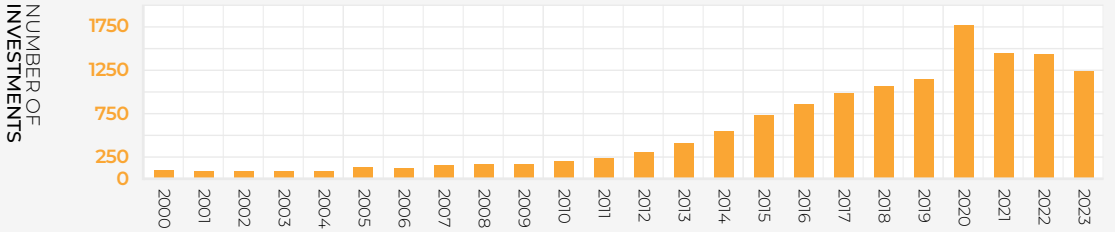
MORE INFORMATION:

go.gesda.global/Impact

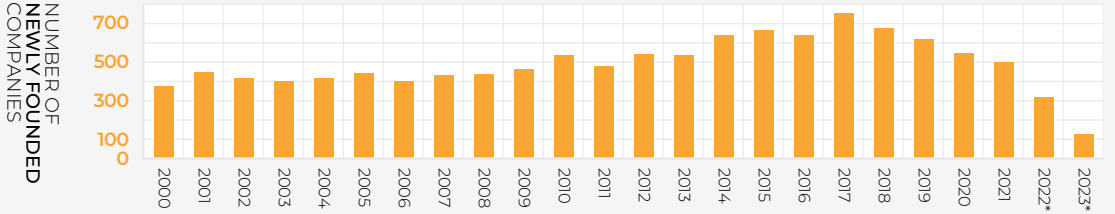
## CUMULATIVE INVESTMENT IN DIGITAL SECURITY COMPANIES




## NUMBER OF NEW INVESTMENTS IN DIGITAL SECURITY COMPANIES




## NUMBER OF NEWLY-FOUNDED DIGITAL SECURITY COMPANIES




IMPACT FOCUS:

# 4.4 Investment and Company Creation in Digital Security

Year-on-year investments in Digital Security have grown exponentially since 2000. The total and yearly value of investments are large compared with other science and technology-related investments surveyed in the Radar, coherent with the established nature of the Digital Security field. This can be observed in the large number of new companies coming into existence each year since 2000. The large jump in investments in 2020 may be a result of the increased reliance on digital infrastructure for remote work during the pandemic and increasing geopolitical tensions and resulting cyberattacks.

Source facing page: Deep View analysis from 1 May 2022 to 30 April 2024; (1) YoY media growth = YoY growth of topic mentions from May 2022/April 2023 to May 2023/April 2024; (2) YoY patent growth = YoY growth of granted topic patents from May 2022/April 2023 to May 2023/April 2024: (*) No patents identified for this topic.

Source, this page: Pitchbook
*Data on newly-founded companies in 2023 is incomplete and will be updated once first funding is raised. Projections indicate similar levels of company creation to 2021.

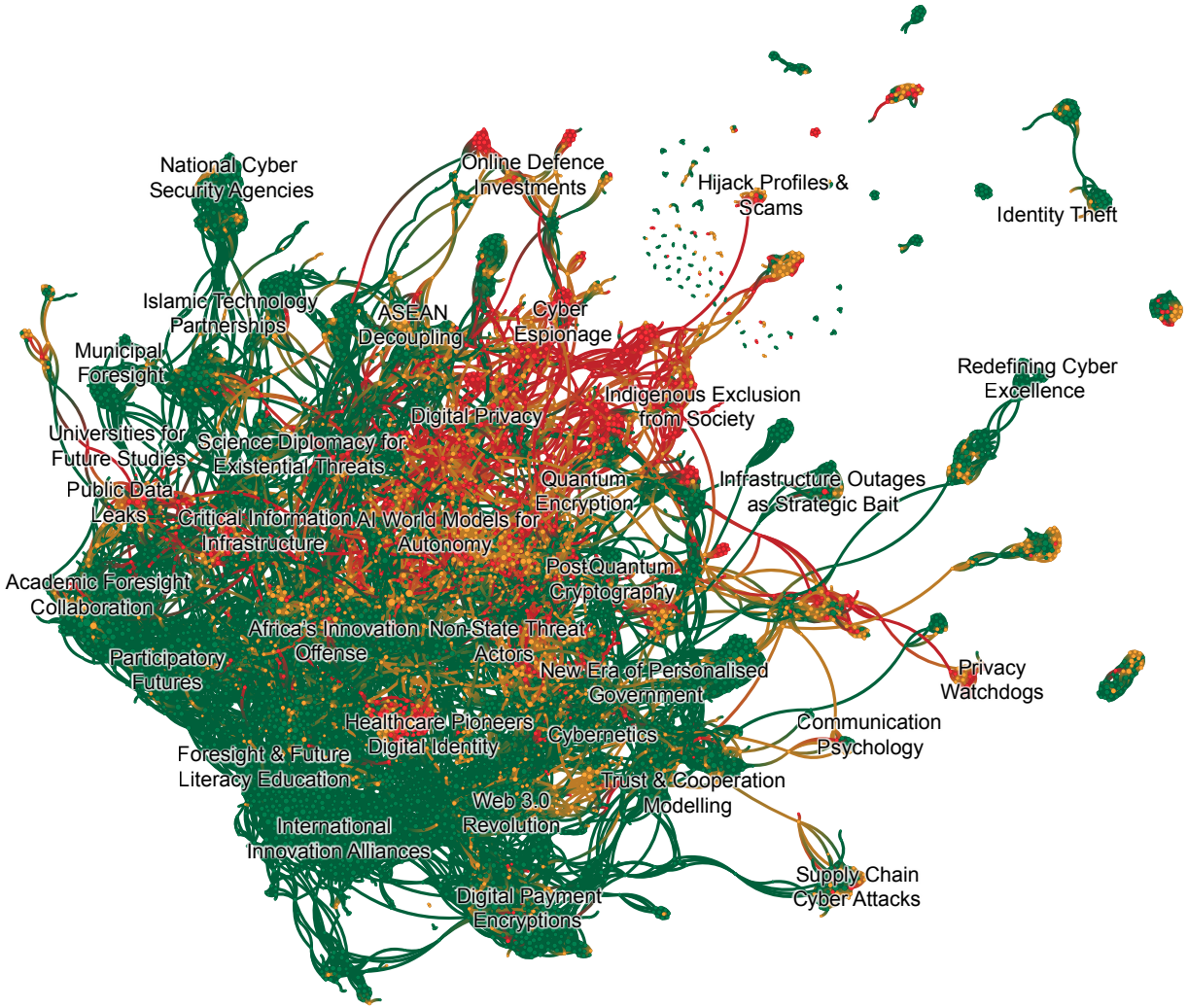
## What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months shows that the discourse around Science & Diplomacy is less optimistic than the other conversations around Scientific Platforms in the Radar, with predominant concerns including the fear that future diplomatic efforts and processes will be unsuited to addressing diverse global perspectives, and fears of increased state surveillance via a transition to digital identity. Science & Diplomacy has a 67 per cent net positive sentiment in mainstream media.

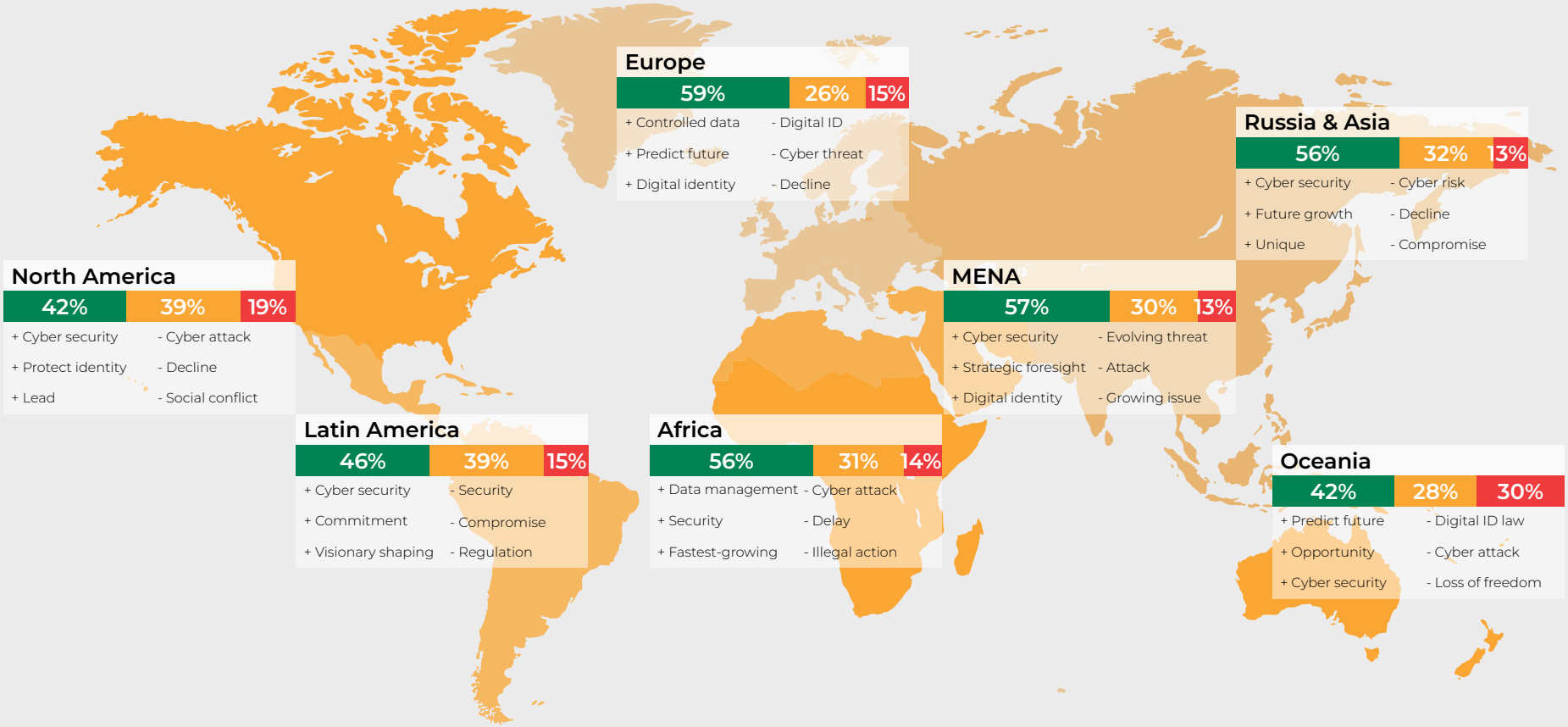
MAINSTREAM MEDIA SENTIMENT

| MAINSTREAM MEDIA | 1 May 2023 to 30 April 2024 |
|---|---|
| UNIQUE ARTICLES | 548k |
| VISUALISED ARTICLES | 6k |
| NET SENTIMENT | 67% |
| ARTICLE UNIQUENESS | 13% |

| SOCIAL MEDIA | 1 May 2023 to 30 April 2024 |
|---|---|
| NUMBER OF POSTS | 1430k |
| VISUALISED POSTS | 10k |
| NET SENTIMENT | 55% |
| UNIQUE IMPRESSIONS | 61b |



## DEMOGRAPHICS & SENTIMENT PER REGION




## GLOBAL SENTIMENT

- Sentiment regarding **Science & Diplomacy varies significantly across the globe. Europe, Russia & Asia and MENA regions** are associated with **more positive sentiments**, whereas **North America, South America and Oceania display less positive sentiments**. In **Oceania**, the discourse around **Science & Diplomacy** is associated positively with leadership, but the relatively high level of negative sentiment is centred around health concerns — pandemics in particular.

- The discourse is predominantly led by the **US** in North America (93%), while in **Europe**, the UK (35%) and Montenegro (38%) are the top contributors the forefront. **Latin America** shows a spread of involvement, including Brazil (23%), Chile (12%) and Mexico (13%). In **Africa**, Nigeria (57%) and Kenya (16%) lead the conversation. **Russia and Asia** see major contributions from India (51%) and Indonesia (11%). In the **MENA region**, Turkey (34%) and the United Arab Emirates (13%) are prominent contributors.

Source: Quid Social, containing the past 24 months of English language data from 10+ social media sources in 200+ countries.

# Media Analysis

## GROWTH

The discourse on Prediction, Foresight and Futures Literacy is witnessing an explosive growth, whereas Digital Security, despite its comparatively lower growth rate of just 13 per cent, remains predominant, accounting for over 50 per cent of all mentions.

## DOMINANCE

In the dominant topic of Prediction, Foresight & Futures Literacy, the science and art of strategic foresight has seen a near doubling of mentions in public discourse. Compared with other topics, Digital Security and Behavioural Science of Groups saw moderate growth rates of 13 per cent and 14 per cent respectively, fuelled by the expansion of concerns around privacy and security.

## SOCIAL SENTIMENT

Discussions around Science & Diplomacy are highly emotionally charged, as indicated by fewer neutral-sentiment posts. Significant changes in net sentiment could indicate a strong influence of political developments on public perspectives regarding topics in this Scientific Platform.

MORE INFORMATION:

**go.gesda.global/Society**

## 4.2 Advances in Science Diplomacy




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 4.3 Prediction, Foresight & Futures Literacy




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 4.4 Digital Security




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24




## 4.5 Behavioural Science of Groups




DOMINANCE




SENTIMENT - 2022-23




SENTIMENT - 2023-24

SCIENTIFIC PLATFORM

5

# Knowledge Foundations

This platform covers areas of foundational knowledge that underlie each of the four other frontier-issue platforms and that have important consequences for us as individuals, society and in relation to the planet. It covers topics from fundamental sciences, engineering sciences, social sciences and the humanities, which draw on research from multiple disciplines and have effects that span numerous human, social and environmental spheres. These foundational topics will serve science — and ultimately society — for generations to come, with anticipated breakthroughs having wide potential impact across many different domains.

GESDA **SCIENCE LENS** (pages 308-311)

Anticipating the Future of Research

PULSE OF **SCIENCE** (pages 266-307)

Containing deep insights into anticipated advances associated with knowledge foundations over the next 5, 10 and 25 years, the GESDA Pulse of Science provides the expert opinions of leading researchers in a diverse set of fields that contribute to foundational knowledge and understanding.

PULSE OF **DIPLOMACY** (pages 312-313)

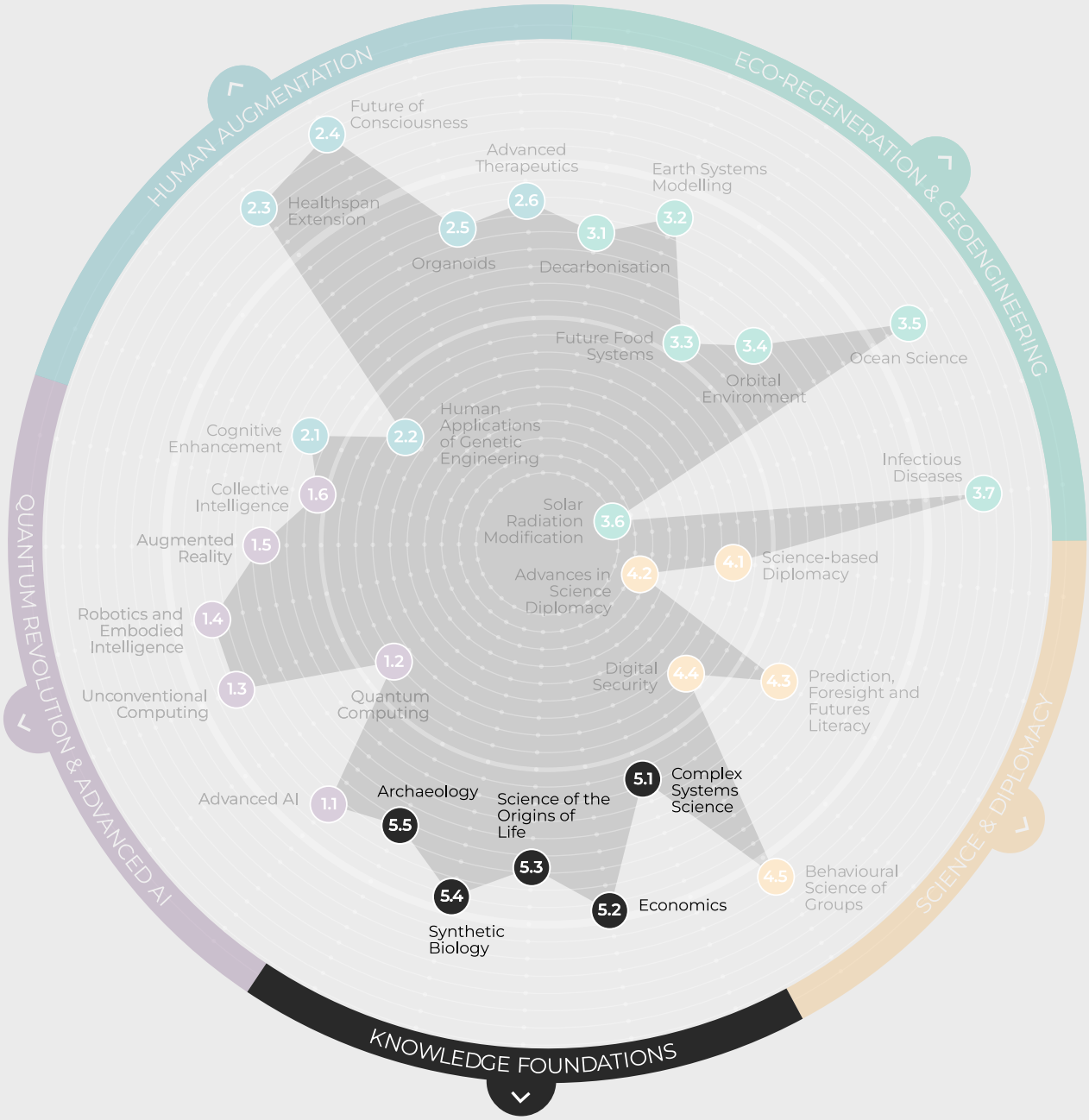
The GESDA Pulse of Diplomacy captures the latest discussions between diplomats and scientists at the 2023 GESDA Science and Anticipation Summit on topics such as the origins of life, digital democracy, sustainable global trade and synthetic biology.

PULSE OF **IMPACT** (pages 314-315)

Current investment trends and dynamics of company creation highlight synthetic biology as an increasingly important topic. The GESDA Pulse of Impact provides data detailing private-sector investment, intellectual-property activity and company creation in this area since 2000.

PULSE OF **SOCIETY** (pages 316-319)

Powered by AI, the GESDA Pulse of Society's network and dynamic sentiment analysis of both mainstream and social media reveals macro- and micro-trends in public opinion around the world on topics relating to foundational knowledge.



5.1

# Complex Systems Science

CHAIR:
**Dirk Helbing**
Professor of Computational Social Science, ETH Zürich, Switzerland

CONTRIBUTORS:
**Carlos Gershenson, Francois Grey, Jeroen Van den Hoven, Maria Rosa Montardi, Mark Klein, Yvonne Hofstetter, Sarah Spiekermann, Isamu Okada, Chang-Won Ahn, Lorenzo Fioramonti, Hans J. Herrmann, Jose Jakob Kalayil, Indra Spiecker, Ranga Yogeshwar, Sanjana Hattotuwa**

**Society consists of a wide variety of densely connected, interdependent systems. These networks of networks enable the flow of information, ideas, goods, services and money. In turn, this leads to huge benefits in the form of free media, open democracy, global trade and international finance.**

However, this connectedness also makes our world vulnerable to extreme events in ways that are hard to imagine and even more difficult to avoid. Examples of the negative consequences of networked society include the 2008 global financial crisis, the COVID crisis and the ongoing climate crisis. In each case, the disaster unfolded over a range of interconnected networks with powerful but difficult-to-predict feedback patterns.

The science of complex systems can help here. This discipline seeks to characterise, understand and ultimately manage systems with emergent, self-organised behaviour that cannot be characterised as the sum of their parts. Human society falls squarely into this category, giving this science the potential to help understand and improve it. In particular, the science of complex systems can help us build our future by alternative scenarios and opportunities, while putting humans, their values and a democratic, participatory-governance approach in the centre. It should also allow us to embrace desirable emergent behaviour such as coordination, cooperation, co-evolution, collective intelligence and truth.

KEY TAKEAWAYS

The complexity of human society in the 21st century poses a challenge for those trying to plan and direct its evolution to ensure positive individual and societal experiences. They do, however, have a number of tools at their disposal, one of which is the discipline of **Computational social science**. This examines and models the multifold relationships at work within society, enabling research to develop better theories and understanding. The complexities of democratic societies are deepened with moves toward **Digital democracy,** where organisations, individuals and governments make use of digital tools. This requires new insights into issues such as how digital participation can be maximised, and how security of democratic processes can be established and maintained. Our deepening understanding of the roots of **Collaborative behaviour** can help here, providing insights from computer models and real-world experiments that will encourage healthy collective behaviour. Another key movement is **Design for values**, which finds ways to create desirable individual and social experiences, and sustainable, affirming social environments.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

Advances in complex systems science will lead to new tools for digital democracy and enhance collaborative behaviours. Both areas have high Anticipation Potential scores because of the likelihood of significant future impacts on society. Further developments in computational social sciences will be transformative for other fields of research and therefore require determined and well-coordinated international action.

MORE INFORMATION

**go.gesda.global/5-1**

# 5.1.1 Computational social science

**Social science explores the relationships among individuals within societies and the forces that influence them. For this reason, it has close relationships with network science. However, the networks at play are multifold and complex. They include social, cultural and institutional networks that encompass activities playing out not only between individuals, but also at local, regional and global scales.**

In recent years, increasingly powerful computational models have allowed researchers to capture many properties of these networks and to study the transitions from one type of collective behaviour to another. This has led to the emergence of the new discipline of Computational social science, which aims to develop better social theories, gather more meaningful datasets in an ever-growing range of experiments and to create increasingly useful models. These models have already given us a better understanding of a wide range of phenomena, such as pedestrian and traffic flows, social inequality and the spread of diseases.[1] The hope is that this approach will help predict the feed-forward effects too, allowing stakeholders such as researchers, commercial entities and governments to collaborate on modelling the potential outcomes of alternative decisions and putting solutions into practice more successfully.

## 5-YEAR HORIZON

**Data-collection protocols are agreed**

The creation of an international forum for computational social science leads to broad agreement between academia, industry and government on the ethics of data collection and data use. This leads to greater collaboration. Grass-roots data-privacy organisations shall play a key role in these discussions.

## 10-YEAR HORIZON

**Modelling finds increasing success**

Models of certain classes of techno-socio-economic-environmental phenomena become increasingly used by diverse stakeholders and civil-society initiatives to explore potential outcomes of a large variety of applications

## 25-YEAR HORIZON

**Outcome-testing guides social interventions**

Computational models of complex techno-socio-economic-environmental systems that simulate networks and interactions become progressively more capable. These models lead to a number of innovative approaches to manage complex dynamical systems that prove the power of the suggested approach: for example, to improve sustainability and resilience, or to prevent or mitigate the spread and impact of diseases.

## 5.1.2 Digital Democracy

One of the challenges for democracy is to engage the widest range of people in its practice and activity. Digital tools offer powerful new ways to do this by offering alternative means for citizens to debate and discuss, to communicate, to find solutions, to allocate resources and, ultimately, to govern. This creates the potential for dramatic changes in democracy, making it more representative, more efficient and more capable. That said, challenges will remain. Much effort will be needed to engage the broadest range of citizenry so that no groups are disenfranchised, particularly the elderly and technologically disadvantaged.[2] Furthermore, digital tools also open the way for malicious actors to subvert democracy and to undermine society: securing public confidence will require a transparent design and operation of a robust, reliable and trustable, sufficiently participatory framework.

### 5-YEAR HORIZON

**Digital tools become commonplace in local community projects**

Small-scale institutions such as town councils and community associations increasingly rely on digital tools that gather data from and about communities to decide how to allocate resources, such as for maintaining roads, funding schools and reducing crime. Concerns about late adopters of digital technologies are given proper consideration.

### 10-YEAR HORIZON

**Digital-aware politicians gain an advantage**

Machine-learning algorithms trained on the output of digitally-gathered data provide new insights into community priorities. Politicians engaging with these priorities grow in popularity, thereby reinforcing the importance of digital inputs and participatory frameworks.

### 25-YEAR HORIZON

**Algorithms become vital tools in the democratic process**

Advances in the science of complex systems combine with digitally-gathered data and increased access to machine-learning algorithms. The result is a mechanism that prompts politicians and policy-makers towards solving real-world problems collaboratively and to measure the success of measures taken.

## 5.1.3 Collaborative behaviour

Technology that enhances collective behaviour clearly has an important role to play in bringing people together, in supporting their collective action and in bringing it to fruition, which is why so much work is being done on collaborative tools. However, collective behaviour does not always produce the intended or best results. Groupthink and herding behaviour can push groups towards dangerously wrong-headed actions and amplify negative trends, such as racism, unhealthy behaviours and online hate.[3] Computer modelling provides a way to study how collective intelligence emerges (and why it sometimes doesn't).[4] Large-scale real-world experiments can help to calibrate these models, provided they can be carried out within a suitable ethical framework. The same models can be used to explore negative outcomes, making it possible, in principle, to find ways to avoid problematic scenarios.

### 5-YEAR HORIZON

**Modelling of complex systems seeds responsive urban infrastructure**

Certain areas in global cities become "smart": they monitor citizen behaviour in a privacy-respecting way and adapt accordingly, such as increasing phone and data capacity for large gatherings, adapting transport timetables and redeploying resources for street cleaning.

### 10-YEAR HORIZON

**Frameworks for ethical research into collective intelligence are agreed**

An international forum allows researchers to reach an agreement on a comprehensive set of ethical rules that will govern future large-scale social and collective-intelligence experiments.

### 25-YEAR HORIZON

**Computer models assist transnational collaboration**

Online collaborative tools build trust in a way that allows small businesses to span the globe, with individuals working towards common goals with others they have not met.

# 5.1.4 Design for values

**The design-for-values movement is based on the idea that technology can promote certain values and discourage others.[5,6] Desirable values include, for example, equality between men and women, healthy living, personal safety, sustainable living, environmental responsibility and valuing democracy. The hope is that, with this approach, positive conversations about such values would be amplified on a suitably designed social media platform, for example, while fake news and and cyber-bullying would be diminished.**

The technologies of intelligent cities that monitor their citizens in a privacy-respecting way and adapt to their behaviour have the scope to embody values of one kind or another. Such cities are already evolving, and it is important for us to consider — and influence — the values they will promote, in accordance with national constitutions and human rights, as well as the UN Sustainable Development Goals.

Design for values is a complex undertaking, however, and (due to feedback and side effects) such interventions are not always guaranteed to achieve their intended purpose from the beginning. As researchers in the field of machine learning have pointed out, without careful, deeply considered design, technologies can create unanticipated and perhaps unwanted consequences. In any cases, design for values has become an urgent approach to master the challenges in our increasingly technological age more successfully.

## 5-YEAR HORIZON

**International design-for-values efforts demonstrate first successes**

International forums such as the IEEE see their agreed design-for-values standards increasingly adopted by developers of products and services.[7] Discussions on the future of artificial intelligence begin to see progress towards designing for values in AI systems.

## 10-YEAR HORIZON

**Awareness campaigns amplify the interest in design for values**

Grass-roots organisations highlight negative issues associated with poorly designed intelligent machines, such as the development of inappropriate relationships with nature and humans, and between them, including poor quality of information sharing. This drives greater interest in the design-for-values approach. Major institutions of higher education provide courses on design for values, complex dynamical systems and global systems.

## 25-YEAR HORIZON

**Policy-makers require design for values as a mandatory part of technology development**

Positive results from various high-profile demonstrations of successful technological design-for-values solutions lead to the formation of a global forum aiming to extend the approach to all intelligent machinery.

5.2

# Economics

CHAIR:
**Jean-Pierre Danthine**
Honorary Director of Enterprise for Society (E4S), Honorary Professor at the Swiss Federal Institute for Technology in Lausanne (EPFL)

CONTRIBUTORS:
**Jean-Philippe Bonnardi, Johannes Buggle, Rafael Lalive, Richard Baldwin**

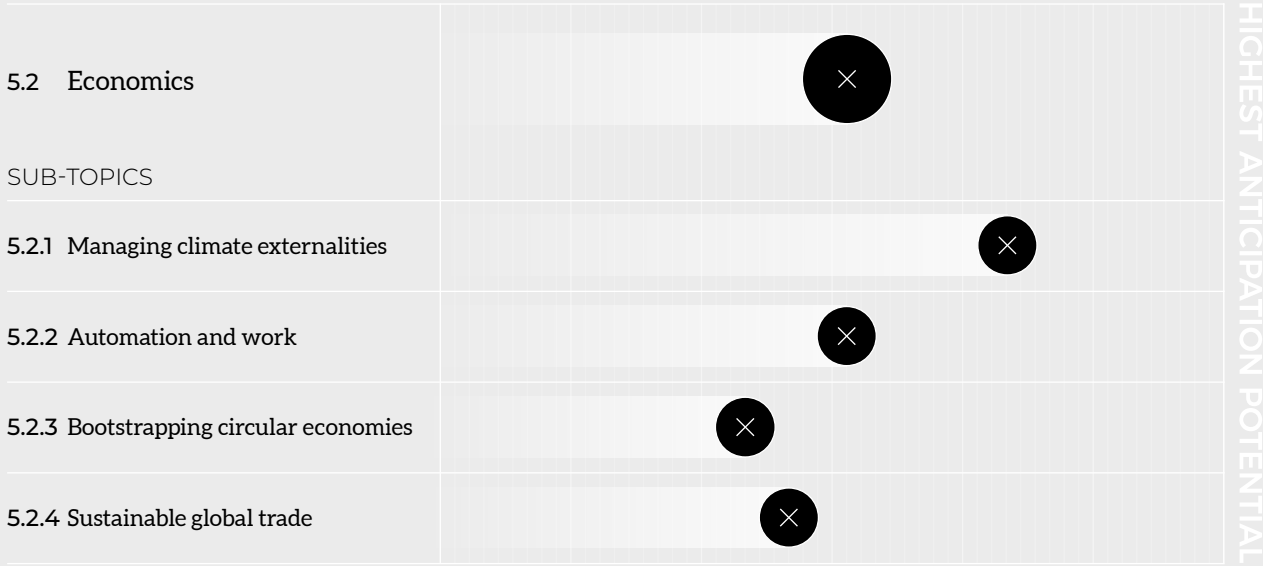
**It is apparent from the challenges facing humanity in the 21st century that externalities need to be better incorporated into the economic decisions of firms, households and governments. Global warming continues to heat the planet, with atmospheric temperatures likely to soon break the 1.5˚C-of-warming threshold that climate agreements had pledged to avoid. Media coverage of this imminent milestone is focusing attention on what more can be done. For this reason, all actors should be more alert to the negative consequences that their decisions have for the well-being of others — near or far — as well as for future generations and for the planet. The market cannot be relied upon to drive positive change towards sustainability, inclusiveness and resilience. Therefore, more government intervention is needed. Societies need to agree on the negative externalities created (for example, by too much automation, excessive emissions or pollution), quantify them and shape economic choices through direct subsidies and incentives.**

Research into these issues is already uncovering many policy solutions that could lead to resilient, inclusive, sustainable societies. There is the circular economy, for instance, where the full life-cycle cost of goods and materials is factored into prices, and where the by-products and waste from one process become the feedstocks for others.[1] Sustainable economic policies must also deal with the externalities of climate change, which lead to forced migration, with all kinds of consequences on the societies at the journeys' origin and the destination, and problems for agriculture through altered environmental conditions. Our societies also have to solve issues of globalisation, automation and employment before they cause significant economic changes that can lead to social unrest. Many of the required economic models and measures have been invented but are yet to be implemented.

KEY TAKEAWAYS

Our understanding of how economic policy and strategies will need to evolve in the 21st century will play a significant role in determining the trajectory of human experience. A key task is **Managing climate externalities**. The consequences of traditional economic models include potentially catastrophic global temperature rises, and it is important that these be mitigated as far as is possible. Also arising from technological progress is the issue of **Automation and work**: economists and policy-makers are now faced with difficult decisions regarding how far technologies such as AI should be allowed to shape the workplace. Sustainable economics will benefit from **Bootstrapping circular economies**, which will reduce resource consumption. There is optimism that these measures can all contribute to an era of **Sustainable global trade**, where the green economy and resilient supply chains offer a chance to develop an economics that contributes to establishing equitable global prosperity while still affirming and improving the lot of individuals, societies and ecosystems.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Faced with a worsening climate challenge and dramatic changes in the workplace, efforts to make our economies more sustainable and resilient are already well under way. The potential impact on society was judged to be among the highest of any assessed by the expert panel. While awareness of these issues is relatively high already, their potentially transformational effects on society and the time it will take for breakthroughs — between 10 and 20 years, according to our experts — suggest it would be unwise to disregard them.

MORE INFORMATION

**go.gesda.global/5-2**

# 5.2.1 Managing climate externalities

**Our traditional economic models have already created substantial challenges. Atmospheric levels of $CO_2$ have been rising steadily since the industrial revolution, leading to global temperature rises that threaten the habitability of parts of Earth. The average level of warming has now reached 1.2°C and may reach 1.5°C by 2027. For some parts of the Earth, that will be catastrophic, leading to the collapse of farming and significant food and water shortages. The prospect of mass migration away from these regions is becoming ever more real. To better understand, predict and plan for these mass movements will require urgent international attention.[2,3]**

Mitigation policies could help, such as the development and commercialisation of heat-resistant crops and of efficient water-management and purification systems based on technologies such as desalination. However, significant adaptation will also be necessary.[4] Some economies will need to prepare for a future in which farming is no longer possible. When that happens, people will need alternative forms of work to pay for imported food. That will mean reskilling the workforce. Certain kinds of economic policies can avert severe climate change by introducing measures such as carbon pricing. There is also increasing academic study of how humans can actively intervene, for example by injecting aerosols into the atmosphere to reflect sunlight. Science diplomacy will need to play a crucial role as this option becomes more broadly discussed.

## 5-YEAR HORIZON

### An era of progress

Media coverage and public pressure forces governments to accelerate efforts to get to zero emissions before 2050. A growing awareness and experience of the negative consequences of climate change lead to implementation of a global $CO_2$ tax. Circular-economy strategies continue to be implemented on key issues such as plastics and waste, if only at a local level.

## 10-YEAR HORIZON

### Farming requires intervention

Some parts of Africa become too hot and too dry to support traditional crops, while efforts to commercialise heat resistant crops have stalled over intellectual-property rights and the limited potential for recouping costs. Nevertheless, the success of some genetically modified crops in extreme conditions provides momentum for a global research effort to develop other heat resistant crops. After the success of COVID-19 vaccine development, this work is funded by governments rather than by commercial profit.

## 25-YEAR HORIZON

### Crisis is avoided through forward thinking

The global effort to develop heat resistant crops largely prevents mass starvation, migration and civil unrest in countries whose traditional crops have failed due to climate change. The retraining of workers in these economies, funded through global cooperation, means that most families can afford imported food. Despite the increased mortality due to high temperatures, fears of mass migration recede. We are heading towards living within sustainable limits and are on track towards zero carbon emissions in 2050, meeting the Paris Agreement.

# 5.2.2 Automation and work

**When ChatGPT launched in November 2022, 100 million people signed up to use it within two months. Since then, this and other generative AI systems have begun to augment and replace human work in industries ranging from law and computer coding to graphic design and customer service. The prospect of even more intelligent and capable machines has generated fears that these devices might replace humans on vast scales and in a relatively short period of time while at the same time concentrating wealth in the hands of a tiny minority of people.[5] Some jobs are already going this way. For example, machine-vision algorithms are currently upstaging radiologists in the task of assessing medical images. Translators are also being replaced by increasingly capable machine-translation algorithms. Robots are already replacing certain kinds of workers, particularly those performing relatively simple, repetitive tasks: certain kinds of machine operators and drivers.[6]**

Although it is unlikely that intelligent machines will replace humans in most jobs on the 25-year timescale, they are likely to lead to considerable changes in society.[7] One report estimates that 80 per cent of the US workforce could have at least 10 per cent of their work tasks affected by current AI systems.[8] The fraction of the workforce that becomes unemployed will need to be looked after and retrained where possible. Several countries have begun experimenting with universal basic incomes or UBIs, such as the UK, Kenya and India. If they are more widely adopted, UBIs will have to be paid for by governments, who will need to find new ways of gathering and redistributing the wealth generated by machines.[9] Having historically raised revenue by taxing labour, governments will have to tax or redistribute capital to support future societies. This will also help to prevent the concentration of wealth in the hands of small group of machine owners. Radical economic innovations like new taxation models will need to be incentivised by regulators — a programme that will require collaborative economic, political and social action on global scales.

### 5-YEAR HORIZON

**Machines perform low-skill work**

Generative AI services such as Bard, ChatGPT, Midjourney and others become routine tools in the workflows of most industries, thanks to their rapid deployment via the global companies, such as Microsoft, Google and Facebook. Some human jobs quickly become obsolete but new classes of job also emerge. Nevertheless, the rapid rate of change causes governments to put policies in place that incentivise the employment of human labour and innovation with labour-augmenting technologies. This is supported by a change in taxation in favour of human labour and against capital, which smooths the transition.

### 10-YEAR HORIZON

**Governments tax automation**

There is significant displacement of jobs because of the coupling of artificial intelligence and robots. Governments implement policies that ensure human capital is not wasted: education and retraining is common, preparing workers and rising generations for a changing workplace. A wide range of economies begin trialling universal basic income, paid for by the taxation of capital and automation.

### 25-YEAR HORIZON

**Machines alter the human experience**

The workplace has changed substantially, with new jobs and tasks in place. People are working significantly less, thanks to the productiveness of machines. Universal basic income allows retraining or support of displaced workers, and allows governments to incentivise the development of technology that enhances human performance rather than replacing it, where appropriate. Policy measures place greater emphasis on the social obligations of companies towards their workers and the communities in which they operate to ensure relatively high levels of employment and to avoid the growth of social and economic inequalities.

# 5.2.3 Bootstrapping circular economies

**A circular economy overcomes the "take, make, waste" of traditional linear economies by attaching costs to the creation of waste and pollution and to the over-exploitation of resources. Circular policies also create financial incentives to make the waste from one process the feedstock for another. The goal is to create giant closed loops that recycle and reuse Earth's resources for as long as possible.[10]**

There are many challenges here. Renewable energy is an important part of the solution because it eliminates generation of $CO_2$ waste from fossil fuels. Properly pricing natural resources will require substantial interventions as well as regulation to direct the use of resources on a global scale.[11] However, the war in Ukraine has significantly increased investment in renewable energy, providing an unexpected boost for efforts to create the foundations for circular processes.

At the same time, trials of circular processes are accelerating. Renault is currently fitting out Europe's first dedicated circular-economy factory for vehicles,[12] Philips has begun a project to remanufacture used medical machinery so it can be resold as new,[13] with the relevant performance and product guarantees, and Dow has begun building chemical plants for turning used plastic into ethylene, which can be used to make virgin plastic again.[14]

## 5-YEAR HORIZON

**Circularity efforts gain momentum on local scales**

City programmes to increase circularity gain powerful grass roots followings. The "right-to-repair" movement forces legislation that makes most products repairable, creating a new cottage industry focused on DIY repair. Artificial intelligence helps to identify and react to eventualities that might cause crises or unsustainable practices in the global supply chain.

## 10-YEAR HORIZON

**The first entirely closed-loop economic processes appear**

International agreement on materials pricing creates the financial incentives that make complete circular economies more viable. The first of these begin to bear fruit.

## 25-YEAR HORIZON

**Circular economies become more widespread**

Truly circular economies appear in some industries on national and regional scales. However, pricing issues still incentivise many linear practices and significant global regulation is needed to bootstrap more circularity.

# 5.2.4 Sustainable global trade

**Globalisation has dramatically changed the nature of trade in the last 25 years. Ensuring this trade is sustainable and resilient towards systemic risks into the future will become a growing focus for many economies and this is already threatening the global nature of certain kinds of trade.**

The COVID pandemic and the war in Ukraine have focused attention on the security of supply chains leading to significant policy changes in many countries. The computer chip industry, for example, is currently in a state of major reorganisation to secure supplies and shorten supply chains. That will also have the effect of reducing transport costs and carbon.

But the most significant economic driver of change is the US Inflation Reduction Act, which has allocated $370 billion in investment and subsidies for the green economy and eco-friendly products such as electric vehicles. This investment is forcing other similarly sized economic operators, such as Europe and China, to reconsider support for their green economies while threatening to leave smaller economies unable to compete.

Another problem is the fragility of supply chains.[15] Governments and industries are developing ways to strengthen these chains in the short term: the "internet of things" is set to play an important role in monitoring where products came from and how far they travel, for example. Blockchain technology has been touted as a way to increase the transparency of these processes. However, many experiments with blockchains by insurance, banking and shipping companies have been quietly dropped amid spiralling costs and limited benefits.[16] The new focus on resilience also places greater emphasis on stress-testing supply chains and on simulations that can predict — and find ways to avoid — the impact of future COVID-scale events.

## 5-YEAR HORIZON

### A race for sustainable technology

US investment in its green economy triggers intense global competition for sustainable technology and increased economic tension. US subsidies for electric cars leads to copycat moves in Europe, China and beyond, and the competition accelerates moves towards net zero. This competition leads to important innovation but also high-profile failures.

## 10-YEAR HORIZON

### Global agreement leads to supply-chain stress tests

To ensure continuity of supply in emergencies, an international standard is agreed that measures the resilience of supply chains in a wide variety of simulated disasters. Investment in electric technologies reduce fossil-fuel use.

## 25-YEAR HORIZON

### The technology of resilience makes supply chains more sustainable

The combination of green-industry investment, AI technologies and sustainable supply chains allows numerous countires to achieve net zero. The technology of resilience makes supply chains more sustainable. The tracking technologies for monitoring resilience provide a powerful tool for measuring environmental impacts. This allows the sustainability of supply chains to be assessed reliably on a global scale. They are now powered by renewable energy for both manufacturing and transportation.

5.3

# Science of the Origins of Life

CO CHAIRS:
**Betül Kaçar**
Assistant Professor, University of Wisconsin-Madison

**Ramanarayanan Krishnamurthy**
Professor of Chemistry at Scripps Research, California

CONTRIBUTORS:
**Moran Frenkel-Pinter, Ryo Mizuuchi, Erik Persson, Davide Pisani, Sudha Rajamani, Eric Smith, Jean-Pierre de Vera, Frances Westall, Lyle Whyte**



**Living organisms as we know them today are the extremely complex products of a long period of evolutionary change. Understanding the origins of life, therefore, can teach us a great deal about the possibilities inherent in biology and potential routes towards new medical insights, as well as providing unparalleled perspectives on cosmological history and our own place in the universe.**

Researching the origins of life involves study of biology, chemistry, geology, palaeontology, physics, cosmology and information theory, among other disciplines. Investigations require that researchers consider conditions on the early Earth and how they changed, understand fundamental issues in systems chemistry and identify the most essential features of living organisms. As a result, progress in this area depends partly on improvements to the geological record, partly on advancements in measurement techniques necessary to study highly complex chemical systems, and to a great extent on progress in fundamental biology.

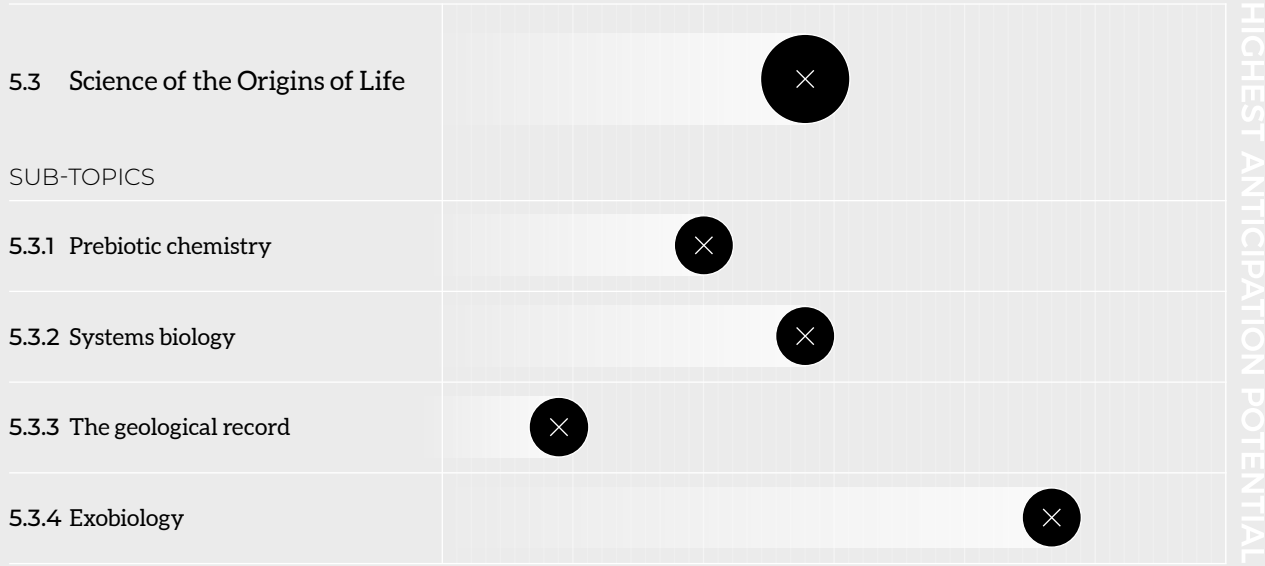
Much progress has been made, but there remain many areas of debate, such as the chronological order in which nucleic acids, other polymers, metabolic reactions, lipid-based compartments and various other components of living systems arose.[1] In order to answer such questions, researchers attempt to experimentally demonstrate geologically plausible processes that lead to life-like behaviours, features and phenomena.

There is also no settled theoretical framework for studies of the origins of life. A recent proposal called assembly theory,[2] for instance, has not yet achieved widespread acceptance. Assembly theory aims to measure the complexity of a molecule by the number of steps required to make it. However, life often acts to simplify the molecules it uses, and furthermore much of the complexity lies not in the individual molecules but rather in the set of interactions between them. This means that researchers must study not only individual chemical processes but also the environment in which they happen — and their effects on neighbouring processes taking place within that environment.

KEY TAKEAWAYS

Understanding the origins of life is of both practical and philosophical interest. Not only does this subject have the potential to add to physics, biology and medicine, it may also inform humanity's understanding of its place and role in the universe. Research efforts in this area involve attempts to understand and create the **Prebiotic chemistry** that can give rise to phenomena associated with life, and to understand the **Systems biology** of how these phenomena interact to create the complexities observed in living systems. These theoretical and experimental investigations are informed and supplemented by ongoing research into the history of life, as revealed in **The geological record** on Earth and in the evidence derived from studies of chemical processes and molecular signatures observed in off-Earth environments. Studies of the surfaces and atmospheres of the solar system's planets and moons, and the light received from planetary environments beyond our solar system, offer promising routes to understanding **Exobiology** and how life might arise in ways that differ from terrestrial biological pathways.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

Understanding the origins of life is an enormously challenging multidimensional problem, but progress is being made. Experts predict breakthroughs in the next five years for Prebiotic chemistry, but breakthroughs in Exobiology are more than 20 years away. The Anticipation Potential score of the latter is also driven by the lack of awareness, the strong impact of the field and the need for coordinated international action to capitalise on its advances.

MORE INFORMATION

**go.gesda.global/5-3**

# 5.3.1 Prebiotic chemistry

**Making the chemical building blocks of life in a way that is "prebiotically plausible" — that is, likely to have occurred naturally on Earth — is a central pillar of research in this area.[3] In the 21st century there has been considerable success in obtaining multiple biochemicals, relevant to different aspects of the living organism, from the same feedstock and environment.[4] Experiments have demonstrated that a small number of starter chemicals can lead, with minimal intervention and often with self-organising, highly robust reaction networks, to hundreds of products.[5]**

Commensurately, researchers are studying how individual chemical reactions can aggregate to form network-level chemical systems that demonstrate attributes that we generally associated with life.[6,7,8] Machine learning may prove to be a useful tool for understanding the properties of these chemical networks.[9]

There is a growing scientific understanding of how systems of chemicals can change over time, and in particular what it might mean for them to "evolve" in the absence of true genetic control. Recent findings indicate multiple characteristics that could be used to define a genuinely "complex" chemical predecessor to life at the systems level.[10,11] These might include: an emergent set of chemicals or processes that is robust even amid changes to the rest of the system; systems that are far from chemical and thermodynamic equilibrium (a non-equilibrium state is one of the central features of life); or emergent chemical systems that are capable of processing information (but which do not require explicit structures, such as genes or the ribosome, to store or process biological genetic information).[12]

### 5-YEAR HORIZON

**Automation begins to pay off**

Chemical systems have been developed that display open-ended evolution, that is, avoiding equilibrium. Increased use of automation and AI allows us to conduct high-throughput experiments.

### 10-YEAR HORIZON

**Chemical computation becomes possible**

"Protocells" with self-replicating nucleic acid driven by metabolic reactions are created. Laboratory experiments utilising a small array of reactive compounds have the topology and kinetics necessary to carry out basic computational processes via chemical reactions. Network-level descriptions of both living and non-living chemical systems are used to distil a small number of correlative factors associated with the expression of "life-like attributes" in those systems.

### 25-YEAR HORIZON

**Predictions of life-like chemistry becomes possible**

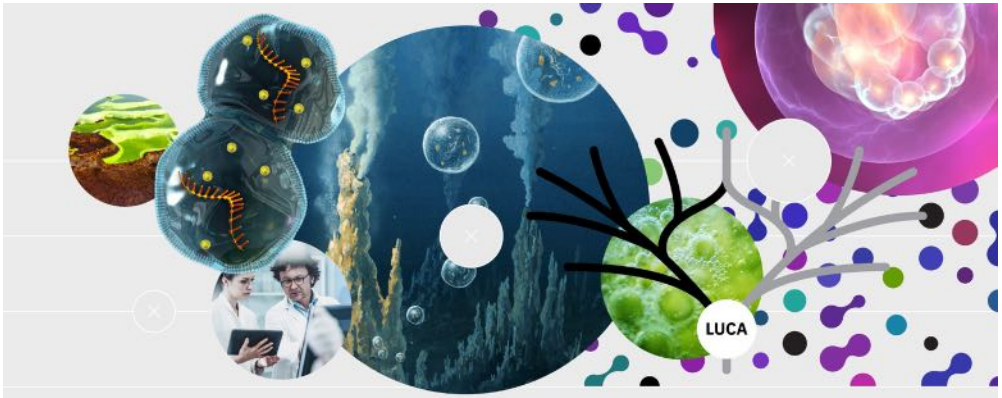
We have systematic comparisons of the prebiotic chemical potential of different geological settings. Naturally occurring reactive compounds are shown to have the necessary topology and kinetics to permit emergent information-processing systems to form as predecessors to living systems. Systems-level descriptions of living entities are sufficiently sophisticated to permit direct predictions of the frequency of occurrence of chemical systems with life-like behaviours, which can in turn be used to infer the probability of life arising spontaneously under generic prescribed conditions.

## 5.3.2 Systems biology

**Any investigation of how life originated aims to conceive and create simplified versions of living systems that are nonetheless self-sustaining.[13] This requires the tools of systems biology, where living organisms are understood as networks of chemicals and systems. Systems biology treats life as a complex system of interacting nodes, each with its own properties, and aims for a holistic and computational level of understanding.[14]**

A key aim is to produce emergent properties, where the overall system has properties and functionalities that are not inherent in the individual parts but emerge from their interactions.[15] One example would be self-organisation: systems of chemicals that can self-assemble into three-dimensional structures or reaction cycles, and which are on some level self-sustaining.

This move towards studies of complex systems presents a considerable analytical challenge. Modern experiments that seek origins for the emergence of life often involve set-ups in which dozens of chemicals, or even more, interact with one another. As a result, research is aiming to develop highly sensitive analytical techniques that can track the changes in these systems.[16]




### 5-YEAR HORIZON

**Evidence of primordial metabolic processes arises**

We accumulate experimental evidence that metabolic processes could have sprung up on the primordial Earth, in the form of non-enzymatic versions of all major metabolic cycles known to be evolutionarily ancient.

### 10-YEAR HORIZON

**Open brain data stimulates research**

Palaeoenzymology uses the tools of synthetic biology and phylogenetics to reconstruct “extinct” biomolecules.

### 25-YEAR HORIZON

**High-resolution devices facilitate access to some brain states**

A model of the last universal common ancestor (LUCA), based on synthetic biology, phylogenetics and palaeontology, provides useful understanding of life’s history.

## 5.3.3 The geological record

**Our knowledge of the early Earth offers a key constraint on hypotheses for the origins of life. Unfortunately, the overwhelming majority of the oldest rocks on Earth have been destroyed or altered by geological processes such as tectonic shift. Consequently, the geological record is extremely poor for the first billion years of Earth's 4.5-billion-year history.[17] The earliest confirmed fossil organisms to have yet been discovered are 3.5 billion years old,[18] and so all we know is that life arose during a 1-billion-year window — an enormous span of time, roughly twice as long as complex animals have existed.**

Improvements in our understanding of the geological record will continue to narrow down when and how life may have formed. This may happen through discovery of hard evidence of life at an earlier date, through innovative synthetic biology and evolutionary systems biology tools that reconstruct ancient life,[19] or through demonstrations that conditions before a certain point were unremittingly hostile to life.[20]

There is currently limited geological evidence to illuminate conditions on the early Earth. New discoveries about the temperature range, the presence or absence of exposed land, and the chemical make-up of the oceans and atmosphere, as well as about the elemental composition, would all provide useful and significant information from which research could gain a better understanding of which scenarios of the origins of life are plausible.[21, 22, 23] These questions are bound up with fundamental problems in geology, notably the origin of modern plate tectonics.[24]

### 5-YEAR HORIZON

**Criteria for assessment of evidence for life is developed**

Explicit criteria are developed for the assessment of purported evidence for early life on Earth.

### 10-YEAR HORIZON

**Earth's formation is better understood**

We have an improved understanding of Earth's formation via study of exoplanets.

### 25-YEAR HORIZON

**Origin of Earth's water clarified**

Greater clarity is achieved on the origin of Earth's water and the initial development of oceans and land.

# 5.3.4 Exobiology

**There is currently no good evidence of life or fossil life on other worlds in the solar system, let alone on exoplanets in other solar systems. That may change as we continue exploring other planets in the solar system. Even if no living organisms are found elsewhere, our investigations will shed light on the processes of Prebiotic chemistry and primordial geochemistry.[25] The planet Mars and the moons Europa, Enceladus and Titan all have or had environmental conditions similar to parts of Earth. Future missions such as ExoMars and Europa Clipper will provide information about processes that are likely to have taken place on the young Earth. A key opportunity for the coming decades will arise with sample-return missions that can bring high-quality samples back to Earth for detailed study.**

Discovering life beyond the solar system remains a possibility, if a remote one. It is theoretically possible to find indirect evidence of life on an exoplanet, for example by detecting the presence of oxygen in the atmosphere through spectroscopic analysis. However, there are issues with interpreting such detections: on Earth, oxygen is only produced by living organisms, but it is difficult (if not impossible) to rule out abiotic processes being the cause on an exoplanet.[26] This problem has already bedevilled researchers who detected methane on Mars and phosphine on Venus, and will be far worse when dealing with extremely distant worlds.[27]

### 5-YEAR HORIZON

**Mars gives clues to Earth-like Prebiotic chemistry**

Data from the Perseverance rover on Mars indicates Earth-like prebiotic chemistry billions of years ago.

### 10-YEAR HORIZON

**Solvents for life are better understood**

We have good evidence on whether water is the only possible solvent for life. The James Webb Space Telescope has given useful information about the conditions in which terrestrial planets formed, and the abundance of specific organics in these conditions.

### 25-YEAR HORIZON

**Mars sample return planned**

Examples of life or fossil life on other worlds are found, helping to expand or clarify our definition of life. A plan for a high-quality sample-return mission to Mars is drawn up.

5.4

# Synthetic Biology

CHAIR:
**Patrick Cai**
Professor and Chair of Synthetic Genomics, University of Manchester, UK; Visiting Professor, Massachusetts Institute of Technology, The University of Hong Kong and Chinese Academy of Sciences

CONTRIBUTORS:
**Junbiao Dai, Tom Ellis, Michael Jewett, Rodrigo Ledesma-Amaro, Julius Lucks, Vivek Mutalik, Harris Wang**

**Synthetic biology is a set of emerging technologies enabling the modification and creation of living cells and organisms, and of their building blocks. It promises breakthroughs in fundamental biology and has possible applications in fields ranging from nutrition to engineering.**[1]

Synthetic biology operates on multiple scales, from molecules to multicellular organisms to whole ecosystems.[2] At the smallest scale, we can manufacture novel molecules and materials that do not exist in nature. Non-living materials may be imbued with properties of living organisms, such as self-repair.[3] Alternatively, micro-organisms can be engineered to produce desirable molecules, for instance by genome synthesis or directed evolution.

At the level of cells, artificial versions of key biomolecules such as nucleic acids can be synthesised and introduced into the genomes of microorganisms.[4] Other engineered cells can be used as biosensors, for instance to detect threats,[5] to produce other useful chemicals or to break down harmful ones such as pollutants. They can also be induced to form tissues and organs, which could be used in place of transplants.[6]

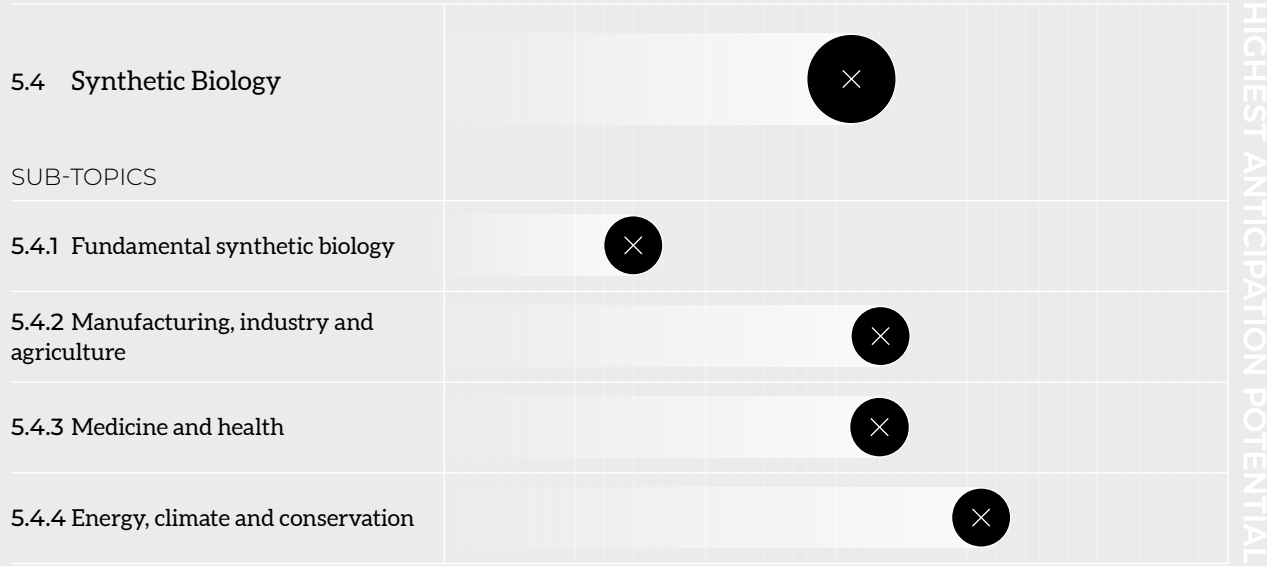
Multicellular organisms can be modified using genome synthesis editing. There have also been preliminary attempts to create wholly artificial multicellular organisms.[7]

Given its wide-ranging applications, there is a need for synthetic biology to be developed alongside ethical and societal expertise in order to shape how and why decisions are being made, and for whom.

KEY TAKEAWAYS

Synthetic biology enables the creation and modification of living organisms, and of their molecular building blocks. The field is advancing rapidly. In **Fundamental synthetic biology**, faster and better genome editing and other technologies are enabling the development of heavily modified organisms. The potential applications of synthetic biology are immensely varied. For example, there is considerable potential to improve **Manufacturing, industry and agriculture**. Synthetic biology enables new technologies such as bioelectronics and the creation of new materials. Bioplastics created from living organisms could replace at least some plastics from fossil fuels. Synthetic pesticides and gene drives may reduce crop losses and also cut costs. In **Medicine and health**, synthetic biology can help to develop genetic therapies for inherited diseases, to engineer new medicines and to design new cancer therapies. Finally, there are emerging applications in **Energy, climate and conservation**. These include engineering at-risk organisms to be more resilient against environmental change and using micro-organisms to produce zero-carbon fuels such as green hydrogen. Because of the potential risks to humans and ecosystems, there is an urgent need to develop security measurements for synthetic biology.

ANTICIPATION SURVEY RESULTS




SURVEY OBSERVATIONS

The ability to modify and create organisms, living cells or their building blocks could lead to major breakthroughs in fundamental biology and unleash new possibilities in nutrition, pharmaceuticals and engineering. While breakthroughs in synthetic biomolecules and tissues are expected in the next six years, progress in synthetic cells and multicellular organisms is further away. Future breakthroughs in synthetic biology will be hugely transformational and therefore the field has a high overall Anticipation Potential score.

MORE INFORMATION

**go.gesda.global/5-4**

# 5.4.1 Fundamental synthetic biology

**The aim of synthetic biology is to treat life as programmable matter and to reprogram it to serve human ends. This requires understanding the intricate mechanisms underpinning living cells and devising ways to manipulate those systems. Genome editing, for instance using CRISPR-Cas, is a key tool.[8] DNA synthesis has become much faster and cheaper, enabling researchers to create micro-organisms with wholly synthetic genomes from scratch.[9] AI will be a major driver for advances in synthetic biology. This has already been seen with AlphaFold's ability to convert DNA sequence into predictable protein structures.**

A major challenge is to create generic platforms for synthetic biology. These will improve the accessibility of the technology, especially in the developing world, and open the way to more repeatable experiments. Synthetic biology platforms could include artificial vesicles for catalysis of reactions and delivery of molecules,[10] programmable systems for glueing proteins,[11] and microorganisms with minimal genomes that are more readily reprogrammed and rationally designed.[12] Ecosystems of synthetic organisms also have potential but are under-explored.[13]

In order to achieve the desired goals quickly and effectively, there is a need to develop new methods of designing synthetic organisms. Multiple avenues are being explored: some focus on designing organisms that exhibit goal-seeking and problem-solving behaviours,[14] while others are aiming for an open-ended evolutionary process that will continue to develop and change.[15]

The opportunities of synthetic biology come with risk. Engineered organisms have considerable potential to harm humans and ecosystems intentionally or accidentally. Hence some synthetic biologists are devising ways to contain their engineered organisms:[16] for instance, ensuring organisms can only survive when given a specific chemical that is not found in nature.[17] The best strategies will use multiple orthogonal control systems, providing several failsafes to minimise the chances of escape.[18]

### 5-YEAR HORIZON

**Synthesis tools mature**

Speedy synthesis of longer pieces of DNA spanning hundreds of kilobases is achieved. Synthetic RNA/DNA devices for cell control begin to make an impact. AI is able to infer function from the structure of all biological molecules, changing how we design, alter and annotate genomes. Computational tools currently used in model organisms are readily adaptable for non-model organisms. Cell-free systems further accelerate design-build-test-learn cycles.

### 10-YEAR HORIZON

**Synthesis costs fall**

DNA synthesis becomes as cheap as DNA sequencing. Generic, widely accessible platforms and chassis for synthetic biology appear. Synthetic biology and biomaterial design are integrated. Dependence on plasmids is reduced, allowing integration of much longer DNA sequences into organisms. Improved genotype-phenotype mapping enables more rational design and prediction of effects of interventions, and AI starts to predict emerging phenomena. Proteins for catalysis are designed. Ethics and access to the technology start to shape its development and use.

### 25-YEAR HORIZON

**AI improves user access for synthesis**

Integration of AI enables users to supply instructions in human language, which are then implemented in the molecular construction. Rational design of synthetic microbial ecosystems is achieved. Researchers develop fully designed microbial genomes for specific tasks. Heavily automated synthetic biology labs function as "cloud labs" for biological research. Massive parallel editing of genomes, with hundreds of thousands of changes at a time, becomes possible. Sustainable partnership with the planet allows the design of entire biological ecosystems that serve those who need them the most.

## 5.4.2 Manufacturing, industry and agriculture

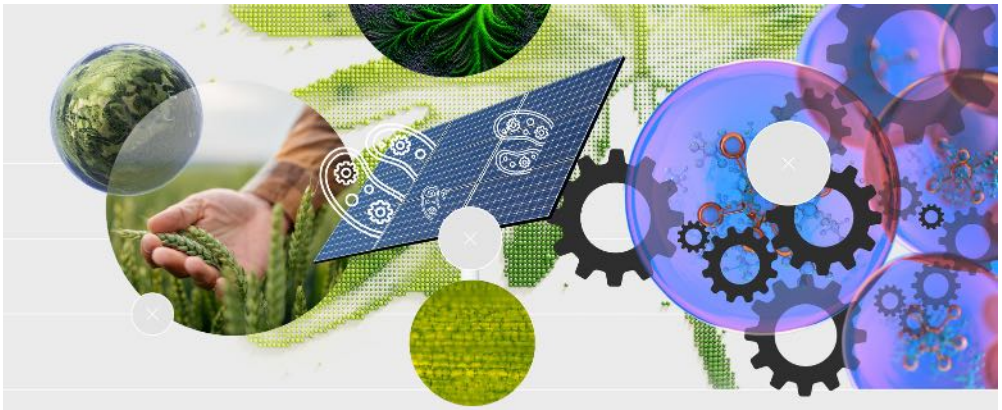
**The tools and products of synthetic biology have potential applications in manufacturing and many other industries, including farming. Much of this work is at an early stage and there are few commercial products as yet.[19] Key challenges include scaling up lab-based experiments in a commercially viable way[20] and controlling synthetic organisms and their interaction with their environment.[21]**

The most obvious potential is in chemistry and materials science, as microorganisms such as bacteria or yeast can be engineered to synthesise chemicals[22] and materials.[23] In effect, living cells are used as factories.[24] Thanks to catalytic enzymes, biological systems can often perform syntheses at lower temperatures and pressures than traditional chemical systems, saving energy and reducing greenhouse-gas emissions. There is untapped potential in the engineering of microbial communities and multicellularity, rather than single cells, for these purposes.[25]

As well as purely biological systems, synthetic biology may be integrated with other forms of technology. For instance, there is growing interest in synthelectronics, which fuses electronics and synthetic biology.[26] Living photovoltaic solar cells[27] are one possible application.[28]

An area of increasing interest is the use of synthetic biology to produce food and its ingredients. Examples of this include the use of microbial cells to produce specific molecules (such as vitamins), the use of plant cells and biomass to make plant-based meat alternatives, and the use of animal cells to make cultivated meat.[29]

Finally, many actors are attempting to apply synthetic biology to agriculture. For instance, it may be possible to re-engineer photosynthesis, the process by which green plants use sunlight to make sugars from $CO_2$. More efficient photosynthesis could lead to increased crop yields.[30] In the longer term, it may also be possible to engineer the fates of plant cells, optimising the morphology of the plants for new environments.[31]



### 5-YEAR HORIZON

**Engineering starts to scale**

Multiple engineered cell lines are used to synthesise chemical products. Increasingly systematised methods are available for engineering cellular factories. New bioreactors are specialised for products like cultured meat, with AI control systems to maximise efficiency and scalability, enabling smooth transitions from lab-scale to industrial scale. New growth media for animal cells are achieved, perhaps derived from microbes. Transgenic crops are made resistant to certain stressors, based on changes to corresponding pathways.

### 10-YEAR HORIZON

**Rational design comes of age**

Rational design of tissues for chemical and materials synthesis becomes the norm. More efficient photosynthesis is achieved in genome-edited crop plants, which are fertilised sustainably and monitored using biosensors. Synthetic systems, including cell-free systems, are starting to be used for manufacturing many products at scale. New feedstocks for manufacturing, including waste and simple carbon molecules like carbon dioxide, are available. Research improves culturing of engineered cells for food production. Cell-based manufacture becomes routine. New approaches for distributed manufacturing mature.

### 25-YEAR HORIZON

**Synthetic biology is integrated into other technologies**

Research achieves widespread integration of synthetic biology into other technologies such as electronics. Generic customisable systems for culturing engineered microorganisms for chemical synthesis begin to appear. Biological catalysis outperforms traditional pure chemistry approaches on efficiency or price. Engineered crop plants are able to resist multiple stressors associated with extreme environments, based on multiple genomic changes. New flavours for food not found in nature are designed, based on detailed mapping of flavour components and their chemical or genetic underpinnings.

## 5.4.3 Medicine and health

**Synthetic biology is already being applied to some areas of medicine and there is considerable potential to expand its use.[32] Many medicines are either sourced directly from living organisms or based on chemicals produced in nature. Synthetic biology has the potential to find many new candidate drugs[33] and to produce medicines in cellular factories.[34] Notably, the first synthetic vaccines have been made and shown to be effective.[35]**

It is theoretically possible to use genome editing to treat genetic diseases.[36] Inherited diseases are a particularly tempting target. A number of technologies exist for precision genome editing of human cells,[37] and some in vivo experiments targeting conditions like mucopolysaccharidosis have already been conducted.[38] However, genome editing's potential goes beyond genetic conditions. For instance, CRISPR-Cas may be used to treat viral infections by targeting the virus's genome within human cells.[39] There is also potential for improving cancer treatments,[40] such as by engineering immune cells to kill tumours.[41] To minimise the risk of off-target effects, improved maps of human genetic diversity are a prerequisite for such therapies.[42]

Therapies based on synthetic cells[43] have shown promise for certain hard-to-treat conditions such as spinal muscular atrophy.[44] In some cases,[45] bacteria act as "living drugs".[46] Controlling such cells remains a challenge,[47] but programmable synthetic receptor systems may offer a means of doing so.[48] There have also been preliminary investigations into the benefits of modifying the skin microbiome.[49] Going beyond cells, engineered tissues have potential as drug-delivery systems,[50] while synthetic transplant organs and induced tissue regeneration remain distant but tantalising possibilities.[51]

### 5-YEAR HORIZON

**Human cells and genomes are re-engineered through AI**

AI guides the re-engineering of human cells and genomes. The human pangenome is used to predict unwanted side effects of genome edits. Cell-based diagnostic systems can be implanted into the human body, and rational design of binding molecules such as antibodies leads to new and targeted treatments. More effective probiotics and symbiotics are available. Many new cell therapies such as CAR T-cell and cancer therapeutics begin to appear, along with rapid design and production of new RNA-based easily programmable vaccines.

### 10-YEAR HORIZON

**Synthetic-cell therapies are customisable**

Generic and customisable systems can create synthetic-cell therapies. Cellular factories allow high-throughput production of new therapeutics. Improved understanding of microbiome-host relationships enables microbiomes to be used for therapy. Cellular sensors, some integrated with electronic systems, monitor fluctuating body systems such as blood sugar. A new base-editing tool that opens up new therapeutic strategies is discovered. Cell-free biosensors are used to assess water quality.[52,53]

### 25-YEAR HORIZON

**Organ production is programmable**

Programmable organ production from stem cells for human transplants becomes possible, along with inducible tissue regeneration for a limited set of organs. Whole-organ engineering begins to happen. Cellular devices can both diagnose and treat conditions, for instance by synthesising a treatment. Long-lasting microbiome therapeutics that can release a drug steadily eliminate the need to take pills. Engineered phage therapies for antibiotic-resistant bacterial infections become available. Synthetic biology approaches to public health are applied, providing clean water, nutrition and improved air quality.

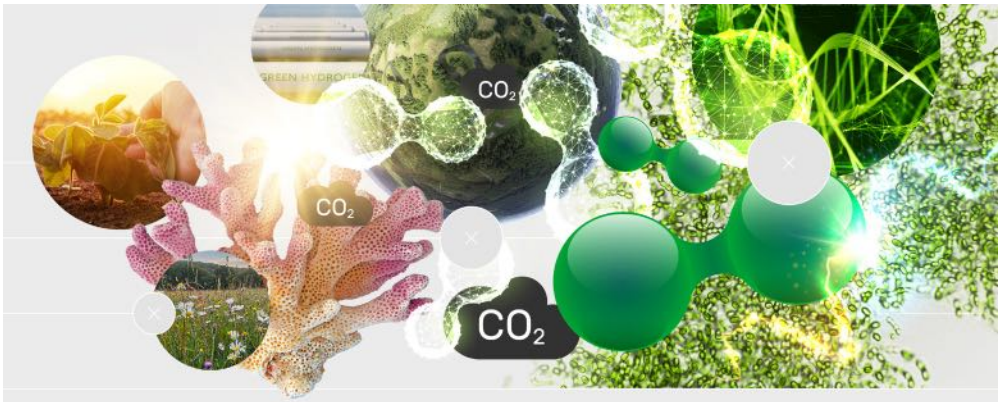
# 5.4.4 Energy, climate and conservation

**There are many theoretical applications of synthetic biology to environmental problems, including tackling biodiversity loss, pollution and climate change. Much of this research is at a preliminary stage.**

There are multiple avenues for using synthetic biology to mitigate climate change. Algae and other cellular factories could be used to produce renewable fuels, offering a less land-intensive alternative to biofuels.[54] Notably, some early work has been done on engineering microbes to produce hydrogen.[55] This would be a low- or zero-carbon method of hydrogen manufacture.[56] Similarly, microbes are being engineered for enhanced carbon capture, potentially removing $CO_2$ from the air.[57]

The flow of pollutants into the environment may be reduced through the use of synthetic biology. For instance, chemical pesticides may be partially replaced by biotechnologies such as RNA interference for pest control, or by engineering the pests themselves — using gene drives, for example.[58] Where pollutants are already present, engineered microbes may speed up their degradation.[59]

Endangered species and ecosystems may be made more robust through synthetic biology.[60] Genome editing may be used to monitor threatened species or to identify the species making up harmful algal blooms.[61] More radically, genome editors could enhance adaptive traits, for instance by making coral holobionts more tolerant of higher temperatures to protect coral reefs from climate change.[62] Any such endeavours would need a reliable understanding of the ecosystems involved: in particular, it is important to gain a better understanding of microbial ecosystems, which are also threatened but are under-studied.[63]




## 5-YEAR HORIZON

**AI accelerates discovery**

Climate-resilient staple crops are developed. Improved catalytic abilities help achieve bioremediation of some organic pollutants, such as oil. Improved fixation of carbon and nitrogen from the air reduces the need for chemical fertilisers. AI enables rapid discovery of new organisms, pathways and molecules with important ecosystem functions. Carbon-negative manufacturing provides proof of principle.

## 10-YEAR HORIZON

**Engineered organisms achieve climate resilience**

Wild species are engineered for resilience to climate change and other stressors, for example corals and their holobionts are engineered for heat tolerance. Microbes are engineered for biodegradation of multiple plastics and for upcycling of waste products. Reliable pest control is achieved using RNA interference. Biological synthesis of replacements for animal products like leather reduce the environmental impacts of livestock farming. Large-scale biosensors are deployed dynamically around the world.

## 25-YEAR HORIZON

**Biodiversity begins to be restored through engineering**

Rational ecosystem engineering is used for biodiversity restoration. Engineered bacteria are able to achieve large-scale green-hydrogen production. Extinct species are generated, and synthetic biology is applied to geoengineering practices such as solar-radiation management and carbon capture.

5.5

# Archaeology

CO CHAIRS:
**Sylvian Fachard**
Full Professor, Institute of Archeology and Classical Studies, University of Lausanne, Switzerland

**Anna Sapfo Malaspinas**
Leader of the Population Genomics Group at the Department of Computational Biology, University of Lausanne

CONTRIBUTORS:
**Qiaomei Fu, Sarah Murray, Kathrin Nägele, Philip Sapirstein, Christina Warinner**



**Advances in science and technology are reshaping archaeology in multiple ways, with new techniques significantly enhancing both practice and knowledge. Molecular techniques enable valuable data to be extracted from fragmentary remains and even from sites that lack discernible artefacts. This is shedding new light on past diseases and pathologies, diets and even migrations.**

New and improved dating techniques mean that some ancient artefacts can be directly and precisely dated, reducing the need for educated guesswork. Improved excavation methods are revealing subtle traces of past human activity, and of climatic and ecological shifts, that would previously have gone unnoticed. As in other fields, artificial intelligence is beginning to be used and has already led to significant breakthroughs.

As a result, questions that were previously unanswerable can now be approached, and concepts that were once taken for granted have been assigned greater nuance or even disregarded. However, certain problems remain to be solved. One is that archaeology is afflicted by severe preservation bias. Materials such as stone can survive well in archaeological deposits, while more perishable substances like wood are prone to decay rapidly. As a consequence, our understanding of the past is skewed towards materials that survive and regions of the world with good preservation conditions.

The field also faces many equity issues. Researchers from the Global South are under-represented in the field generally, while also being particularly underrepresented in more technical fields such as molecular-level analysis.[1] There is also a need to clarify questions of ownership of ancient materials, which are often cross-national, and the field has yet to deal with a legacy of betrayal of Indigenous people by past generations of archaeologists.

There is also an urgent need for many more open-access online databases and standardised formatting to improve the general accessibility of archaeological data. Nonetheless, a growing diversity of peoples and approaches in archaeology is questioning long-standing dogmas. A more nuanced understanding of concepts like gender, hierarchy and societal resilience is reshaping our understanding of many past societies, providing a dynamic narrative that, along with the new generation of tools and techniques, offers reasons for optimism concerning future developments in the field.

KEY TAKEAWAYS

New scientific techniques have proved a boon to archaeology, enabling researchers to fill gaps in data and answer previously unanswerable questions about the past. Progress in **Molecular-level analysis of ancient human remains** has enabled the extraction of ancient human DNA even when no other remains are extant. The field of proteomics has supplemented this, providing valuable information about remains even where no viable DNA exists. In-depth isotopic analysis has revealed new details of hominin diets. Similar techniques have allowed the **Molecular-level analysis of ancient non-human remains**, revealing details about the ecosystems, diet, illnesses and existential threats associated with hominin life across a broad sweep of space and time. Scientific advances are also improving **Palaeoclimate studies**, allowing links to be made between extreme climatic events and societal disruptions, potentially giving insights into adaptability and resilience of ancient hominin populations. Advances in remote sensing, isotopic analysis, non-invasive scanning and radio-dating techniques are **Exposing and decoding world heritage** with unprecedented clarity, providing new insights into the origins of artefacts, the extent of ancient trade networks and the details of cultural achievements.

ANTICIPATION SURVEY RESULTS

SURVEY OBSERVATIONS

New interdisciplinary approaches to archaeology are transforming and accelerating the field. Major breakthroughs are less than 5 years away and will be very impactful for the future of research in this area. But this will require the collection and analysis of material spread out across continents and nations and therefore will rely on strong, international coordinated action.

MORE INFORMATION

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Archaeology

# 5.5.1 Molecular-level analysis of ancient human remains

**Thanks to scientific and technical advances, mostly developed in the last 25 years, it is now possible to extract multiple forms of molecular data from the remains of ancient humans. The host of available new techniques are being rapidly enhanced, enabling faster analyses that extend further back in time and obtain increasingly detailed information about human origins, migrations, diets and other questions.[2]**

The most prominent molecular technique is the extraction and analysis of ancient DNA.[3] Genetic material obtained from bones and other remains has yielded near-complete genome sequences from tens of thousands of years ago. As well as dramatic results like Neanderthal-human interbreeding, ancient DNA has revealed when and how humans have migrated throughout the world as well as family relationships and kinship patterns.[4] More recent techniques have even enabled extraction of ancient DNA from sediments, allowing species to be identified when no physical remains are left.[5] Researchers are now developing techniques for obtaining ancient DNA underwater.[6]

More recently, proteomics has been developed to a high standard. Certain proteins preserve better than DNA, notably in teeth, so proteomics can sometimes be used even when all DNA has been lost.[7] While not as informative as DNA, these proteins can be used to identify species, as well as traits such as sex. Proteins can also be recovered from dental calculus (mineralised dental plaque), and entrapped dietary proteins in calculus can be used to reconstruct detailed information about foods that are otherwise archaeologically invisible, such as dairy products and spices.

Researchers can also now make extensive use of isotopes to reveal details such as the diets of ancient humans,[8] providing evidence of the consumption of meat, fish and plants.[9,10] While isotope chemistry is a long-standing field, new isotopic systems are regularly introduced and new applications identified.[11] Combined with other forms of evidence such as microwear on teeth, these analyses have significantly altered our ideas about past hominins' diets.[12]

## 5-YEAR HORIZON

### Larger datasets provide new insights

More comprehensive reconstructions of lifestyles of past human populations become possible, including societal behaviours like family norms and social structure. Evolutionary pressures such as selection can be inferred directly from large numbers of ancient genomes. Significant improvements in data archiving and metadata for archaeology are made, such as the ability to tag genomic datasets as ancient.

## 10-YEAR HORIZON

### AI reconstructs ancient life stories

Discoveries facilitate systematic estimates of population size and interpersonal interactions in past societies. AI makes it possible to integrate ancient DNA with other data to create life stories of ancient peoples. Global biobanks for human biological resources such as data and ancient DNA libraries, enable improved access and more analyses.

## 25-YEAR HORIZON

### Interdisciplinarity provides new archaeological tools

Archaeology becomes more interdisciplinary, enabling the development of principles governing past human societies. Gene editing is used to restore adaptations from particular populations in specific environments, enabling study of their function. New technologies to study DNA in situ within a fossil — that is, without extraction — allow the acquisition of high-quality ancient DNA from more than 1 million years ago.

# 5.5.2 Molecular-level analysis of ancient non-human remains

**Molecular data has enabled archaeologists to reconstruct flora and fauna, including pathogens, from ancient environments. This tells us about the ecosystems in which ancient peoples lived and how they affected them. Analyses of pathogens reveal the diseases and epidemics suffered by past societies, where diseases come from and how pathogens evolve. This is vital information for avoiding or preparing to face future pandemics.**

Animals, plants and other organisms can be identified from their physical remains, from DNA and from proteomics. A particularly valuable technique developed in the last decade is ZooMS, which involves extracting protein from tiny fragments of bone in order to identify species.[13] This has enabled the identification of animal foods in ancient hominin sites,[14] and revealed hominins' interactions with other large animals.[15,16]

These new techniques have also enabled us to revise our understanding of the environments in which hominins lived,[17] and to tease out the interactions between humans and their environments. There is growing evidence that our ancestors and relatives had negative impacts,[18] contributing to the extinctions of many species, especially "megafauna".[19] Environmental shifts also impacted hominins and their evolution,[20,21] even driving the evolution of new species.[22]

The reconstruction of ancient pathogens relies on the ability to separate pathogen DNA from that of its human host.[23] Combined with existing techniques, such as identifying traces of disease on skeletons and burial patterns,[24] such studies help us understand the ecology and evolution of diseases. They also reveal how societies and technologies, such as the invention of farming, have impacted the spread of pathogens.[25] In addition, they offer support for the contention that human health is inextricably connected with ecosystems, as suggested in the One Health model.[26]

## 5-YEAR HORIZON

**More pathogen genomes are sequenced**

There is a rapid increase in numbers of microbial genomes sequenced, including palaeopathogens. Molecular evidence like DNA and palaeoproteomics becomes sufficiently precise to track mutations and selection pressures on past organisms.

## 10-YEAR HORIZON

**Past ecosystems are reconstructed through AI and environmental DNA**

AI enables identification of the most common flora and fauna specimens, such as pollen and teeth. Environmental DNA from sediments and other sources is routinely used to reconstruct past ecosystems. Researchers reconstruct past food webs using a combination of isotope analyses, tooth wear and other tools.

## 25-YEAR HORIZON

**Drivers of past extinctions brought to light**

High-resolution ecological models are applied to reconstructions of past ecosystems, enabling analyses of drivers of significant shifts such as extinctions. Researchers construct a global history of hominin diseases, from the origin of our species to the present.

# 5.5.3 Paleoclimate studies

**Improvements in technology and methods are enabling ever more precise sampling of past climates (palaeoclimates). Traditional data sources such as tree rings have been supplemented with additional sources like speleothems (stalagmites and stalactites) as well as isotope geochronology. These are making it possible to reconstruct not just average temperatures and rainfalls, but also seasonality and extreme events such as droughts. Climate-related phenomena such as changing sea levels and palaeotsunamis are also being reconstructed in unprecedented detail. The dataset has also been extended further back in time, with palaeoclimate data spanning the entire 7 million years of hominin evolution. However, significant gaps remain.[27]**

The accumulating palaeoclimate data enables archaeologists to link ancient climatic trends and events with hominin evolution and historical events.[28] Shifts in climate and the associated modifications to ecosystems have been associated with key moments in hominin evolution in Africa,[29,30] including diversification and the formation of new species.[31] Similarly, climatic impacts on distributions of hominin species have been identified.[32,33,34,35] In some cases, palaeoclimate data suggest where hominins might have lived during periods where no actual archaeological data are available.[36]

Data suggest that extreme climatic events may be linked to societal disruptions like wars and even collapses. Understanding how and why some societies endured while others folded may offer insight for our own climate-threatened future.[37,38]

There is an urgent need to gather palaeoclimate data as rapidly and widely as possible because contemporary climate change is erasing many key forms of evidence, such as the air bubbles trapped inside the ice of glaciers that are now melting.[39]

## 5-YEAR HORIZON

**A greater range of past climate conditions are explored**

New and improved palaeoclimate proxies enable the sampling of a greater range of past conditions, such as pressure and wind regimes. Cheaper and more accessible sampling techniques facilitate the expansion of palaeoclimate studies to previously understudied regions, such as Central Asia and South America.

## 10-YEAR HORIZON

**Palaeoclimate reconstructions become more reliable**

Researchers achieve standardised methods for assessing palaeoclimate proxies, in particular for controlling for confounding factors, enabling reliable and systematic reconstructions. Reliable identification of multicentennial trends and cycles in palaeoclimate becomes possible.

## 25-YEAR HORIZON

**The impacts of climate change on hominin history are clarified**

Research achieves high-resolution global palaeoclimate records for the entire span of hominin evolution — that is, from 7 million years ago to the present. This enables detailed reconstruction of the impacts of climatic change on hominin evolution and hominin habitats. Massive online databases of paleoclimate data improve accessibility of information and enable new analyses.

# 5.5.4 Exposing and decoding world heritage

**Archaeology is now able to take advantage of a range of methods and technologies for revealing, recording and preserving hominin artefacts. Some of these operate at the landscape scale: satellite technology and LiDAR (light detection and ranging) are increasingly used to identify habitations and other large-scale structures.[40,41] These techniques are particularly useful in inaccessible regions such as dense forest. Many ancient settlements and geoglyphs in the Amazon rainforest have been identified by airborne LiDAR,[42,43] and some researchers are exploring LiDAR's usefulness for underwater archaeology.[44]**

At smaller scales, advances in the use of isotopes, including non-traditional isotopes, are enabling archaeologists to trace the materials in artefacts like swords back to their mineral sources.[45,46] These studies are revealing continent-spanning exchange networks long before empires or modern globalisation.[47] Similarly, new dating techniques like uranium-thorium are proving invaluable for determining the age of artefacts such as rock art, providing some of the first hard evidence that other hominins such as Neanderthals made art.[48] AI is also proving useful. It has helped to identify the chemical signatures of heating in ancient rocks, for example, providing evidence of controlled use of fire a million years ago.[49]

New methods are being brought to bear on the interpretation and decoding of artefacts. Photogrammetry, which enables the 3D scanning of artefacts, is increasingly used to reveal hidden details and patterns.[50] AI can restore degraded ancient texts and identify their sources and ages.[51] Similarly, ancient scrolls that are tightly wrapped and damaged can now be 3D-scanned and some of the text read.[52]

## 5-YEAR HORIZON

### Technology enables digitalisation and sharing of knowledge

Rapid and accurate 3D digitalisation of artefacts, buildings and landscapes becomes possible. Customisable laser-scanning equipment is used for rapid assessment of different-sized artefacts. Cheaper and faster internet facilitates more equitable data sharing.

## 10-YEAR HORIZON

### Standardisation improves archaeological insight

Global standardisation of archaeological protocols enables systematic comparisons, increasing depth of insight. There is a new, widespread availability of experimental methods for completing and interpreting damaged and incomplete texts, such as clarifying strokes and inscriptions. AI-based translators give approximate translations of texts in ancient languages. Higher-resolution scanners, going beyond the current 20-micron limit to 1 micron or less, enable finer analysis of cut marks and other forms of wear, while higher-resolution LiDAR, down to 1 centimetre, improves aerial analysis of structures.

## 25-YEAR HORIZON

### Scanning improvements give new views of artefacts

3D scans extend beyond the visible spectrum, for instance including data on the composition of pigments on surfaces or materials in soil. AI enables much faster analyses of large numbers of artefacts, speeding up "routine" work and data publication. Regular global LiDAR coverage reveals — and monitors — heritage sites.

INVITED CONTRIBUTION

# The Future of Fusion

**Ian Chapman**
Chief Executive Officer, UK Atomic Energy Authority (UKAEA)

**Mike Porton**
Chief Engineer, Tokamak Energy

**Ahmed Diallo**
Program Director for the Advanced Research Projects Agency-Energy (ARPA-E)

**Susana Reyes**
Vice President for Chamber and Plant Design, Xcimer Energy Corporation


*This invited contribution originated from a public talk at the Royal Institution, an independent charity that brings leading-edge science and research to public audiences in London and globally.*

MORE INFORMATION:

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**Fusion, often referred to as "putting the Sun in a bottle", could help meet our energy needs using nothing more than the hydrogen atoms found in seawater. Squeeze together two hydrogen atoms at a high enough temperature and pressure, and they fuse together, releasing vast amounts of energy. This is the process that powers the sun.**

In the ultra-high-pressure environment of the very innermost part of the sun, every fusion of two hydrogen atoms creates the energy that would keep a 60-watt light bulb shining for over 100 years. On Earth, we can't recreate those enormous pressures, but we can compensate for that by achieving much higher temperatures. This, in addition to the use of particular isotopes of hydrogen that have extra neutrons and are thus more susceptible to fusing, means that we can now routinely achieve fusion on Earth.

Taking this to the next level requires that we do this over sustained periods, and at scale. If this can be achieved, nuclear fusion will provide zero-carbon, sustainable, essentially limitless baseload energy. This is nothing new: we have known it to be possible for around a century. What is new is that, though the field still faces a number of significant challenges, research achievements over the last five years have created genuine optimism that these challenges can soon be overcome.

In 2022, for example, the US National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California achieved ignition, obtaining more energy from its fusion reaction than was required to start it for the first time ever in a laboratory setting, and demonstrating the scientific feasibility of laser inertial fusion. Since then, it has surpassed its own record several times, almost doubling the net fusion energy output. In 2023, the UK's Joint European Torus (JET), based at Culham in Oxfordshire, set a new world record for the amount of fusion energy produced. Also in 2023, the Experimental Advanced Superconducting Tokamak at the Institute of Plasma Physics in Hefei, China, achieved a "steady-state high-confinement long-plasma operation" — a key component of sustained fusion-power system operation — for a record-breaking 403 seconds.

Of the significant science and engineering challenges that remain, the most basic one is the challenge of fuelling fusion-power systems. The hydrogen isotopes that fuel fusion plants are generally deuterium, which is available in seawater, and tritium, which is more difficult to source. There are only a few tens of kilograms of tritium globally, and fusion-power plants will typically require several kilograms per year of operation. So fusion plants will probably make their own tritium by channelling the high-energy neutrons emitted in the reaction into a lithium blanket. The nuclear interactions between the neutrons and the lithium are a source of new tritium that can be fed back into the device, creating a sustainable fuel cycle inside the machine.

Another key challenge is in materials science. The high-energy neutron flux and the elevated temperatures of a fusion-power system pose a danger to the fusion-containing structure. Maintaining the integrity of its containment structure will require advances in materials science.

The optimal design for a power plant-style fusion-power system is still a matter of debate. A number of options are being explored, with the torus (or tokamak), where fusion is provoked within a doughnut-shaped vessel, being the most-researched and tested approach for magnetic-fusion energy, and lasers (like NIF) being the most-studied and tested driver for inertial-fusion energy concepts. The tokamak configuration was chosen as the design for ITER, the International Thermonuclear Experimental Reactor. This collaborative project brings together scientists and engineers from the US, China, Europe, Russia, India, South Korea and Japan. 85 per cent of the world's population is represented in this project.

ITER will produce 500 megawatts of fusion power within the next couple of decades. Although it will not function as a commercial power station, it will show that we can build power plant-scale components for fusion. ITER involves about a million components and 10 million individual parts, most of which have never been designed or built before. ITER is thus priming the pump for the industrial supply chains necessary for fusion power, and bringing the types of components required off the drawing board on a scale that is consistent with the fusion power plants that will follow it.

Progress in fusion research is also demonstrating, through the investment that has been made, that fusion is of interest to the industrial sector. More than $6 billion of investment has gone into private fusion companies in the last few years. There are now more than 40 companies in the fusion space, eight of which have been selected by the US Department of Energy for a milestone-based public-private partnership programme to develop fusion power in the next decade.

Investment is also spurred by the fact that regulatory considerations for fusion are progressing. Fusion has some inherent safety characteristics: it cannot have a runaway chain reaction, and in the case of laser fusion, turning off the fusion reaction is as easy as flipping a switch. As a result, it is fully recognised that fusion-power systems should be regulated very differently from fission reactors. In the US, the Nuclear Regulatory Commission is in the process of modifying the framework that is used to regulate particle accelerators and make fusion a part of that regulation. The UK government plans to regulate fusion under the Health and Safety Executive rather than the fission power plants' governing body.

When commercial fusion is up and running, the electricity produced will likely be used as baseload to ensure the stability of electricity production. But it could also help with surge provision, putting it into competition with some very different types of energy production and storage. Fusion can also support hydrogen production through electrolysis, as well as thermal-energy applications. If fusion's coolants are driven in certain ways, they can provide industries such as paper and chemical production, and other industries that are difficult to decarbonise, with a clean low-carbon source of heat. Another possibility is to take the nuclear component of the energy that's released from the fusion reaction in the form of high-energy neutrons and use it to produce radioisotopes such as a xenon, technetium and lutetium, which are used in medical imaging and cancer treatments.

Fusion has the potential to solve the challenge of energy equity and is a flagship demonstration of science diplomacy. Current projects operate in a wide range of jurisdictions and bring together scientists, engineers, managers, administrators and policy-makers from almost every nation. ITER, it is worth emphasising, is a collaboration between a number of nations that are experiencing enormous amounts of friction at the geopolitical level but are nonetheless finding ways to collaborate in this technical sphere. When power-plant-scale fusion is achieved, it will not only be a major technological advancement that democratises energy production, nor just a significant step towards decarbonisation, but also a signifier of hope for humanity.

INVITED CONTRIBUTION

# Future of Social Science and the Humanities

**Yasuo Deguchi**
Co-Chair of the Kyoto Institute of Philosophy, Dean and Professor of Philosophy at the Graduate School of Letters, Kyoto University

**Markus Gabriel**
Professor and Chair in Epistemology, Modern and Contemporary Philosophy, University of Bonn

**Jun Sawada**
Co-Chair of the Kyoto Institute of Philosophy, Chairman and Member of the Board, Nippon Telegraph and Telephone Corporation


MORE INFORMATION:

go.gesda.global/5-IC-2

**Anticipation of scientific and technological breakthroughs is critical for enabling society and its legitimate decision-makers to craft inclusive, global solutions and progress toward sustainable futures. However, such techno-scientific anticipation is not enough by itself. It only makes sense when framed within more fundamental questions about humans, society and the planet — questions at the heart of the social sciences and humanities. We must also anticipate the future of these latter disciplines if we are to cope fully with the complexities of today and tomorrow.**

Humans are sense-making beings. Our understanding of ourselves, other people and the world around us influences who we can be, what we can think, and how we can live together. Just as science and technology build and alter the material and virtual infrastructures of our reality, the social sciences and humanities furnish us with the conceptual and framework infrastructures needed to interpret how human beings and societies evolve within that changing reality. The social sciences and humanities thus do more than merely describe the backdrop for technoscientific advancements: they actively contribute to shaping them.

Conversely, techno-science-driven transformations challenge some of the most foundational concepts in the social sciences and humanities, such as "intelligence" in the era of general-purpose AI, "rights" in the context of neurotechnologies and "environment" amid climate-engineering initiatives. The reason is simple: as technoscientific infrastructures transform reality's basic features, traditional concepts and frameworks may no longer fully apply. Scientific and technological advancements, therefore, necessitate rethinking the tools that social sciences and humanities use to understand and explain reality, thus opening the space of opportunities and action for new possible orientations. To this end, again, we must anticipate the future of social sciences and the humanities.

This is no trivial task. Akin to Hegel's "owl of Minerva", which spreads its wings after the day's main events have taken place, these disciplines are traditionally reflective and backward-looking, making sense of a world just as it passes away. Transitioning to future-oriented, anticipatory and constructive social sciences and humanities thus involves a paradigm shift towards imagining the futures of individuals, societies and planet, and the related fundamental interrogations they raise. Key questions to guide this shift include:

- What are the disciplinary trends, emerging research fields, potential disruptions and transformative questions ahead in the social sciences and humanities?

- How can we foster anticipatory dialogue and synergies between the social sciences and humanities, science and technologies?

Exploring these questions across the individual, collective and global levels offers a glimpse into this future-oriented approach.

At the individual level, the focus is on our human nature and existential condition. A future topic in the social sciences and humanities will be fully integrating the situatedness of human agency in context, where no single agent exists independently but is instead always embedded within a network of other agents and technologies that co-produce the individual self.

Moving away from an egocentric to a relational model of future technology-powered subjectivity will challenge the perceived uniqueness of our human condition and maybe even call for extending kinship to non-human agents, including artificial ones. Anticipatory dialogue and synergies between the social sciences and humanities, science and technologies will be essential to align interests and needs in the creation of such relational subjectivities, ensuring that they support new forms of individual freedom and self-determination throughout all human-machine interactions.

At the collective level, the focus is on how we live together in societies. A critical issue for future social sciences and humanities will be determining what can be universalised based on our shared humanity within multi-layered societies of values. Welcoming "otherness" in diverse sociocultural environments will be vital for negotiating legitimate universal values that respect divergent value systems across various societal scales, against the non-negotiable baseline of upholding human rights.

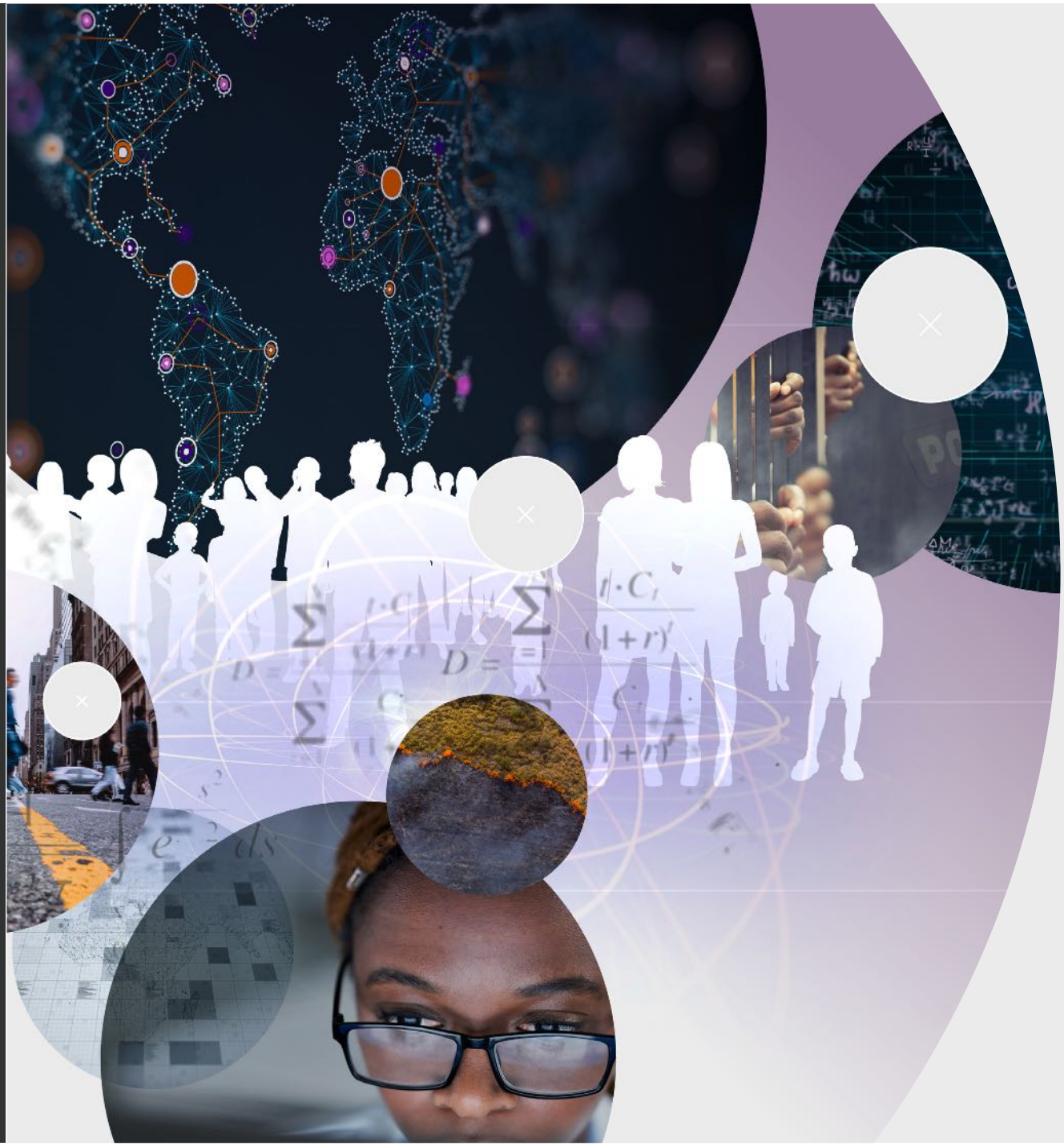
Beyond cosmopolitanism, new social models will need to catalyse transcultural, multi-perspectival experiences of human collectivities. Cross-disciplinary anticipatory dialogue and synergies will be needed to balance the risks and opportunities of techno-scientific governance in technologised societies while promoting social freedom and collective human flourishing.

At the global level, the focus is on our relationship with the planet, geared toward sustainable futures. A critical challenge for cross-disciplinary anticipatory dialogue and synergies will be to continue bridging the theory-practice gap by engaging local practitioners with scientific research to match ecological priorities with social opportunities through knowledge co-production and co-learning.

Reconciling technology, nature and humans in new futuristic imaginaries powered by shared aspirational narratives will be instrumental in achieving the radical transformations required for beneficial planetary outcomes. Future-oriented social sciences and humanities will provide the concepts, methods and frameworks for societies to collectively create realistic fictions about the kind of world they want to help bring into being and act upon them.

The future of social sciences and humanities lies in operationalising new imaginaries for future orientations in our multi-layered, pluralistic societies. This will involve designing, negotiating, translating and implementing innovative concepts and frameworks. Along these processes, interdisciplinary exchange alone is insufficient: cross-sectoral cooperation and integration must materialise to comprehensively understand and anticipate shifts of mindsets that will reshape the world. Only then can we embrace accelerating global change in forging a path toward more inclusive and sustainable futures.

HUMAN RIGHTS



INVITED CONTRIBUTION

# Mathematics for humanity

**Minhyong Kim**
Director, International Centre for Mathematical Sciences, Edinburgh and the Edmund Whittaker Professor of Mathematical Sciences, University of Edinburgh

MORE INFORMATION:

go.gesda.global/5-IC-3

**In an ever more fractured world, unification can be a valuable process. It might be political, such as the unification of East and West Germany. It might be scientific: physicists have long been searching for a "grand unified theory" that will reveal the common origin of the various forces of nature. But it can also be mathematical.**

The future of mathematics will bring about a drive towards greater unity on a number of levels. At the technical level, there will be increasing unity among the different areas of mathematics. For example, my own research falls within a great scheme of unity between the areas of algebra, topology, geometry and number theory. This unity was brought about by way of a careful mathematical analysis of the fundamental structure of the natural world as described by particle physics, general relativity and research on the possible states of matter. This analysis suggests that many of the difficult problems in all these areas have a common core of "higher algebra" that needs to be understood precisely in order to make fundamental progress.

We are also seeing increasing unity between what is sometimes thought of as "pure" and "applied" mathematics. It's unlikely that this distinction has ever been serious in the practice of the subject: it appears to have been emphasised mostly as a framework of organisation within various universities in the 20th century. Unfortunately, this created boundaries that have mostly been harmful. However, at the moment — partly as a consequence of the revolutions in data science and AI — more and more "pure" and "applied" mathematicians are working together, and with other scientists, to understand the same phenomena.

Data science and AI are now central to our societal discourse, and their bringing together of mathematicians and scientists acts as an exemplar of an even more valuable unification: that which must now occur between the subject of mathematics and the most profound human concerns.

For centuries — if not millennia — an ideology that views mathematics as belonging to some other-worldly realm has exerted undue influence and spread confusion, sometimes leading the subject to be seen as an ivory tower even within the ivory towers of academia.

However, this isolationist model of mathematical scholarship has always been problematic. Ultimately, mathematics aims to increase and sharpen our understanding of the world around us. It arises out of a tradition and history that has developed with — and within — human civilisation. It seems only right, then, that the basic goals of the discipline should combine its commitment to an increasingly precise understanding of the nature of reality with a deeply humanistic outlook that attempts to engage with the human condition.

This is a vision that will undoubtedly expand and deepen in the coming years, both at large and small scales in mathematical education, research and knowledge exchange. Importantly, the vision is already leading to a great eagerness, on the part of young mathematicians in particular, to engage with a diverse array of specialities and to apply their findings in real-world situations.

In fact, the boundaries between mathematics and neighbouring disciplines are routinely being broken down. Even though the bulk of my own research has been in number theory with a bit of mathematical physics, I find myself collaborating with experimental physicists, engineers and biologists to embed my work in real-world issues such as the prediction of new states of matter, image classification by machines and the mathematical structure of biological evolution. Many of my mathematician colleagues are employing machine-learning techniques to investigate classical problems in topology, geometry and number theory, with insights from these areas are impacting cryptology, information theory, health sciences and many more areas of human concern.

Unfolding in parallel with this — and essential to its success — is a geographical unification in mathematics. I lead a project, Mathematics for Humanity, that hopes to foster collaboration between regions of the world with varying levels of prosperity, bringing mathematics to disadvantaged groups in all countries. This includes efforts to address natural or social crises facing these societies and, in particular, to increase the research capacity and access to mathematics of low- and middle-income countries. That means that we are globally united in using mathematics to address issues in climate change, economics, democratic processes and the justice system, amongst other areas.

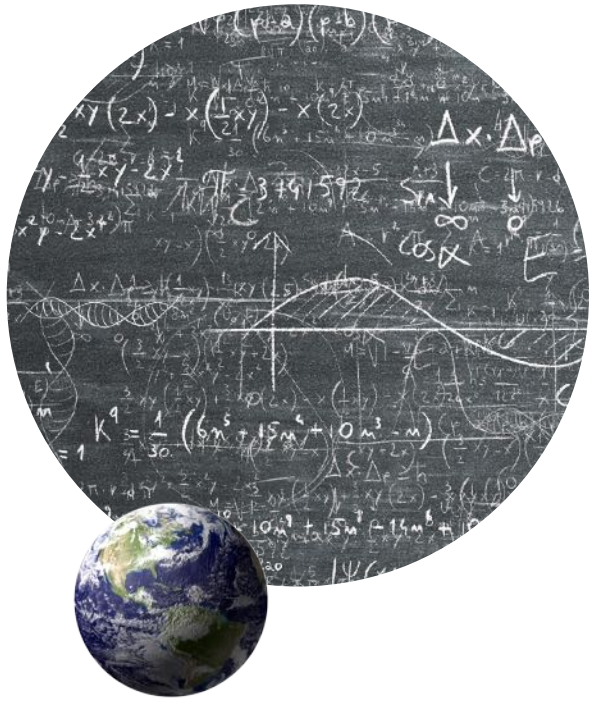
This shouldn't be surprising: mathematics has always had such utility. There are many people working on fluids, dynamics or mathematics having to do with current flows, for example, who could contribute to ocean science and efforts to address the issues arising from climate change.

Regarding justice, researchers are looking into mathematical, statistical and machine-learning research to examine issues related to the justice system and how to keep AI from incorporating the social biases that these systems tend to have. In fact, some of my colleagues are applying abstract conceptual tools from information theory and category theory to explain what bias and diversity are at a fundamental, mathematical level, an understanding of which can then be applied to both biological and social systems.

Such initiatives are an exciting frontier for mathematicians because many of them, even when they are working on applied mathematics, are not routinely talking to people who confront these kinds of problems in the wide world. That can be because of institutional isolationism, but sometimes mathematicians don't feel that they have a voice or a platform to share useful insights they might have. Part of the goal of our programme is to promote more solidarity among, and collaboration between, mathematicians whose work is relevant to these pressing problems. The hope is that they will then feel more empowered to share their understanding of what can be done. We call it "knowledge exchange for humanity".

The future of mathematics, then, will involve a wide range of researchers harnessing the full potential of mathematics for enhancing human welfare. But that will require yet another unification: a full inclusivity that embraces all of the contributors to mathematics throughout its history. From its inception, mathematics has been a global endeavour, and the development of an accurate, inclusive conception of the history of mathematics that reflects its genuinely global heritage is long overdue.

While mathematics has been viewed as a largely cosmopolitan endeavour that transcends national boundaries, it is only recently that we have come to acknowledge that such cosmopolitanism was understood within a rather narrow framework built by groups of privileged people. Many people are now interested in expanding the framework into a true globalism that leaves no individual or groups out of the mathematical community. This is the only viable way to move towards global peace and understanding — a goal that mathematics can help humanity to achieve.



GESDA SCIENCE LENS:

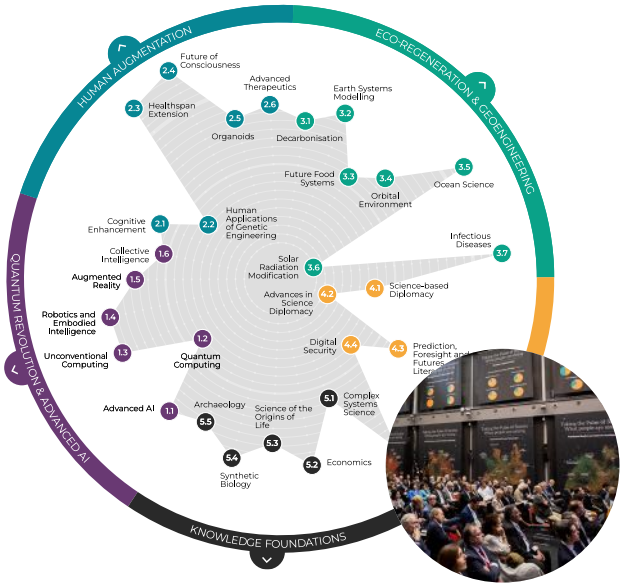
# Anticipating the Future of Research

**Sophie Gilbert**
Programme Lead, GESDA Science Breakthough Radar®

**Martin Müller**
Executive Director, Science Anticipator, GESDA

An expanded version of this essay can be found at:

go.gesda.global/5-Lens




**October 2024 marks the release of the fourth annual edition of the GESDA Science Breakthrough Radar®, a unique and growing collection of data and insights about anticipated breakthroughs in science and technology. To develop and compile the Radar, GESDA has engaged with more than 2000 researchers across over 60 different fields of scientific, technological, social and diplomatic research.**

GESDA is primarily concerned with anticipating the transformational changes that such breakthroughs will bring to society and with identifying opportunities to improve how we will live in the future as individuals, in societies and on our planet. But we recognise that how research and innovation is undertaken, and how the questions that arise are addressed, also require consideration if we are to harness the potential of future research for the global good.

The Radar therefore not only reflects expert opinion about the breakthroughs we might expect over the next 5, 10 and 25 years, and their consequences, but also provides an anticipatory tool for changes in how research itself will be carried out. Advanced technologies — such as our ability to collect and analyse vast datasets, breakthroughs in our ability to synthesise novel DNA and the power of machine learning to model hitherto unknown phenomena — are all examples of breakthroughs that have the potential to significantly affect the course of scientific progress.

Who chooses what research is conducted, and by whom, is a crucial component of the research endeavour, and is largely determined by those who provide the resources needed and those who set the policy agenda. The question of who owns and controls the resources critical for future research, as well as changing global circumstances, approaches and philosophies, are challenging this status quo.

At the extreme, the future research agenda may not even be designed by humans. In some fields, such as synthetic biology, increasing automation of labour and data-intensive laboratory work raises the possibility of future research being carried out by robots guided by artificial agents, operating within entirely autonomous systems. At the same time, this automation is expected to drive down the cost of novel biological synthesis and make it more accessible to those without the resources needed to run their own full-scale laboratories, further diffusing decision-making power.

Even in the nearer term, there are likely to be shifts in power which will have transformative consequences for the process of science and research. Researchers are anticipating three major trends over the next 25 years: research unification, the further development of artificial intelligence and the interplay between research and geopolitical shifts.

The first of these trends is a move towards research unification, with the consequent breakdown of “siloed” disciplines and “isolationist” institutions. Researchers are already engaging in wider, more diverse collaborative networks than ever before, as they engage with a broad range of expertise to address increasingly sophisticated research questions. This is catalysing new partnerships between individuals, teams and research disciplines.

For example, collaborations between psychologists, data scientists, physicists and evolutionary biologists are expected to identify the driving factors behind different societal group behaviours within the next 10 years as well as ways to precisely manipulate these dynamics in the real world. Another example is the increasingly essential collaboration between AI specialists, neuroscientists and philosophers in developing more capable robots and autonomous systems. A third is the coalitions of ecologists, molecular biologists, data scientists, anthropologists and ethicists who will be required to monitor and restore or augment ecosystems.

Such collaborations blur the conventional dividing lines between research disciplines and schools of thought. The conceptual frameworks and infrastructures which researchers use to make sense of the world are also being revised and reframed to reflect changes to our societies and environments. There is an expectation that impactful research with relevance to acute real-world problems will require the complete erasure of divisions between previously disparate fields of research.

In parallel, historians and philosophers of science are providing insights into the decolonialisation of research practice and the tools to consciously and intentionally shape its future to meet the diversity and globality of wants and needs. This in turn is increasing awareness of the importance of maintaining and developing different knowledge systems, embracing the understanding provided by, say, Indigenous knowledge as well as that gained using Western research frameworks.

For example, Indigenous knowledge is likely to be key to realising the potential of psychoactive compounds for therapeutic use, developing food systems robust enough to overcome a changing climate or shaping future ecosystems. Unification of research practice promises to span geographic, cultural and social distinctions between researchers, bringing about an inclusive “globalism” able to embrace multiple perspectives, and discarding “othering” in research and knowledge generation.

The second transformational effect on research comes from artificial intelligence. While the technology has only just begun to be used, it has already yielded striking results. For example, gaining any indication of the structure and function of a protein has traditionally involved many years of laborious laboratory work by a team of scientists. But in 2020, DeepMind released its AlphaFold modelling tool, which can predict the structure of a protein from its sequence in a matter of mere seconds. By August 2024, the *Nature* paper accompanying the AlphaFold release had been accessed 1.67 million times and cited more than 15,000 times in subsequent scientific papers

It is noteworthy that while AlphaFold is rapidly becoming a staple tool of the research community, much of which is publicly funded, it is owned by Google, a commercial non-state entity, and the knowledge created using it may also be held by such entities. For example, Ginkgo Bioworks uses AlphaFold to generate databases of protein structures for industrial clients and is one of the world’s most successful synthetic biology companies. Paid access to its proprietary database of these biological building blocks is a key component of its business model. This is knowledge that might previously have been done by academic research organisations and placed in the public domain. Such privatised control of technologies and data fundamental to research raises key questions about where decision-making power sits within the research ecosystem, and how this will constrain who can carry out research, what research is being done, and where it can be carried out.

Furthermore, the ability of AI to uncover hitherto obscure patterns and associations is reliant on the quality of the datasets themselves. Lack of adequate data can create bottlenecks for entire fields of research. The robotics community, for example, has only fragmented and non-standardised data for artificial sensory stimulation, which severely limits researchers' ability to train artificial intelligence to control a robotic "body". Another example, from medical research, is the chronic lack of data on the early human embryo during the time window when most pregnancies fail, severely limiting development of interventions. A third is the existence of "darkspots" in our knowledge of the world's ecosystems; for example, our paucity of knowledge about the vast number of microbes that are difficult to culture in laboratories.

So while AI has much promise, it remains powerless without such "big data" resources, and the ability to access and process standardised, high-quality and well-annotated data is becoming a fundamental requirement for researchers. While there are now fewer technical barriers, there are potentially more logistical, legal and commercial obstacles: for example, data may be held by multiple organisations of different kinds and with different expectations of the uses to which it can be put. So, for example, there are also ecological "greyspots" where data about an ecosystem does exist but is not readily available for research. The question of who "owns" data — whether historical archives, creative assets such as digital artworks or genetic sequences — thus has significant implications. How datasets, archives and infrastructures are created, accessed and understood; who owns them or is responsible for them; and how their longevity and security can be guaranteed, given their dual digital and physical natures, will be fundamental issues for the future of research.

Finally, science and research do not take place in isolation from other forces in society. There are many examples described in the Radar of how the geopolitical climate is changing research agendas both nationally and internationally, both for governments and for private entities. That might mean investing individually for reasons of economic advancement or commercial gain; or it might mean working collectively to mitigate threats or generate the platforms on which future research and prosperity rests.

Examples include the vast investments made in the technology sector following the release of ChatGPT in 2022; the continuing tensions surrounding deep-sea mining and the use of the ocean to support the renewable-energy transition; and fears that advances in synthetic biology will fuel new forms of biological warfare. Outbreaks of armed conflict, as well as increased polarisation both within and between nations, are stimulating research into diverse fields such as behavioural science, neuro-augmentation and satellite capabilities.

In the future, therefore, this question of who can carry out what research is likely to be an even greater determining factor in the distribution of power beyond the research ecosystem. Quantum computing and its promise to outperform current computing paradigms is an excellent example of how a technological gap between different states, entities or groups has the potential to grow exponentially wider and very quickly become impossible to bridge. Scholars examining the tight interplay between science, scientific practice and power anticipate that the relevance of these relationships will only continue to grow.

As we further develop the Radar, we hope that it will become an invaluable resource for anticipating the future of science and research practice, for identifying the changes most likely to have transformative effects and for anticipating the implications of these changes and the place that research holds within our society. Finally, we hope to integrate insights on anticipated trends in the practice of research into future releases of the GESDA Science Breakthrough Radar® in order to develop it as a useful and impactful resource for scholars and policy-makers, generating new insights into how science and society may change in the future.

CONFERENCE PROCEEDINGS

# Anticipating the Future of Peace and War

## 5.1 Complex Systems Science

**Geopolitics has been increasingly volatile in recent years with the war in Ukraine, unravelling Sino-Western relations and increasing food insecurity, to name a few of the issues that have arisen. How can new methodologies for anticipation in peace and security be developed to safeguard the future of humanity?**

MORE INFORMATION:

go.gesda.global/5-1-Diplomacy

PARTICIPANTS
Moderated by:

**Enrico Letta**
Former Prime Minister of Italy; President, Jacques Delors Institute; GESDA Board Member

Presentations by:

**Jean-Marie Guéhenno**
Former UN Under-Secretary-General for Peacekeeping Operations; Arnold A. Saltzman Professor of Practice in International and Public Affairs; Director of the Kent Global Leadership Program on Conflict Resolution, Columbia University

**Thomas Greminger**
Former Secretary-General, Organization for Security and Cooperation in Europe; Director, Geneva Centre for Security Policy

With:

**Michael Møller**
Former UN Under-Secretary-General; Former Director-General, U.N. Office at Geneva; GESDA Board Member

**'Funmi Olonisakin**
Professor of Leadership, Peace and Conflict, King's College London, UK

**Dingli Shen**
Professor of International Relations, Fudan University, Shanghai, China

TAKEAWAY MESSAGES:

*"Whether it be the Israel-Hamas war or Russia's assault on Ukraine, the 21st-century versions of peace and war are 'more complicated than ever' and an anticipatory approach is needed."*

*"Anticipation does not come without its own challenges: to avoid focusing on present-day concerns, one must look at a multiplicity of trends and counter-trends on global topics ranging from climate to migration and their interactions with one another."*

*"During two high-level workshops in Geneva and New York in 2023, GESDA, Columbia University's School of International and Public Affairs, and the Geneva Centre for Security Policy convened experts who focused on a systematic two-axis approach to anticipation: a vertical axis for the continuum between war and peace, and a secondary axis for the impact of science and technology on societies from enhancing to disrupting the distribution of power."*

*"Despite rising threats from technology, there are some positive signals which deserve more attention and encouragement, such as global youth movements advocating for causes such as climate action and against gender discrimination, which in some countries has triggered major changes in policies toward long-established social injustices."*

*"Thinking about the future of peace and war also requires thinking about how people will live in the future and who will govern the world in 2050."*

*"Conflicts are likely to become far more dangerous if technologies like autonomous weapons evolve beyond our control and remain in the hands of a few, which is why GESDA's anticipatory approach gives diplomats and policy-makers 'a futuristic compass' to find a way forward."*

# Defining the Red Line in Research

5.2 Economics

With new technologies advancing ever more rapidly, there is an urgent need to put more adequate and efficient regulatory mechanisms in place while not hindering the progress and benefits of science. As scientists are in the best position to anticipate where and when their research could cross the line, is self-regulation the answer?

MORE INFORMATION:

go.gesda.global/5-2-Diplomacy

PARTICIPANTS
Moderated by:

**Andrea Boggio**
Professor of Legal Studies, Bryant University, Smithfield, Rhode Island

With:

**Patrick Aebischer**
Vice-Chairman, GESDA; President Emeritus, Swiss Federal Institute of Technology Lausanne (EPFL)

**Matthias Kaiser**
Professor Emeritus, Centre for the Study of the Sciences and the Humanities, University of Bergen, Norway

**Robin Lovell-Badge**
Head of the Laboratory of Stem Cell Biology and Developmental Genetics, Francis Crick Institute, London

**Cheryl Moore**
Chief Research Programmes Officer, Wellcome Trust, London, UK; GESDA Board Member

**François Rivasseau**
Senior Consultant, Science and Diplomacy, World Intellectual Property Organization, Geneva, Switzerland

TAKEAWAY MESSAGES:

*"There is growing debate on whether more regulatory mechanisms are necessary to ensure accountability and transparency in the development of transformative technologies like AI and quantum computing. The challenge is how to establish red lines in research without impeding progress."*

*"The GESDA Science Breakthrough Radar® highlights the importance of responsible anticipation, emphasising the need or duty of the scientific community to contribute to the ethical aspects of breakthroughs."*

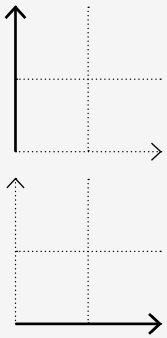
*"While scientists might be best positioned to determine potential red lines in research, conversations that include perspectives from all groups of society are needed, including the public, public and private funders of research, publishers, civil society and policy-makers."*

*"One of the problems in drawing red lines in research is that different jurisdictions and different countries may want to put those red lines in very different places for a variety of historical, religious or other cultural reasons, so any regulation for modern scientific collaboration must be worldwide — otherwise it will not work."*

# Media-Innovation Analysis

While Future Economics sees a lesser increase in mentions, it is gaining momentum in the number of patents filed. Conversely, innovations in Complex Systems Science lag behind, unable to match its 28 per cent growth in media coverage.

LEGEND:

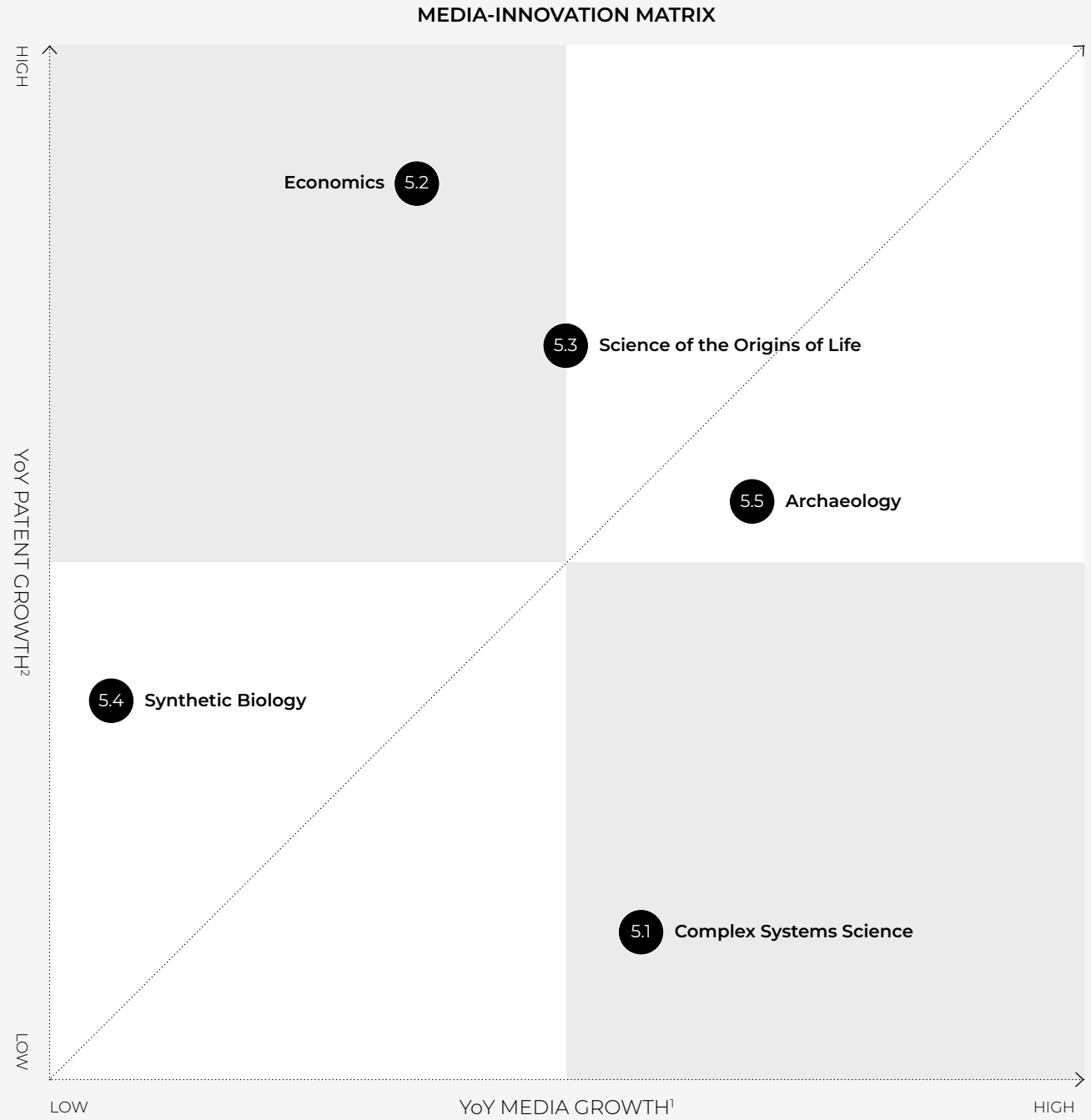


**YoY PATENT GROWTH**
YoY (year-on-year) growth of granted topic patents[1] from May 2022/April 2023 to May 2023/April 2024

**YoY MEDIA GROWTH**
YoY (Year on Year) growth of topic mentions in news & blogs from May 2022/April 2023 to May 2023/April 2024

MORE INFORMATION:

go.gesda.global/Impact

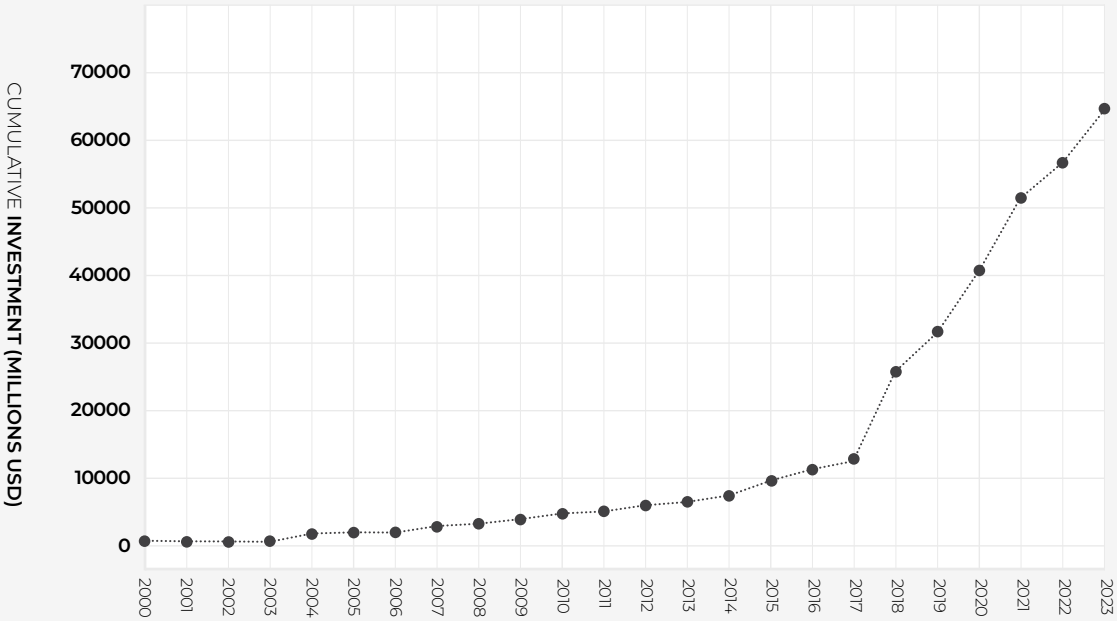


IMPACT FOCUS

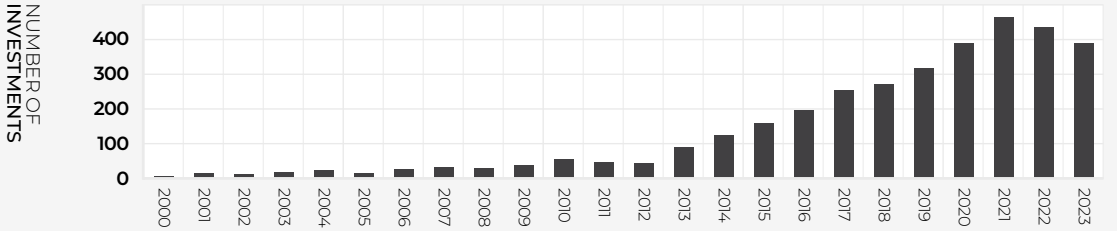
# 5.4 Investment and Company Creation in Synthetic Biology

Synthetic biology as a field first captured the attention of private investors in 2010, with the first complete synthesis of a working bacterial genome by a team at the J. Craig Venter Institute. This was followed in 2012 with the work of Jennifer Doudna and Emmanuelle Charpentier on the gene editing system CRISPR-Cas9. This has led to a steady growth of private investments in the field, accelerating after 2017 upon the convergence of synthetic biology and artificial intelligence with the release of Deepmind's revolutionary AlphaFold. The rate of investment in synthetic biology shows no signs of slowing, reflecting the acute interest of the private sector in biotech solutions for both health and environmental applications.

## CUMULATIVE INVESTMENT IN SYNTHETIC BIOLOGY COMPANIES




## NUMBER OF NEW INVESTMENTS IN SYNTHETIC BIOLOGY COMPANIES




## NUMBER OF NEWLY FOUNDED SYNTHETIC BIOLOGY COMPANIES

Source, facing page: Deep View analysis from 1 May 2022 to 30 April 2024; (1) YoY media growth = YoY growth of topic mentions from May 2022/April 2023 to May 2023/Apr 2024; (2) YoY patent growth = YoY growth of granted topic patents from May 2022/April 2023 to May 2023/Apr 2024.

Source, this page: Pitchbook
*Data on newly founded companies in 2023 is incomplete and will be updated once first funding is raised. Projections indicate similar levels of company creation to 2021.

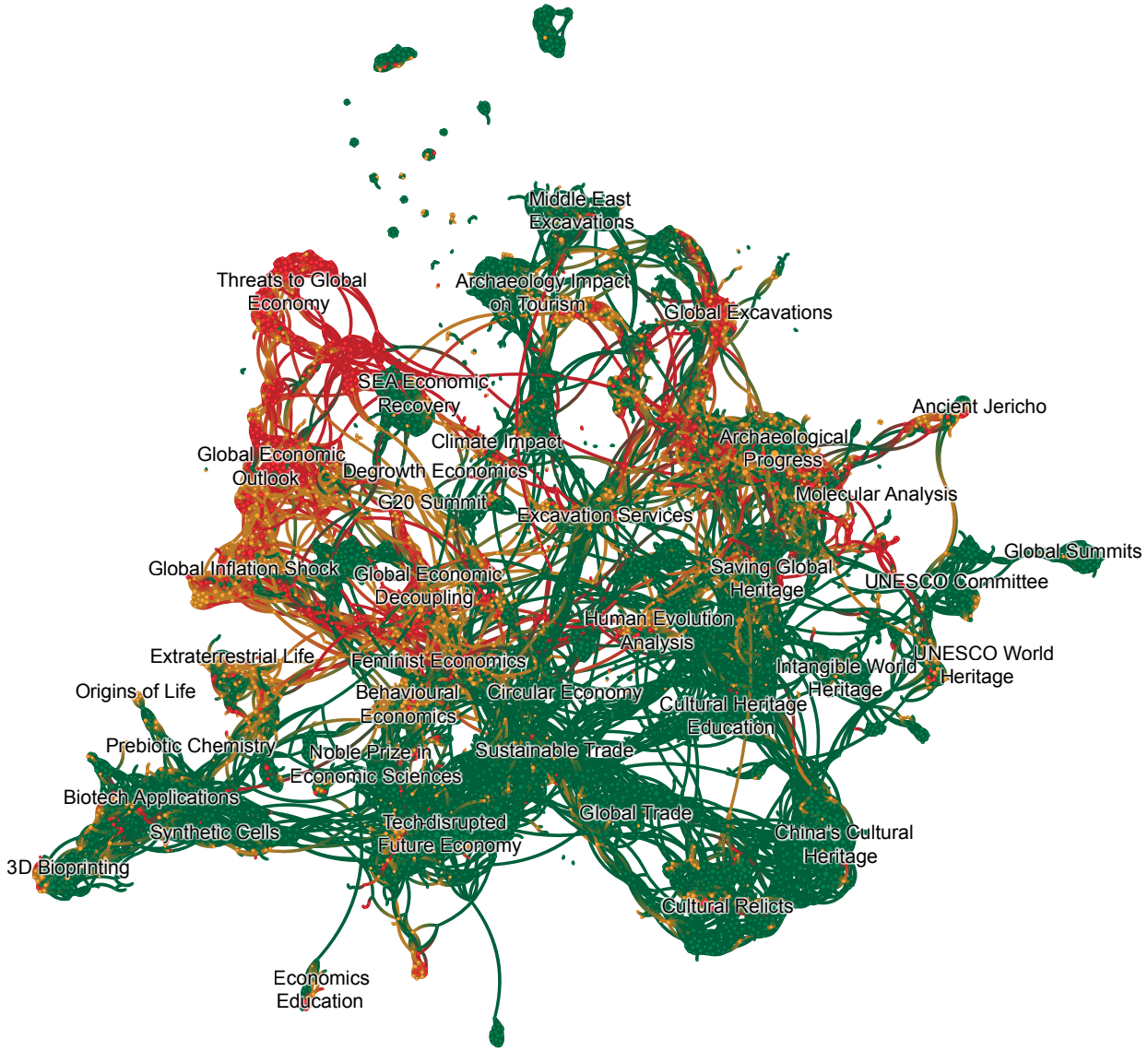
## What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months shows that, while the public discussion surrounding topics covered in the Knowledge Foundations Platform maintains a positive net sentiment in mainstream media, it is framed more negatively compared with discussions on other Scientific Platforms at 68 per cent. Despite this trend, significant positive developments are evident, highlighted by a notable 10 per cent increase in net positive sentiment towards Economics and a 6 per cent rise in positive sentiment concerning the Archaeology from 2023 to 2024.

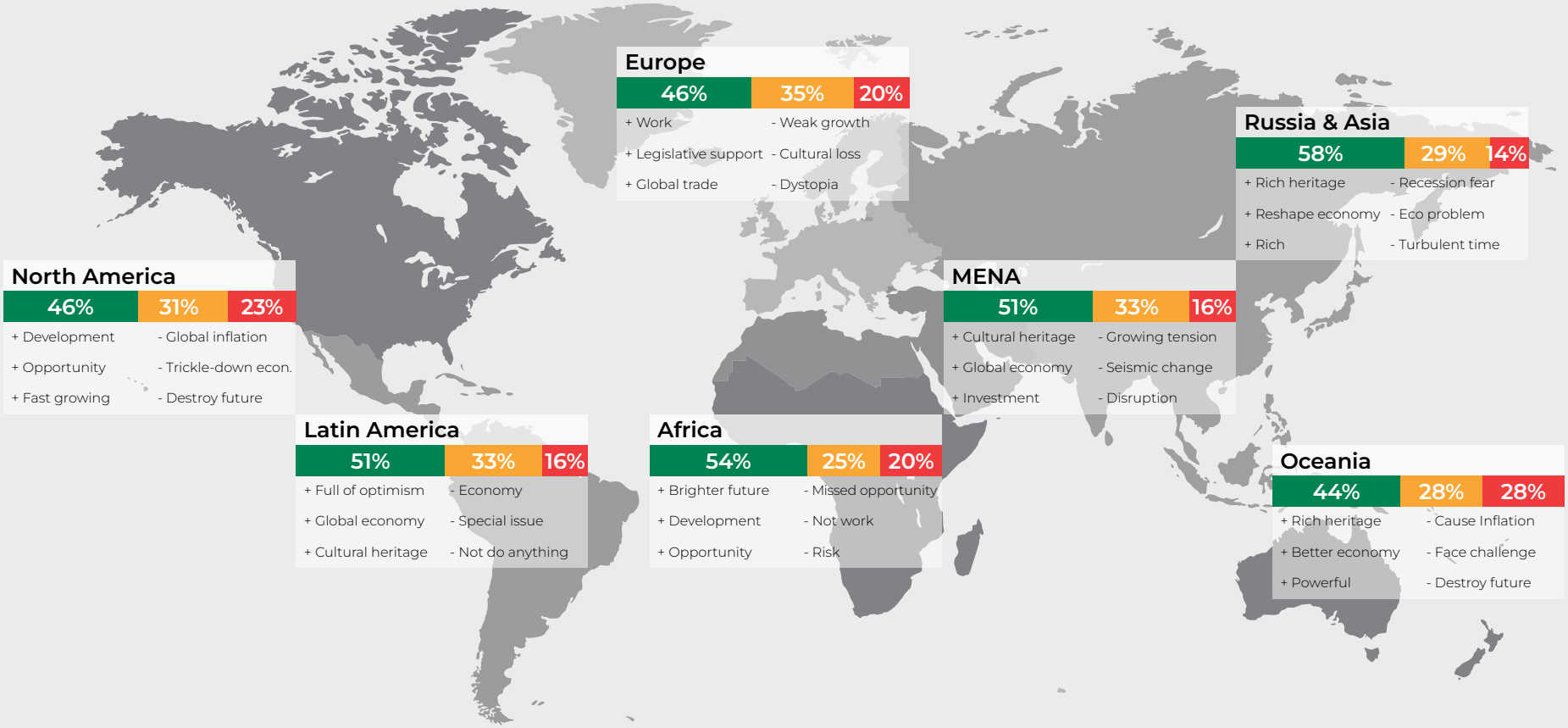
MAINSTREAM MEDIA SENTIMENT

| MAINSTREAM MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| UNIQUE ARTICLES | 638k |
| VISUALISED ARTICLES | 5k |
| NET SENTIMENT | 68% |
| ARTICLE UNIQUENESS | 48% |

| SOCIAL MEDIA | 1 May 2023 - 30 April 2024 |
|---|---|
| NUMBER OF POSTS | 2867k |
| VISUALISED POSTS | 10k |
| NET SENTIMENT | 43% |
| UNIQUE IMPRESSIONS | 260b |



DEMOGRAPHICS & SENTIMENT PER REGION




GLOBAL SENTIMENT

- Sentiment around **Knowledge Foundations is broadly neutral outside of Russia & Asia and Africa**, where posts are more positively associated. Globally, the primary positive sentiment drivers focus on cultural heritage. In contrast, concerns primarily centre around the potential for future economic disruptions, framing the discussion negatively.

- Participation in discussions about **Knowledge Foundations shows a strong male presence**, with male contributors comprising up to three-quarters of all posters in **Latin America and Russia & Asia**.

- Geographically, the conversation is led by the **US** in North America (93%). In **Europe**, the UK (52%), Germany (11%) and France (5%) are the top contributors. **Latin America** sees equal participation from Brazil and Mexico (20% each). In **Africa**, Nigeria (36%), South Africa (19%) and Kenya (13%) lead the discourse. **Asia** is dominated by India (63%), with smaller contributions from Indonesia (5%) and China (4%). For the **MENA region**, Turkey (30%), the United Arab Emirates (16%) and Saudi Arabia (11%) are key contributors.

Source: Quid Social, containing the past 24 months of English language data from 10+ social media sources in 200+ countries.

# Media Analysis

## GROWTH

The discourse on Knowledge Foundations is being driven by discussions around Archaeology and Complex Systems Science. Although Economics shows a smaller growth rate of 14 per cent, its overall presence in the media is still large, second only to Archaeology.

## DOMINANCE

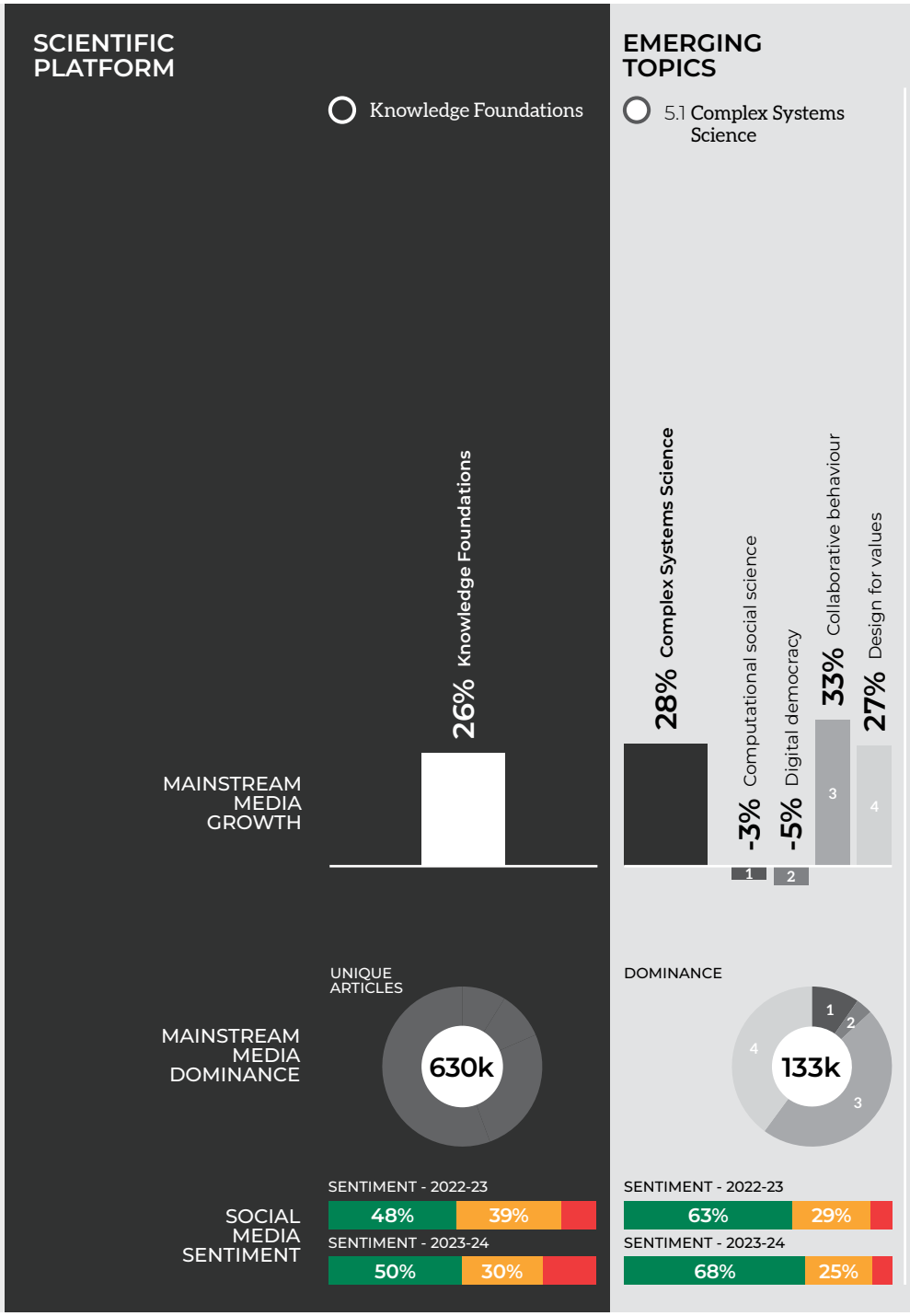
The substantial growth in discussion around Complex Systems Science and the Science of the Origins of Life can be attributed to the major increase in articles concerning their most dominant sub-topics, namely Collaborative behaviour and Systems biology. The most dominant topic, Archaeology, is primarily shaped by public discussions focusing on Exposing and decoding world heritage.

## SOCIAL SENTIMENT

A slow but positive increase in public discourse surrounding topics in the Knowledge Foundations Platform is reflected in the increase in positive sentiments in social media, with the exceptions of Economics and the Science of the Origins of Life.

MORE INFORMATION:

**go.gesda.global/Society**



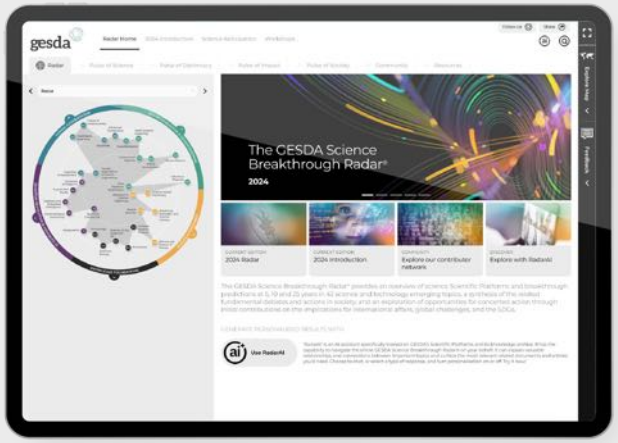
5.2 Economics
14% Economics
16% Managing climate externalities
12% Automation and work
-8% Bootstrapping circular economies
36% Sustainable global trade
DOMINANCE
137k
SENTIMENT - 2022-23
42%
32%
SENTIMENT - 2023-24
46%
30%
5.3 Science of the Origins of Life
25% Science of the Origins of Life
28% Prebiotic chemistry
18% Systems biology
17% The Geological record
45% Exobiology
DOMINANCE
40k
SENTIMENT - 2022-23
52%
28%
SENTIMENT - 2023-24
47%
27%
5.4 Synthetic Biology
6% Synthetic Biology
-6% Fundamental synthetic biology
12% Manufacturing, industry and agriculture
5% Medicine and health
0% Energy, climate and conservation
DOMINANCE
17k
SENTIMENT - 2022-23
57%
33%
SENTIMENT - 2023-24
58%
33%
5.5 Archaeology
33% Archaeology
200% Molecular-level analysis of ancient human remains
-41% Molecular-level analysis of ancient non-human remains
32% Palaeoclimate studies
58% Exposing and decoding world heritage
DOMINANCE
303k
SENTIMENT - 2022-23
51%
37%
SENTIMENT - 2023-24
62%
27%

DIGITAL PLATFORM

# Explore our online digital platform

All citations included in this book can be found in the resources tab on the digital platform using the URL or QR code below.

## radar.gesda.global



HUMAN AUGMENTATION
ECO-REGENERATION & GEOENGINEERING
SCIENCE & DIPLOMACY
KNOWLEDGE FOUNDATIONS
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4.3 Prediction, Foresight and Futures Literacy
1.1 Advanced AI
5.5 Archaeology
5.4 Synthetic Biology
5.3 Science of the Origins of Life
5.2 Economics
5.1 Complex Systems Science
4.5 Behavioural Science of Groups

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**A Swiss Foundation located in Geneva**

Campus Biotech
Chemin des Mines 9, 1202 Geneva
www.gesda.global
info@gesda.global

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